# Shear Strength of *Eucalyptus saligna* Wood Joints Bonded with Polyvinyl Acetate Adhesive

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Reforestation wood is interesting for construction, due to its potential as material source for manufacturing. For this purpose, the *Eucalyptus* genus has resulted in a better characterization of the material properties. During the production process, wood is machined at some stage, which influences the wood gluing quality. This study considered the performance of *Eucalyptus saligna* wood joints bonded with four commercial polyvinyl-acetate-based resins with different physical characteristics and chemical compositions. The surfaces of samples were prepared and machined by an up-milling process, using a planer, with wood feed rates of 6 m/min, 11 m/min, 16 m/min, and 21 m/min, which had advances per tooth of 0.25 mm, 0.45 mm, 0.66 mm, and 0.87 mm, respectively. The samples were prepared for shear strength testing of the glue line. During the preparation, all pieces were randomly bonded with regards to the formation plans of wood growth rings. Shear strength values were statistically compared to analysis of variance and Tukey test. Only C4 adhesive reached good results at all feed rates as well as having the best shear strength compared to other resins. Commercial adhesives had distinct interactions on the adhesive-wood interface, which resulted in different adhesion strengths.

*Keywords: Eucalyptus saligna; Timber; Machining; Feed rate; Adhesion; Shear strength*

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## INTRODUCTION

There has been an increasing demand for raw materials from renewable sources (Silva *et al*. 2012). In recent years, reforestation wood has generated interest for civil construction because of its potential as a raw material source for manufacturing, which has motivated studies on better characterization of its properties (Vital *et al*. 2005). Eucalypts are consolidated as important materials for different industrial applications (Plaster *et al*. 2012) because of its advantages, such as useful management, rapid growth, and large plantation availability (Peres *et al*. 2015). Multiple properties of eucalypt wood must be evaluated, and the adhesion capacity is one of the most important, which can involve the behavior of bonded joints. Some eucalypt species have shown good adhesion, while other forest essences have been considered unsatisfactory (Vital *et al*. 2005). The saligna variety (*Eucalyptus saligna* Sm, Myrtaceae) originates in Australia, and the best regions for its growth in Brazil are Rio Grande do Sul, Minas Gerais, and São Paulo (Gonzaga 1983).

This species is also known as Sydney blue gum (Boland *et al*. 2006; Mansouri *et al*. 2010; Cademartori *et al*. 2015; Mattos *et al*. 2015). *Eucalyptus saligna* timber has easy sawing (workability), easy machining (turning, drilling, and sanding), and good finishing, and therefore can be used in several sectors of the construction and furniture industries, as well as in compositions of general utility laminae, plywood, and packaging, despite the presence of cracks and warps from drying (IPT 1989). Wood machining and eucalypt rationalization have improved due to technological development over the years, which has improved characteristics and reduced waste (Ferreira *et al*. 2012).

Machining is part of the manufacturing process of several products that are processed in the timber sector, and wood is machined at some point or stage during the production process. Thus, understanding the concepts of these processes and their variables is necessary for a better view of the market and product quality within the industry (Souza *et al*. 2009). Gonçalves (2000) mentioned that there are two options in milling. These options are conventional or up-milling, where the tool performs a contrary movement to that of the piece, and down-milling, where the tool and wooden piece move in the same direction. This classification is only valid for parallel peripheral milling.

The end gluing of short, clear wood segments from low-quality logs enables the production of high-quality products from low-quality timber (Zobel 1984). To improve structural building components, wide knowledge of the physical-mechanical properties of local timber is necessary and of utmost significance. Testing of these components can be influenced by several intrinsic and extrinsic factors (Kollmann and Côté Jr. 1968; Silva *et al*. 2012; Pichler *et al*. 2018).

The machining process of wood can influence its adhesiveness. According to Frihart and Hunt (2010), finishing the wood surface after processing is important. This ensures that it is smooth, planed, and free of machining marks or other irregularities, including "smashes" from the planer, crushed spots, barbs, and loose fibers. This is important because adhesive bonding involves uniting surfaces. Kollmann *et al*. (1975) and Kollmann and Côté Jr. (1968) claimed that there are other factors that influence the adhesive bonding of wood, such as the anatomical, physical, mechanical, and chemical properties of the wood. Galembeck and Gandur (2001) reported two physical-chemical phenomena that occur during the bonding process, which are adhesion and cohesion. Adhesion is related to the mechanical strength of the interface between the adhesive film and substrate; According to Mano and Mendes (2004) cohesive resin strength depends on the molecular size, macromolecular organization, and super molecular uniformity.

