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Bonding performance of wood of fast-growing tree species eucalyptus (*Eucalyptus grandis*) and radiata pine (*Pinus radiata* D. Don) with polyvinyl acetate and emulsion polymer isocyanate adhesives

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Abstract. Fast-growing imported plantation tree species have become an available wood resource for Europe's wood industry in the last decades. This sustainable alternative may reduce the gap between the increasing demand for and decreasing supply of the local tree species. The aim of the study was to evaluate the performance of eucalyptus (*Eucalyptus grandis*) and radiata pine (*Pinus radiata* D. Don) wood in face-bonding with polyvinyl acetate (PVAc) and emulsion polymer isocyanate (EPI) adhesive for the production of non-structural semi-finished glued laminated timber members for window manufacturing. Test specimen preparation and testing were performed according to European standards. Tensile shear strength and wood failure percentages were determined as bonding performance indicators for 3 adhesives and 3 selected bonding parameters (pressure, pressing time and adhesive spread) in 27 variations after boiling the specimens in water. According to the results, the bonding variables influence the glue-line tensile shear strength and wood failure percentages. Bonding pressure and pressing time were evaluated as the most significant factors influencing shear strength of bonded joints. For all bonding variations the average level of shear strength from 3.45 to 5.23 MPa were reached for PVAc adhesive and from 3.78 to 9.65 MPa for EPI adhesives. Both EPI adhesives provide higher performance compared to PVAc adhesive. In the case of bonding fast-growing tree species, the highest shear strength values were achieved using the lowest pressure of 0.8 MPa, adhesive spread from 150 to 180 g m^{-2} and longest pressing time of 40 min. Based on the general evaluation of the results, it can be stated that the wood of eucalyptus and radiata pine bonded with both EPI adhesives presents great potential for non-structural semi-finished glued laminated timber member production, especially for the use in humid conditions.

Key words: bonding, EPI, *Eucalyptus grandis*, fast-growing wood, *Pinus radiata* D. Don, PVAc.

INTRODUCTION

Fast-growing imported plantation tree species have become an available wood resource for the European wood industry. Two tree species - eucalyptus (*Eucalyptus grandis*) and radiata pine (*Pinus radiata* D. Don) are at the top of the list in this respect.

These sustainable alternatives may replace some of the local tree species for the production of wooden windows and structural elements (Liao et al., 2017).

Radiata pine (*Pinus radiata* D. Don*)* is the most widely spread commercial forestry fast-growing tree species covering an estimated 1.8 million ha in New Zealand (Palmer et al., 2010) where its rotation period is 28 years for sawlog production and the annual growth rate is evaluated at 17 m^3 ha^{-1} $year^{-1}$ (Cubbage et al., 2010). In total, 13.7 million m^{-3} of radiata pine pulpwood and sawn timber were exported from New Zealand in 2011 (Ministry of Primary Industries, 2020).

Eucalyptus is one of the fastest growing tree species in the world and the most commonly planted forest species in Uruguay (over 0.25 million ha) (Rachid–Casnati et al., 2019). Its rotation period is 16 years for sawlog production and the annual growth rate is evaluated at 30 m^3 ha^{-1} $year^{-1}$ in Uruguay (Cubbage et al., 2010) and up till 50 m^3 ha^{-1} $year^{-1}$ in Turkey (Gürses et al., 1995). The availability of eucalyptus sawn timber is evaluated at 0.7 million m^{-3} according to Dieste et al. (2019).

Physical and mechanical properties of eucalyptus and radiata pine wood differ significantly depending on the growth region and growth conditions. The majority of radiata pine wood properties do not differ significantly from Scots pine (*Pinus sylvestris* L.) properties but some of mechanical properties of eucalyptus even exceed the properties of the common European oak (*Quercus robur*) which is a conventional species for manufacturing wood windows in Europe (Iejavs et al., 2021). Good shape, acceptable price, mechanical properties and high growth rate of fast-growing plantation wood species Eucalyptus and Radiata pine make them an ideal choice for local wood species substitution in Europe (Iejavs et al., 2018).

The declining availability and decrease in the quality of wood resources significantly increase the importance of wood bonding in the woodworking industry in Europe. The strength of the glued joint is of crucial importance in the production of glued wood products; therefore, special attention should be paid to the process of manufacturing the glued joint and the selection of appropriate bonding technological parameters. Glued joints should be compatible with environmental conditions to which the wooden structure will be subjected during its service life (Pereira et al., 2016).

Polyvinyl acetate (PVAc) is one of the most common adhesives used in non-structural applications. PVAc is capable of producing strong and durable bonds on both hardwoods and softwoods. However, PVAc adhesives are not generally recommended for joints under continuous load or those subjected to high temperature and/or high humidity (Jokerst, 1981; Vassiliou et al., 2006).