There are four main existing theories about adhesion regarding the adhesive-wood interaction, which are mechanics, adsorption, diffusion, and chemical (Pizzi 1994). Authors like Kollmann *et al*. (1975) and Schultz and Nardin (2003) have believed that combination of adhesion theories is the closest scenario to reality.

Schultz and Nardin (2003) have emphasized that the proposed theoretical models are complementary and contradictory, but they do not cancel each other out and depend on the selected system. Each of these theories is valid to some extent, depending on the nature of the materials being bonded and the formation conditions of the bonded system. These authors also mentioned that these models usually differ in the mechanics and specific adhesion, considering that the latter is calculated depending on several types of bonds that can occur between two solids, which are electrostatic, secondary, and primary.

According to Jakes *et al*. (2007) and Follrich *et al*. (2010), adhesive penetration in the porous wood structure can occur in the micrometer (adhesive penetration occurs in the cell lumen) and nanometer ranges (adhesive penetration occurs in the cell wall).

Follrich *et al*. (2010) claimed that the adhesive application, pressure applied, and surface properties from the machining process, such as the cleanliness, structural damage, and roughness, may affect the adhesion results.

Frihart (2005) stated that resins based on polyvinyl acetate (PVAc) are currently used by various sectors of the furniture and/or logging industries for interior uses. Petrie (1999) and Salvini *et al*. (2010) have claimed that PVAc is the most versatile vinyl resin, and it is usually available in the form of a solution or emulsion. According to Bomba *et al*. (2014), PVAc adhesives have been developed for the industrial production of furniture, whose use has been intensified. The main advantages are its curing time at 10 °C, resistance to inorganic influences, simple application, and no-release of harmful substances due to a water-based character. It also has a low cost compared with other commercial resins. According to Kim and Kim (2006) and Özçifçi and Yapıcı (2008), PVAc resins are easy to apply and do not damage the tools during the cutting process. The mechanical strength of PVAc decreases at higher temperatures and loses its bonding strength above 70 °C.

Construction-grade timber and engineered forest products are some of the highest value products obtained from trees (Ramage *et al*. 2017). Then, there is a need to study wood-based materials. The objective of this study was to evaluate the bonding quality of *E. saligna* wood using shear strength testing of the glue line to qualify wood-adhesive interactions with different commercially available PVAc resins. Different feed rates were evaluated to generate distinct surface examples, with random bonding plans with regards to the disposition of the wood growth rings.

## EXPERIMENTAL

### Sample Preparation

*Eucalyptus saligna* wood was acquired in the city of Bauru (SP), Brazil, in the form of boards with a 5.0-cm thickness, 10.0-cm to 25.0-cm width, and 1.2-m to 1.8-m length. After sectioning the boards in battens, they were subjected to planing using a planer, trowel, and surfacer. They were sectioned in a trimmer with circular saw for length standardization, which created surfaces free of irregularities and warp. Wood parts were previously selected for removal of anomalies, such as the presence of regions of sapwood, knots, imperfections, malformation with resin pockets, and other irregularities.

The new format was a rectangle with the dimensions 3.5 cm × 4.0 cm × 90.0 cm. Thus, 34 wooden samples of *E. saligna* were selected and machined again to obtain 17 pieces with the nominal dimensions 2.5 cm × 3.5 cm × 90.0 cm and 17 pieces with the dimensions 3.5 cm × 3.5 cm × 90.0 cm. After sawing process, wooden parts were moved to a climate room at 12 °C with 20 °C air conditioning and a dehumidifier at 60% so that the parts could reach 12% moisture content. The stabilized battens were then planed in surface planer machines to remove surface imperfections that may have appeared because of warping from the pre-drying of battens or natural drying. This was done to standardize the pieces. After planing the surfaces and standardizing the dimensions, the parts had the nominal dimensions 2.2 cm × 3.5 cm × 90.0 cm and 3.2 cm × 3.5 cm × 90.0 cm. They were milled on one of the sides, previously selected and marked, in a milling machine.