Emulsion Polymer isocyanate adhesive (EPI) is a two-component adhesive that combines an emulsion component and an isocyanate functional cross-linking componet. The glue line is cold curing, it has high flexibility, low creep, contains no formaldehyde and provides excellent water resistance in both cold and boiling water. EPI systems have very good adhesion to wood and metal and glues difficult wood species. EPI adhesive systems have been used since the early 1970s in Japan but the first EPI adhesive was approved for structural glued laminated timber production in Europe only in 2005 (Grøstad & Bredesen, 2014), therefore there is a lack of information about the EPI adhesive performance for non-structural glued laminated timber production, especially for fast-growing plantation wood species.

The choice of optimal bonding parameters is crucial to obtain an appropriate bonding strength of the joint. Too low of bonding pressure does not ensure the mechanical penetration of the glue into the wood, which forms mechanical adhesion, but too high of a pressure leads to a thin bond line, which reduces the cohesion strength of the bond line (Vick, 1999; Tienne et al., 2008). Pressing time plays an important role in the process of bonding to provide the necessary mechanical strength of the glued joint (Vick, 1999; Mölleken et al., 2016). The pressing time should be as short as possible to reduce the production time of glued products. The increase of adhesive spread can significantly increase the strength of the glued joint (Vick, 1999; Follrich et al., 2010; Fonte & Trianoski, 2015), but the economical aspect of the adhesive losses during at the bonding process should be taken into consideration. Surface preperation before bonding (sawing, planing and sanding) has a significant effect on the final bond strength. Both closed and open assembling time during the bonding process affects the bonding quality, especially when 2 component EPI adhesives are used with very short open assembling time (Pitzner & Lind, 2005). In general, the increase in wood surface roughness significantly reduces the strength of bonded joints (Vick, 1999; Iždinský et al., 2021), but under certain specific conditions the surface roughness increases the bondig area, resulting in the increased shear strength of the bonded joint (Follrich et al., 2010).

Wood moisture content during the bonding process and the end use conditions affect the bond strength. According to Bomba et al. (2014), for PVAc adhesive and beech wood (*Fagus sylvatica* L.) shear strength of the joint decreases by 37% if wood with moisture content of 20% is bonded instead of 8%. Test specimen immersion in water for 24 hours decreases shear strength of joint by 87% for PVAc adhesive.

The temperature of the environoment and the wood during the bonding process affect the strength of solid wood and wood joints. Wood joints with PVAc and EPI adhesives are more sensitive to temperature decrease from 20 °C to -20 °C compared to PUR and PRF (phenol-resorcinol-formaldehyde adhesive) (Pitzner & Lind, 2005; Wang et al., 2015). A significant decrease in timber bending strength of fingerjointed aspen (*Populus tremula* L.) was observed for PVAc adhesive when wood temperature increased from 20 °C to 100 °C (Iejavs et al., 2018).

The strength of thermoplastic PVAc and EPI adhesive joints is most significanly influenced by the combined effect of incresed temperatures and humidity, reducing the shear strength by 88% (Bomba et al., 2014). Such specimen pretreatment is provided by standard LVS EN 204 (2016) conditioning sequence 5. According to Iwakiri et al. (2019) shear strength results of bonded eycalyptus wood species, after humid pretreatment, were not found in the literature.

Limited or inconsistent information is available on bonding fast growing imported plantation wood species, especially with EPI adhesives (Calil Neto, 2010; Calil Neto et al., 2016) in contrast to conventional wood species such as Beech (*Fagus sylvatica* L.), Scots pine (*Pinus sylvestris* L.) and Spruce (*Picea abies* L.), which have been frequently investigated and used industrially in Europe (Pitzner & Lind, 2005; Vassiliou et al., 2006; Bomba et al., 2014; Wang et al., 2015; Konnerth et al., 2016). The determination of the optimal bonding parameters of fast growing wood species allows us to choose appropriate adhesives and bonding regimes for industrial manufacturing of wooden window blanks and other non-structural wood products with PVAc and EPI adhesives.

Therefore, the main goal of the study was to find the correlation between changing bonding parameters of polyvinyl acetate (PVAc) and emulsion polymer isocyanate (EPI) adhesives and the degree of shear strength of the glued fast-growing imported plantation timber species eucalyptus (*Eucalyptus grandis*) and radiata pine (*Pinus radiata* D. Don) wood after boiling pre-treatment.

MATERIALS AND METHODS

Wood

For this study the wood of two fast-growing plantation tree species eucalyptus (*Eucalyptus grandis*) from Uruguay ('Rivera' Department) and radiata pine (*Pinus radiata* D. Don) from New Zealand ('Taupo' region) was used. The raw material was kiln dried sawn timber (moisture content = 12 ± 3%) with nominal cross section dimensions of 35x150 mm and a length of 4 m. A total of 30 straight grained, defect free boards were randomly selected from both wood species with an angle between the growth rings and the surface between 30° to 90° to prepare test specimens according to standard LVS EN 205 (2016). After the timber delivery, all boards were conditioned to a constant mass in a standard atmosphere (air temperature 20 ± 2 °C; air humidity 65 ± 2%). The average moisture content after the conditioning of timber was 12.0% for eucalyptus and 12.7% for radiata pine. The corresponding average density was 588 kg m^{-3} for eucalyptus and 504 kg m^{-3} for radiata pine. Other physical and mechanical properties of timber used in the study are presented in the literature (Iejavs et al., 2021).