Parts were subjected to parallel peripheral milling and regulated to 1.63 mm for the cut depth. Four feed rates were used: V1 = 6.0 m/min, V2 = 11.0 m/min, V3 = 16.0 m/min, and V4 = 21.0 m/min, which values corresponded to advances per tooth ($fz$) of the cutting tool for planing: $fz_1$ = 0.25 mm, $fz_2$ = 0.45 mm, $fz_3$ = 0.66 mm, and $fz_4$ = 0.87 mm.

A milling machine used in this study was the Plaina Moldureira Plus Advance 5E of 5/6 axis (Ibirama, Brazil), which presents an axis rotation of 6045 rpm and milling cutter diameter of 125 mm with four knives based on high speed steel with a cutting speed ($V_c$) of 39.45 m/s. After parallel peripheral milling, the parts became two with the nominal dimensions 2.0 cm × 3.5 cm × 90.0 cm and 3.0 cm × 3.5 cm × 90.0 cm. The parts were sectioned for length standardization using a trimmer with a circular saw, and then had the nominal dimensions 2.0 cm × 3.5 cm × 45.0 cm and 3.0 cm × 3.5 cm × 45.0 cm, respectively. The parts were not sanded and were only planed on a milling machine.

## Sample Bonding

Samples were bonded for the mechanical strength tests of the glue line with four commercial PVAc resins, which were C1 (*Cola branca Madeiranit*, Leme, Brazil) with classification D1 in EN 204 (2001); C2 (*Cascola Cascorez Extra*, Henkel, Itapevi, Brazil), D1 in EN 204 (2001); C3 (*Cascola Cascorez Cola Taco*, Itapevi, Brazil), D2 in EN 204 (2001); and C4 (*Eucafloor*, Botucatu, Brazil), classified as D3 in EN 204 (2001).

The single recommendation from the manufacturer Henkel for *Cascola Cascorez Extra* was followed. The weight was 200 $g/m^2$ and the pressure was about 13 $kgf/cm^2$ ($1.275 \times 10^6$ $N/m^2$). The other resin brands did not mention any recommendation about it.

The mass of the adhesive used for bonding the parts was 3.15 g, which was used for all of the resins. The process was performed randomly with regards to the formation plans of the wood growth rings, and each adhesive was spread with a brush on the wood surface to ensure uniformity. After adhesive application (by brushstroke), the parts were bonded immediately, not exceeding a period of five minutes to avoid an efficiency loss of the adhesive. The ends of the battens were bound with adhesive tape so that they would not slide off when pressed in the hydraulic press. Pressing was performed with a pressure for 4 h (13 $kgf/cm^2$ / $1.275 \times 10^6$ $N/m^2$). After removing the battens from the press, they were cured for 24 h, which followed the Henkel's recommendation.

## Processing Samples into Testing Specimens

After the bonding process, testing specimens were made and underwent shear strength tests of the glue line (Fig. 1). All of the analyzed shear strength tests of the glue line of *Eucalyptus saligna* wood were performed at the Laboratory of Physical and Mechanical Properties of Wood of São Paulo State University (UNESP), Campus of Itapeva.


(a) (b) (c) (d)

**Fig. 1.** Rupture of the testing specimens: (a) universal testing machine, (b) shear strength test on the adhesive line, (c) rupture of the specimens at the glue line and (d) bonding failure on the test.

A universal testing machine (DL 3000, EMIC, Instron Brasil, São José dos Pinhais, Brazil) was used to perform mechanical tests, with a capacity of up to 300 kN. These tests to determine the shear strength were performed according to ABNT NBR 7190 (1997). The load on the testing specimens in the machine was applied at rate of 2.5 MPa/min.

### Statistical Analysis

The statistical evaluation was performed using the software R (Version 3.4.2, R Foundation, Vienna, Austria). This software performed an analysis of variance, which considered differences between the means of the treatment at a significance level of 5%, as well as Kolmogorov-Smirnov and Bartlett tests. Tukey test was also applied at 5%.

## RESULTS AND DISCUSSION

The results of the mean values obtained from the shear strength tests of the glue line of the specimens are discussed hereafter. Table 1 shows the mean values obtained from the shear strength tests of the adhesive line of the specimens at a rate of 6.0 m/min.