Adhesives and bonding parameters

Three different adhesives were used in this study to assess their ability to bond fast-growing wood species in face bonding: a one-component cross-linking polyvinyl acetate emulsion (PVAc) Dynea Prefere 6415 and 2 two-component emulsion polymer isocyanate adhesives (EPI–1) Dynea Prefere 6151 with hardener 6651 and (EPI-2) Dynea Prefere 6170 with hardener 6670. All materials and adhesives for this study were kindly provided by 'Kokpārstrāde 98' Ltd. The technical data of the adhesives are presented in Table 1.

Table 1. Technical data of the adhesives

Characteristics	Adhesive codes				
	PVAc	EPI–1		EPI–2	
		adhesive	hardener	adhesive	hardener
Commercial name	Prefere 6415	Prefere 6151	Prefere 6651	Prefere 6170	Prefere 6670
Adhesive type	PVAc	EPI		EPI	
Durability class LVS EN 204 (2016)	D4	D4		D4	
Appearance	white, viscous liquid	white, viscous liquid	brown liquid	milky-white liquid	brown liquid
No. of components	1	2		2	
Viscosity at 23 °C, mPa s^{-1}	6,500–8,500	6,000–10,000	250–400	5,000–6,000	200
Density, kg m^{-3}	1,100	1,260	1,240	–	–
pH	2.5–3.5	6.5–8.5	–	6.4–8.4	–
Solid content, %	49–52	59–61	–	56–60	–
Glue spread, g m^{-2}	100–250	175–400		120–250	
Pressure, MPa	0.5–1.2	0.6–1.2		0.7–1.6	
Minimal pressing time, min	15–35	10–30		15	
Wood moisture content, %	–	6–15		6–15	
Mixing ratio	–	100	15	100	15

From each of the boards several pairs of panels were prepared with nominal dimensions of 7×130×350 mm to bond 2 fast-growing wood species with 3 different adhesives. Shortly before bonding, all the surfaces to be bonded were lightly planed to obtain panels with a nominal thickness of 5 mm.

In total, a full factorial design (3×3×3) with 27 bonding parameter combinations (pressure 0.8, 1.0 and 1.2 MPa, pressing time 20, 30 and 40 min and adhesive spread 150, 180 and 210 g m^{-2}) were used in the study for each species and adhesive combination. For both EPI adhesives, the adhesive and hardener were mixed in a ratio of 100:15 (based on the weight percentage). The adhesive was applied on one side of the panel using a hand roller and the glue spread was controlled by a weighing method (Fig. 1, a). Pressing was done with the 1,500 kN press 'Joos' LAP 150 (Fig. 1, b). Maximum open assembling time was 1 min, and maximum close assembling time was 5 min in all cases.

Figure 1. Adhesive spread control (a) and panel pressing (b).

Test specimens and pre-treatment

The cutting of test pieces was done 7 days after specimen pressing and keeping in standard atmosphere. Each bonded panel with definite bonding parameters was cut into 10 test specimens with nominal dimensions of 20×150 mm. The final thickness was 10 mm. Flat bottomed cuts 2.5 mm wide in the bonded section across the grain were made completely through the bond line, so that the overlap of length was 10 mm. The final shear area of the test pieces was 10×20 mm. In total, for 2 wood species, 3 adhesives and 27 bonding parameter combinations 1,620 specimens were produced and tested. As a reference, 20 solid wood specimens of eucalyptus and radiata pine were produced and tested in the same manner as for glued specimens, with the exception of panel bonding, to compare the results with the solid timber shear strength. Test specimen dimension, test arrangement according to LVS EN 205 (2016) and a graphic of shear strength results for one set of 10 test specimens are presented in Fig. 2.

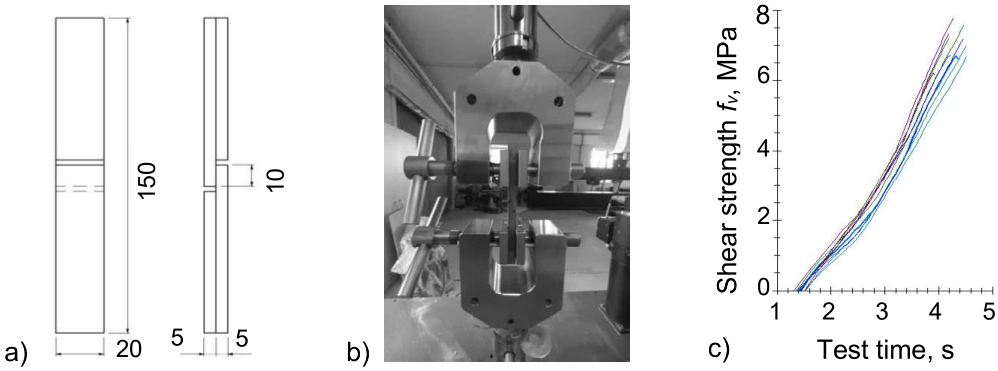

Figure 2. Test specimen dimensions in mm (a), tensile shear test arrangement (b) and the graphic example of 10 test specimens set shears strength results (c).