The best result for the shear strength was with adhesive C4 compared with the others. In contrast, adhesive C2 presented the lowest result. This occurred because of the formula of the adhesives, which interfered with bonding. According to Iwakiri *et al*. (2013), different wood species present great variability between trees and parts of the same tree, which influences the bonding of wood with different types of adhesives. Vital *et al*. (2006) verified the performance of *E. saligna* and *E. gris* bonded with PVAc adhesives (*Cascorez 2250* and *Cascorez 2280*), and the strength values obtained for both species with adhesive 2250 were 10.03 MPa and 8.95 MPa, respectively. For adhesive 2280, the strength values were 9.32 MPa and 8.49 MPa for *E. saligna* and *E. gris*, respectively. Vital *et al*. (2006) noted that the interaction between the wood species and adhesive type have different effects. The shear strength analysis of the *E. saligna* wood (Fig. 2) at a feed rate of 6 m/min determined according to ABNT NBR 7190 (1997).

**Table 1.** Mean Shear Strength Values of the Specimens at 6.0 m/min

| Feed Rate | Adhesive | $f_{v0}$ (MPa) | Standard Deviation | Coefficient of Variation (%) |
|---|---|---|---|---|
| V1 = 6.0 m/min | C1 | 6.6a | 0.56 | 8.51 |
| | C2 | 4.8b | 0.83 | 17.39 |
| | C3 | 6.8a | 1.68 | 24.67 |
| | C4 | 11.4c | 1.03 | 8.976 |

* Means followed by the same letter do not differ among themselves at a 5% significance level

Adhesives C1 and C2 had values that were below the mean results of the shear strength tests (Fig. 2). This occurred due to randomized bonding of the parts, which disregarded the wood growth rings, meaning that the fiber directions varied. According to Lobão and Gomes (2006), the variation in the fiber directions influence the bonding and shear strength results. Another possible reason that these two values were below the mean could have been that extractives migrated to the wood surface after machining, which could have interfered with bonding (Stehr and Johansson 2000). Figure 1d shows a bonding failure that could have happened because of the migration of extractives to the surface of the testing specimens. De Conti (2011) studied the *E. saligna* joints bonded with PVAc resins (*Cola Wonderbond 2555* and *Cascorez Cola Taco*) submitted to shear strength tests with a feed rate of 6.0 m/min and advance per tooth of 0.86 mm from the cutting tool. The mean values for *Cola Wonderbond* and *Cascorez Cola Taco* adhesives were 10.55 MPa and 8.34 MPa, respectively. Compared with the values obtained in this study, adhesives C1, C2, and C3 had lower values than those from De Conti (2011).

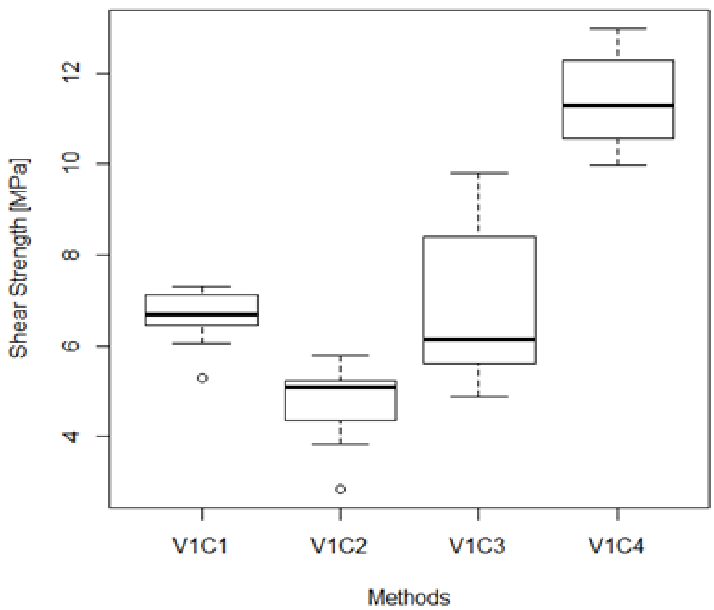


**Fig. 2.** Boxplot for the analysis of the shear strength of the *Eucalyptus saligna* wood for a standard feed rate of V1 = 6 m/min, determined according to ABNT NBR 7190 (1997)

Silva (2013) studied the mechanical strength of *E. saligna* wood bonded with polyurethane (PU) adhesives (one-component *Cascola* and derived from bi-component castor oil) with a feed rate of 6.0 m/min and advance per tooth of 0.86 mm from the cutting tool. The values obtained were 8.47 MPa (one-component) and 8.17 MPa (bi-component). Compared with this study, only adhesive C4 had a greater strength value.