Each bonded specimen was marked with: wood species symbol G – for eucalyptus and R – for radiata pine; followed by adhesive symbol 64 (for PVAc adhesive 6415), 61 (for EPI–1 adhesive Prefere 6151/6651) and 617 (for EPI–2 adhesive Prefere 6170/6670), pressure symbol 0.8, 1.0 or 1.2 MPa; adhesive spread symbol 150, 180 or 210 g m^{-2} pressing time symbol 20, 30 or 40 min; and specimen No. from 1 to 10 within each bonded panel.

The following pre-treatment was applied to all specimens keeping them for 7 days in a standard atmosphere; 6 h in boiling water and 2 h in water at 20 °C before testing according to LVS EN 204 (2016) sequence 5. This pre-treatment is part of a procedure to determine the shear strength of adhesives for durability class D4 (for exposure to running or condensed water in the interior or for exterior use exposed to weather with an adequate surface coating).

Test procedure and evaluation

The test was carried out according to standard LVS EN 205 (2016) p. 6.5. procedure with Zwick Z100 test machine to determine tensile shear strength and an extra parameter - wood failure percentage *Wf*. Test speed 50 mm min^{-1} was used for all mechanical tests. The target average shear strength f_v of bond line should be equal or greater than 4 MPa according to the standard LVS EN 204 (2016). *Wf* was evaluated as suggested in standard LVS EN 314–1 (2005) with a 25% step and was as follows: 0%; 25%; 50%, 75% or 100% for individual specimens. Individual and average shear strength and *Wf* values were determined in 10 test specimens for each bonded panel. An example of *Wf* failure mode is presented in Fig. 3.

Figure 3. Wood failure percentage examples with wood failure 0%, 50% and 100%.

The results were analysed using programme ‘R’ version 4.1.0. Tukey *HSD* test at 5% significance level was performed to determine the difference between the grand average of shear strength (average between all bonding regimes within the wood species and adhesive combination) between adhesives. The average shear strength between bonding regimes (adhesive spread, pressing pressure and pressing time) was compared with pairwise *t*–test with ‘Bonferroni’ adjusted *p*–values with 95% confidence level. Analysis of variance (ANOVA) with interaction effects was used to identify the most significant factors and interaction effects influencing bonded joint shear strength. Due to the properties of wood failure percentage data (lack of normal distribution) no statistical analysis of these data was carried out.

RESULTS AND DISCUSSION

Both wood species with full factorial analysis of 3 adhesives and 3 selected bonding parameter combinations (pressure, pressing time and adhesive spread) in 27 variations provide a certain level of *fv*. Bonded joint failure during the specimen boiling procedure was not observed. The results of the study are presented in Fig. 4 for eucalyptus and in Fig. 5 for radiata pine. The average values of *fv* and standard deviation *SD* as the average wood failure percentage *Wf* are given for each adhesive and bonding regime. All tests were carried out in wet condition of the specimens. The target *fv* value for each species, adhesive and bonding parameter combination was ≥ 4 MPa according to standard LVS EN 204 (2016).

Shear strength of solid timber

The shear strength of 20 solid wood samples was also determined in the same manner as for glued samples for comparison. The results were as follows: the mean f_v was 8.40 MPa (standard deviation *SD* 1.25 MPa) for eucalyptus wood and 5.83 MPa (*SD* 1.08 MPa) for radiata pine.

Shear strength and wood failure percentage of bonded eucalyptus wood

The average values of *fv* for bonded eucalyptus wood varied from 3.45 MPa with PVAc adhesive (bonding pressure P – 1.2 MPa; adhesive spread S – 150 g m^{-2} and pressing time T – 20 min) to 9.65 MPa with EPI–1 (P – 0.8 MPa; S – 150 g m^{-2} and T – 40 min) according to Figure 4. The highest value 9.65 MPa for EPI–1 adhesive was significantly higher ($p < 0.05$) compared to other adhesives and bonding parameter combinations. The shear strength of the bonded joint even exceeds *fv* of solid timber by 15%. This can be explained by the difference between the average solid timber and individual bonded panel density. The average density of eucalyptus was 588 kg m^{-3} but maximum reached 738 kg m^{-3} with a 25% difference (Iejavs et al., 2021). The next highest result for EPI–1 adhesive was 8.68 MPa obtained with the same pressure and bonding time, but with an increased adhesive spread to 210 g m^{-2}. Similar shear strength results from 4.94 MPa to 8.07 MPa were obtained by Iwakiri et al. (2019) after the immersion of specimens for 24 h in water for 2 eucalyptus wood species (*Eucalyptus camaldulensis*, *Eucalyptus urophylla*) bonded with PVAc and EPI adhesives. According to Iwakiri et al. (2014) the adhesive spread used industrially for face bonding varies from 180 to 220 g m^{-2}.

From 27 bonding regimes in bonding eucalyptus wood with PVAc adhesive, 11 bonding regimes did not reach the average target shear strength value of 4 MPa according to LVS EN 204 (2016). Both EPI adhesives within all bonding regimes exceeded that of 4 MPa threshold value.

Statistically significant differences ($p < 0.05$) were found between the grand average *fv* between all adhesives used (Fig. 4). EPI–1 adhesive *fv* was significantly higher than for EPI–2 and PVAc. Accordingly, EPI–2 adhesive provides significantly higher *fv* compared to PVAc adhesive. The same tendencies can be observed for *Wf* data. *Wf* values vary within great amplitude between each wood species and adhesive combination. The highest values for eucalyptus were observed for EPI–1 and the lowest for PVAc adhesive. For 13 gluing parameter combination of 27, the lowest average *Wf* 0% was observed for PVAc adhesive and the highest for EPI–1 in 4 cases reaching *Wf* from 95 to 98%. A significant decrease in both *fv* and *Wf* values was observed for wet specimens (24 h immersion in water) compared to the dry (after air conditioning) specimens when several eucalyptus species were bonded with PVAc and EPI adhesives as described by Iwakiri et al. (2019) and when 13 hardwood species were bonded with PVAc adhesive by Iždinský et al. (2021).

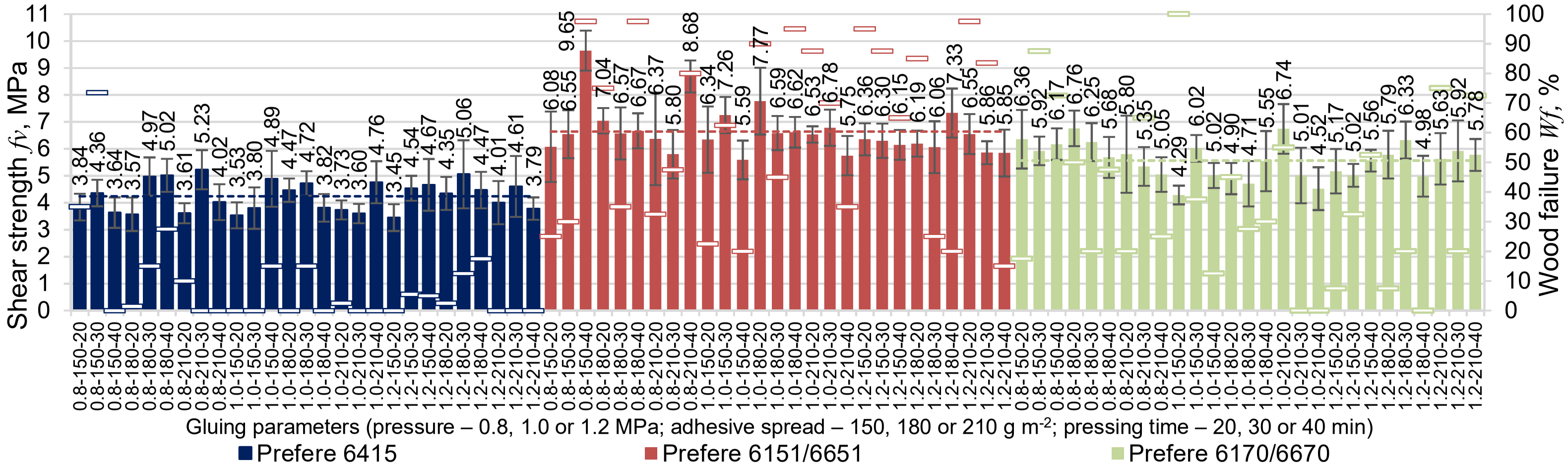

Figure 4. Average shear strength and wood failure percentage of bonded eucalyptus wood joints with three adhesives.