Table 2 presents the mean values obtained from the shear strength tests of the adhesive line of the specimens at a feed rate of 11.0 m/min.

De Conti (2011) obtained values of 12.84 MPa for *Cola Wonderbond 2555* and 10.12 MPa for *Cascorez Cola Taco* at a feed rate of 11.0 m/min and advance per tooth of 1.57 mm. When compared, all of the values obtained in this study were below the values reported by De Conti (2011).

**Table 2.** Mean Shear Strength Values of the Specimens at 11.0 m/min

| Feed Rate | Adhesive | $f_{v0}$ (MPa) | Standard Deviation | Coefficient of Variation (%) |
|---|---|---|---|---|
| V2 = 11.0 m/min | C1 | 6.6a | 1.08 | 16.42 |
| | C2 | 3.4b | 0.67 | 19.68 |
| | C3 | 6.5a | 1.07 | 16.38 |
| | C4 | 7.8c | 1.42 | 18.15 |

* Means followed by the same letter do not differ among themselves at a 5% significance level

Alves (2012) studied the shear strength of the glue line of *E. saligna* wood joints with sanded surfaces bonded with the *Cola Wonderbond 2555* resin at a feed rate of 11.0 m/min and advance per tooth of 1.55 mm. The mean results obtained were 11.69 MPa, 11.46 MPa, 10.83 MPa, 11.47 MPa, and 13.67 MPa for particle sizes P80, P100, P120, P150, and P220, respectively. These results are greater than those obtained in this study.

Silva (2013) verified the shear strength of the glue line of *Eucalyptus saligna* joints, sanded and non-sanded, bonded using two types of PU resins with a feed rate of 11.0 m/min and advance per tooth of 1.57 mm. The values for the non-sanded joints were 7.34 MPa (*Cascola* one-component polyurethane) and 10.75 MPa (resin PU derived from bi-component castor oil). The particle sizes used were P80, P100, P120, P150, and P220. The results obtained for one-component resin on the sanded joints (and their respective particle sizes) were 7.62 MPa (P80), 7.80 MPa (P100), 7.07 MPa (P120), 8.04 MPa (P150), and 5.89 MPa (P220); and for the bi-component adhesive, they were 11.90 MPa (P80), 15.23 MPa (P100), 10.67 MPa (P120), 10.97 MPa (P150), and 13.54 MPa (P220).

Figure 3 presents the shear strength analysis of the *E. saligna* wood at a feed rate of 11 m/min, respecting ABNT NBR 7190 (1997). Table 3 shows the mean values from the shear strength tests of the adhesive line of the specimens at a rate of 16.0 m/min.

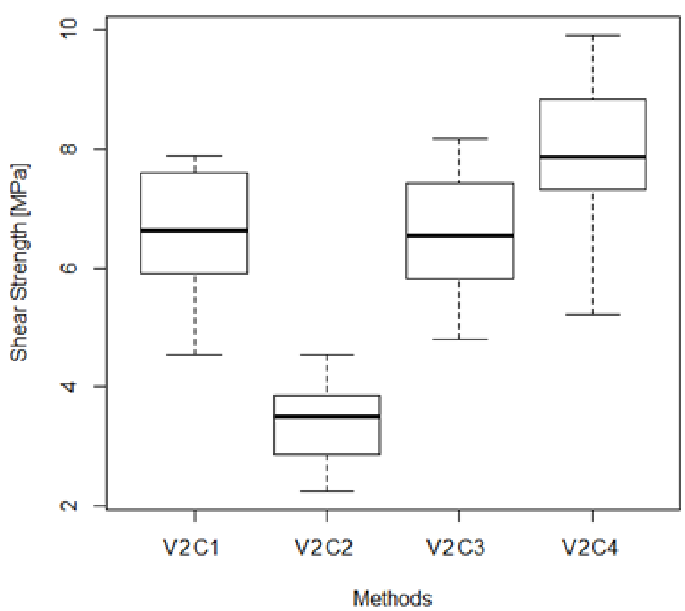


**Fig. 3.** Boxplot for the analysis of the shear strength of the *E. saligna* wood for a standard feed rate of V2 = 11 m/min