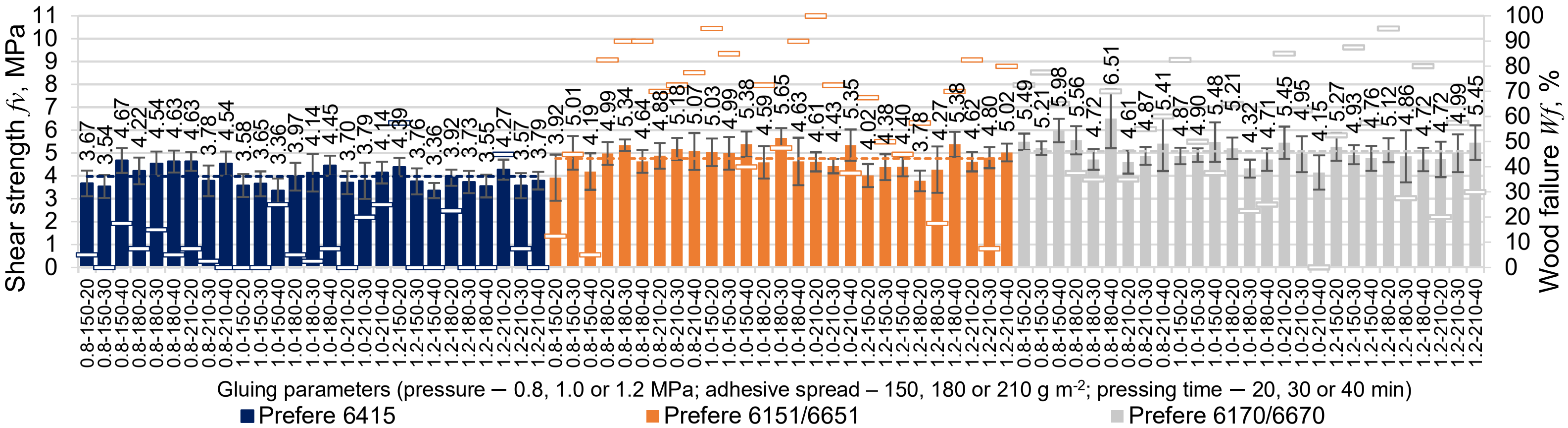

Figure 5. Average shear strength and wood failure percentage of bonded radiata pine wood joints with three adhesive.

This study confirmed the superiority of both EPI adhesives over PVAc adhesives, when testing eucalyptus wood in wet conditions. Previously the same conclusion was reported by Iwakiri et al. (2019). The differences in shear strength found for EPI and PVAc adhesives were attributed to their different penetration ability resulting from their chemical structures as well as their physicochemical characteristics such as rheological properties. The bonding of the wood is complex manufacturing process where majority of bonding parameters and timber characteristics matters. Usually umber joints should be kept under certain pressure and time period until they have enough strength to withstand handling stresses that tend to separate the pieces of wood.

The EPI adhesives used in the study compared to lower curing reactivity PVAc adhesive are designed so that the added hardener minimizes the time required for pressing the samples, as a result of which sufficient mechanical strength of the joint is achieved already during short 20 min pressing, but with increased pressing time of 40 min adhesives continues currying reaction with lower speed, which significantly improves the mechanical strength of the joint, especially, it can be seen with 0.8 MPa pressing pressure.

According to Vick (1999) time for cold pressing of lumber can be little as 15 min or as long as 24 h, depending on the temperature of the room and the wood, the curing characteristics of the adhesive, and the thickness, density, and absorptive characteristics of the wood.

The bonding performance between eucalyptus and EPI adhesive 6151/6651 was affected by bonding pressure ($p < 0.05$) and pressing time ($p < 0.05$). The adhesive spread ($p = 0.17$) had insignificant effects for a single bonding parameter. The interaction between bonding pressure and pressing time most significantly influences the shear strength of bonded joint ($p < 0.05$) according to Fig. 6a. No significant effect between other bonding parameters was observed.

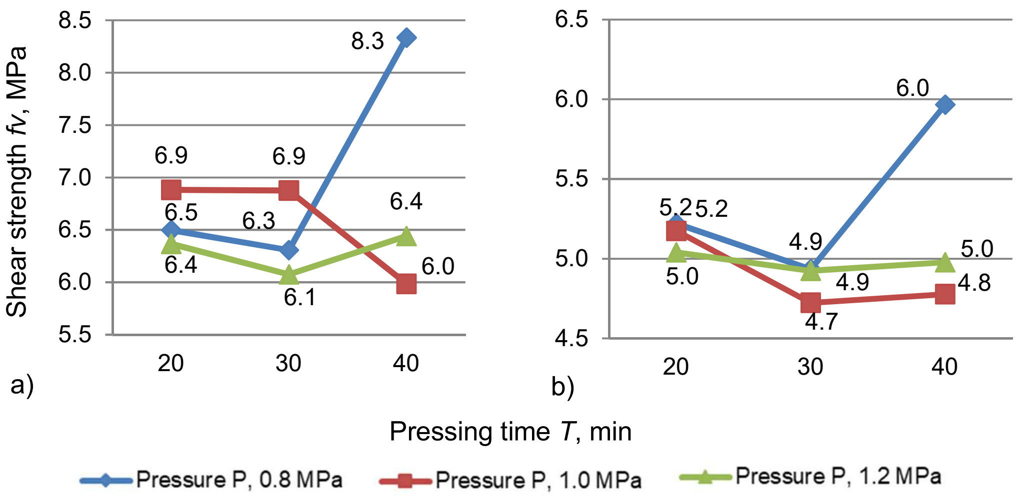

Figure 6. The influence of pressing time T and bonding pressure P interaction on the shear strength of: a – eucalyptus wood bonded with EPI–1 adhesive and b – radiata pine wood bonded with EPI–2 adhesive.

Boding pressure *P* 0.8 MPa and 1.2 MPa interacted with pressing time *T* 20 and 30 min showed an insignificant (p = 0.52–0.09) decrease in bond line *fv* of eucalyptus wood according to Fig. 6a. The most significant increase ($p < 0.05$) in *fv* was observed for *P* 0.8 MPa and *T* 40 min when *fv* 8.3 MPa was observed. For *P* 1.2 MPa the increase in *T* from 30 to 40 min did not influence *fv* significantly (p = 0.11). For *P* 1.0 MPa the same average *fv* values were observed for T 20 and 30 min, but a significant decrease ($p < 0.05$) was observed when *T* 40 min was used for bonding of specimens. No significant effects between other bonding parameters were observed.

The relationship between adhesive consistency and bonding pressure strongly affects adhesive wetting, flow, and penetration, particularly the transfer of adhesive to an unspread wood surface, when pressure is applied to the assembly. Since in the study the highest shear strength values of the joint with EPI adhesives was reached with relatively low bonding pressure of 0.8 MPa, it means, that pressure is optimal: to entrap the air from the joint, to brings adhesive into molecular contact with the wood surface; to form the optimal thickness adhesive film and holds the assembly in position while the adhesive cures. When pressure is too high, the adhesive can overpenetrate porous wood and cause starved joints that are inferior in bond strength (Vick, 1999).

Shear strength and wood failure percentage of bonded radiata pine wood

The average values of *fv* for bonded radiata pine wood varied from 3.36 MPa with PVAc adhesive (*P* – 1.0 MPa; *S* – 150 g m^{-2} and *T* – 40 min) to 6.51 MPa with EPI–2 (*P* – 0.8 MPa; *S* – 150 g m^{-2} and *T* – 40 min) according to Fig. 5. The obtained shear strength values of radiata pine wood are comparable with values of *Pinus Teada* wood (3.36 to 5.36 MPa) bonded with PVA adhesive according to Endo et al. (2017).

The value 6.51.MPa and corresponding bonding regime for EPI–2 adhesive provide a significantly ($p < 0.05$) higher *fv* value compared to the 20 bonding regimes, but *fv* of 6 regimes did not differ significantly (p = 0.2–1.0). For example, the bonding regime: *P* – 0.8 MPa, *S* – 150 g m^{-2}, *T* – 40 min provided 5.98 MPa average *fv* value and *P* – 0.8 MPa, *S* – 180 g m^{-2}, *T* – 40 min provided 5.98 MPa. EPI–1 adhesive with bonding regime *P* – 1.0 MPa, *S* – 180 g m^{-2}, *T* – 30 min provided comparable (p = 0.06) *fv* result 5.65 MPa to the highest value of EPI–2 adhesive. In all other cases the results are significantly lower ($p < 0.05$). All PVAc adhesive bonding regimes for radiata pine provide significantly lower results compared to EPI–1 and EPI–2 adhesives. The highest *fv* of a bonded joint exceeds *fv* of solid radiata pine wood by 12%. This can be explained in the same way as for eucalyptus wood. The average density of radiata pine was 504 kg m^{-3} but the maximum can reach 568 kg m^{-3} with a 13% difference (Iejavs et al., 2021).

From 27 bonding regimes in bonding radiata wood with PVAc adhesive, 16 bonding regimes did not reach the average target shear strength value of 4 MPa according to LVS EN 204 (2016). Two bonding regimes with the lowest *T* – 20 min (*P* – 0.8 MPa, *S* – 150 g mm^{-2}, *T* – 20 min and *P* – 1.2 MPa, *S* – 180 g mm^{-2}, *T* – 20 min) with EPI–1 adhesive did not reach 4 MPa threshold value.

Statistically significant differences ($p < 0.05$) were found between grand average *fv* of all adhesives used (Fig. 4). EPI–2 adhesive *fv* was significantly higher than for EPI–1 and PVAc. Accordingly, EPI–1 adhesive provided significantly higher *fv* compared to PVAc adhesive.

Despite the significantly higher grand average *fv* values of EPI–2 adhesive compared to EPI–1 adhesive, high *Wf* rates are more often observed for EPI–1 adhesive reaching 90–100% for 5 bonding regimes instead of 1 EPI–1 bonding regime. For 11 gluing parameter combinations of all the adhesives the lowest average wood failure percentage 0% was observed for 10 PVAc bonding regimes and 1 for EPI–2 adhesive.

Radiata pine and EPI–2 adhesive bonding performance is affected by adhesive spread *S* ($p < 0.05$) and bonding pressure *P* ($p < 0.05$), pressing time *T* had insignificant ($p = 0.42$) effects on bonding performance for the single bonding parameters.