**Table 3.** Mean Shear Strength Values of the Specimens at 16.0 m/min

| Feed Rate | Adhesive | $f_{v0}$ (MPa) | Standard Deviation | Coefficient of Variation (%) |
|---|---|---|---|---|
| V3 = 16.0 m/min | C1 | 6.5a | 0.83 | 12.77 |
| | C2 | 4.1b | 0.50 | 12.30 |
| | C3 | 6.9a | 1.34 | 19.38 |
| | C4 | 9.1c | 1.10 | 12.08 |

* Means followed by the same letter do not differ among themselves at a 5% significance level

Iwakiri *et al*. (2013) studied the shear strength of *E. benthamii* wood joints bonded with PVAc. The mean value obtained was 9.04 MPa. This value was greater than the results here at a feed rate of 16.0 m/min. In contrast, Lima *et al*. (2008) tested clones of *Eucalyptus* sp. wood bonded with a polyvinyl alcohol (PVA) adhesive (*Movicol* PVA), and the values obtained for the shear strength ranged from 6.98 MPa to 7.94 MPa.

The analysis of the shear strength of the *E. saligna* wood at a feed rate of 16 m/min determined according to ABNT NBR 7190 (1997) is presented in Fig. 4.

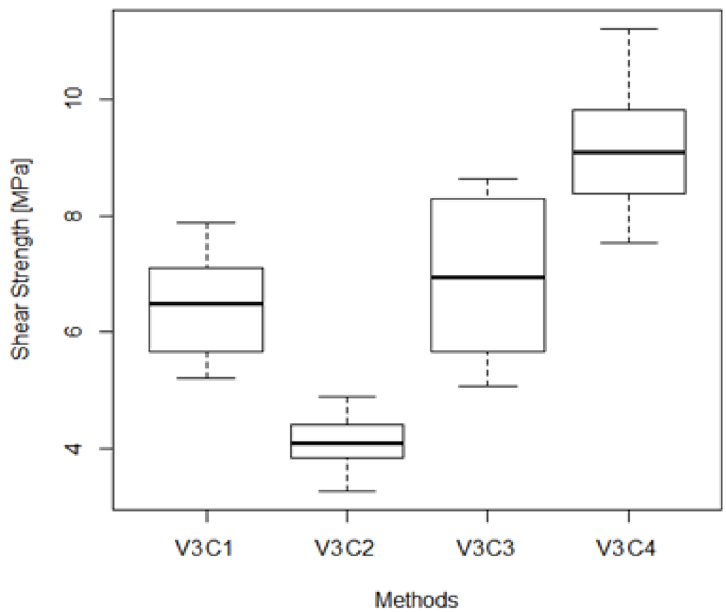


**Fig. 4.** Boxplot for the analysis of the shear strength of the *E. saligna* wood for a standard feed rate of V3 = 16 m/min

At a feed rate 15.0 m/min and advance per tooth of 2.14 mm, De Conti (2011) obtained strength values of 10.84 MPa and 9.68 MPa for *Cola Wonderbond 2555* and *Cascorez Cola Taco*, respectively. These results were greater when compared with the results of this study. This did not occur when comparing these results with those of Silva (2013) at a feed rate of 15.0 m/min and advance per tooth of 2.14 mm. The mean strength values were 6.41 MPa (one-component) and 12.62 MPa (bi-component).

Table 4 shows the mean values obtained from the shear strength tests of the resin line of the specimens at a rate of 21.0 m/min. Figure 5 presents the shear strength analysis of the *E. saligna* wood at a feed rate of 21 m/min based on ABNT NBR 7190 (1997).

The best shear strength was obtained with adhesive C4 compared with the others. In contrast, adhesive C2 had the lowest value. Adhesive C3 had a value below the mean. Also, there were two values greater than those of adhesives C2 and C3.

**Table 4.** Mean Shear Strength Values of the Specimens at 21.0 m/min

| Feed Rate | Adhesive | $f_{v0}$ (MPa) | Standard Deviation | Coefficient of Variation (%) |
|---|---|---|---|---|
| V4 = 21.0 m/min | C1 | 6.0a | 0.71 | 11.72 |
| | C2 | 3.5b | 0.63 | 17.75 |
| | C3 | 7.4c | 1.04 | 14.13 |
| | C4 | 10.5d | 0.96 | 9.16 |

* Means followed by the same letter do not differ among themselves at a 5% significance level

Lastly, with respect to the obtained results from whole experimental stage, about 4% of all samples presented wood failure.