The bonding pressure and pressing time interaction most significantly influence the shear strength of bonded radiata pine joints ($p < 0.05$) according to Fig. 6b. For bonding *P* 0.8 MPa interacted with *T* 20 and 30 min, a significant ($p < 0.05$) decrease in *fv* was observed. But the most significant increase ($p < 0.05$) in *fv* from 4.9 to 6.0 MPa for *P* 0.8 MPa was observed when pressing time increases from 30 to 40 min. The most significant decrease ($p < 0.05$) in *fv* from 5.2 to 4.7 MPa was observed for *P* 1.0 MPa when *T* was increased from 20 to 30 min. Insignificant *fv* changes ($p = 0.55$ and 0.78) were observed when *P* 1.2 MPa was used between pressing time variations. The results of the study show that for *Eucalyptus grandis* and *Pinus radiata* D. Don wood the best bonding performance with EPI adhesives was achieved with a low bonding pressure of 0.8 MPa compared to 1.0 MPa, in contrary to the study carried out by Martins et al. (2013) when *Eucalyptus benthamii* Maiden et Cambage wood was bonded with PVAc adhesive. According to River & Okkonen (1991), Corrêa (1997) and Muenchow (2002) bonding pressure from 0.9 to 1.3 MPa are optimal to bond medium density wood.

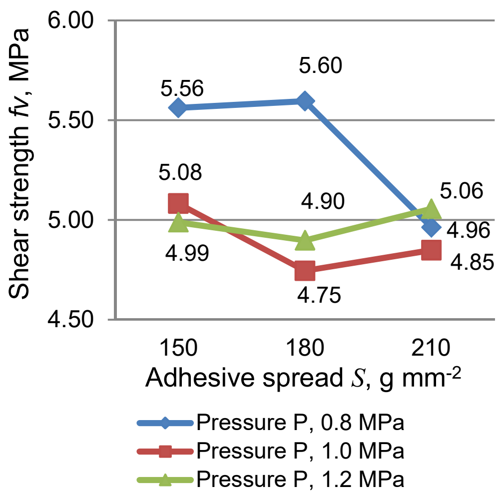

Figure 7. The influence of adhesive spread *S* and bonding pressure *P* interaction on shear strength of radiata pine wood bonded with EPI–2 adhesive.

The second significant interaction was observed for *P* and *S* according to Fig. 7 for radiata pine and EPI–2 adhesive. In this case only for the lowest *P* 0.8 MPa and highest *S* 210 g mm^{-2} interaction, significant ($p < 0.05$) changes were observed when the average *fv* decreased from 5.6 MPa to 4.96 MPa with increased *S* from 180 to 210 g m^{-2}. A significant effect between other bonding parameters was not observed.

Regarding the adhesive spread, no significant increase in shear strength values was observed when adhesive spread was increased from 150 to 210 g m^{-2} within the range recommended by the adhesives manufacturer (Table 1), as a result the adhesive joint of optimal thickness is formed, which does not significantly affect the shear strength of the glued joint. In cases when the adhesive spread is too small, there are not enough adhesives in the pores of the wood, as a result of which the optimal adhesion force between the adhesive and the wood is not achieved, which significantly reduces the mechanical strength of the glued joint. In turn, increased adhesive application results in too thick bond line, which reduces the internal cohesion forces of the adhesive joint itself, which also leads to a reduced mechanical strength of the bonded joint (Follrich et al., 2010). These results indicate that it is possible to use the lowest glue spread for non-structural semi-finished glued laminated timber member production from eucalyptus and radiata pine wood. Similar statements were reported by Iwakiri et al. (2016), Campelo et al. (2017) and Iwakiri et al. (2019).

In other studies was concluded that bonding pressure and glue spread have a significant effect on the shear strength of the glue joint, while after sufficient hardening the pressing time does not have a significant effect on the bonding quality (Li et al., 2015; Mölleken et al., 2016). But the effect of glue spread on the shear strength was not observed (Fonte & Trianoski, 2015). The range of gluing parameters considered in various studies is crucial for assessing their effect on the shear strength of glued joints.

The anatomical structure, density and porosity of wood, as well as the chemical composition and absorption properties of adhesives in the wood can be mentioned as the most important factors causing the difference between PVAc and EPI adhesive bonds (Iwakiri, 2005).

CONCLUSIONS

Eucalyptus (*Eucalyptus grandis*) and radiata pine (*Pinus radiata* D. Don) wood in face bonding with PVAc and EPI adhesives provides certain level of bond line shear strength. Failures of bonded joints after boiling pre–treatment were not observed within the range of bonding parameters used.

The bonding performances of both EPI adhesives were significantly higher compared to PVAc.

Bonding pressure and pressing time were evaluated as the most significant interacting factors influencing shear strength of eucalyptus and radiata pine wood bonded with EPI adhesive Prefere 6151/6651 or EPI adhesive Prefere 6170/6670.

Based on the general evaluation of the results, it can be stated that the wood of eucalyptus and radiata pine bonded with both EPI adhesives presents great potential for non-structural semi-finished glued laminated timber member production, especially for the use in humid conditions.

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