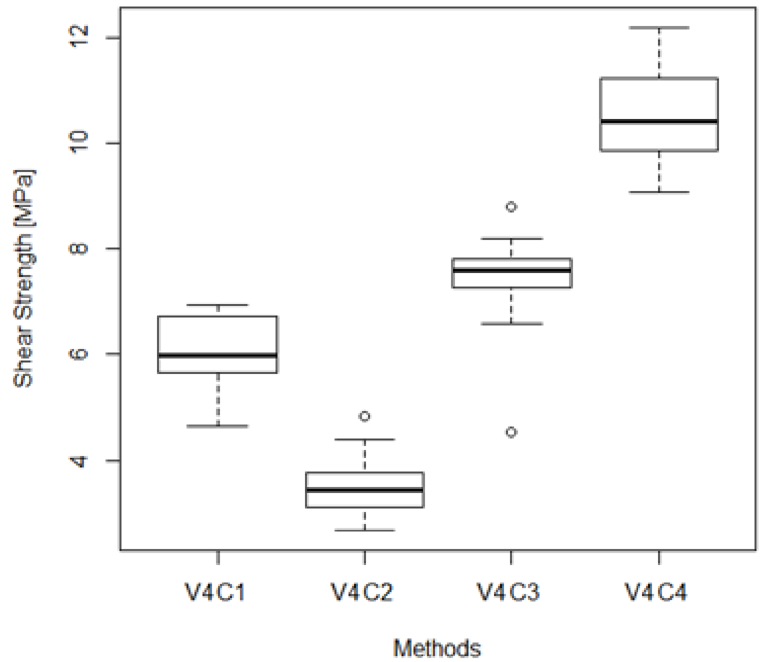


**Fig. 5.** Boxplot for the analysis of the shear strength of the *E. saligna* wood for a standard feed rate of V4 = 21 m/min

Plaster *et al*. (2008) studied the performance of *Eucalyptus* sp. joints bonded with a PVAc adhesive (*Cascorez 2590*). The obtained value of 13.75 MPa was greater than the results obtained in this study at a feed rate of 21.0 m/min. Plaster *et al*. (2012) used the PVAc resins *Cascorez 2590* and *Wonderbond WB-25* to bond clonal hybrids of *E. urophylla* × *E. gris* for three handling conditions, whose mean values are in Table 5.

**Table 5.** Mean Shear Strength Values of the Glue Line for Handling Conditions

| PVAc Adhesive | *E. urophylla* (MPa) | *E. gris* (MPa) | Handling |
|---|---|---|---|
| *Cascorez 2590* | 10.67 | 9.41 | 1 |
| | 12.69 | 8.67 | 2 |
| | 9.99 | 9.07 | 3 |
| *Wonderbond WB-25* | 12.84 | 9.57 | 1 |
| | 14.07 | 8.84 | 2 |
| | 12.27 | 9.37 | 3 |

Plaster *et al.* (2012)

The results obtained by Plaster *et al*. (2012) for *E. urophylla* with the adhesive *Wonderbond WB-25* were greater than the results of this study at a feed rate of 21.0 m/min. For *E. gris* with both adhesives, only adhesive C4 had greater values.

## CONCLUSIONS

1. For all the test specimens bonded randomly with regards to the formation of the wood growth rings and subjected to shear strength tests, only adhesive C4 had satisfactory results for all of the feed rates compared with the results in the literature.

2. Regarding the different feed rates, there were no significant differences for adhesives C1 and C3. The feed rate had no influence on bonding (wood/adhesive interface). For adhesives C2 and C4, the feed rate had a significant influence on adhesion.
3. For the adhesives criteria, adhesive C4 had the best shear strength value compared with the others. In contrast, adhesive C2 had the lowest value. This occurred because of the formulation of the adhesives, which interfered with bonding. However, resins C1 and C3 presented no significant differences, despite having different formulations. Other considered factors could be the resin penetration in the porous structure of the wood, formation of "hooks", viscosity, and solid content of the adhesive.
4. From the foregoing, this study evinced that lower feed rates provided decreases in the advance per tooth for machined parts as well as better results in wood surfaces, which resulted in better quality gluing. Thereby, this finding contributed to a better quality wood processing for forest product industrialization such as furniture, lamination, *etc*.

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