Floresta e Ambiente

Adhesion quality of quaruba cedar wood glued joints under internal and external service conditions

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Abstract

The objective of this study was to determine the adhesion quality of quaruba cedar wood glued joints by means of tensile strength, shear strength before and after exposure to weathering simulated conditions, and delamination tests. Wood glued joints were bonded with three adhesives: resorcinol, resorcinol-tannin (90:10) and resorcinol-tannin (80:20) at 25 and 60^{0}C curing temperatures with 0 and 10 % methanol contents. Wood glued joints bonded with resorcinol adhesive at 25^{0}C without methanol presented high tensile strength, with values similar to solid wood. Wood glued joints bonded at 25^{0}C presented the highest shear strength values even after the exposition to weathering simulated conditions.

Key words: quaruba cedar wood, shear strength, tensile strength, wood glued joints.

Introdução

Recently, environmental pressures have encouraged the using of fast-growing and/or alternative hardwoods species to replace noble and high quality woods, and also increased the demand for wood-based composites and glued wood products. Nonetheless, the great challenge of the researchers has been to adjust commercial adhesives for these species.

Major developed structural adhesives throughout the world are for softwoods and do not for hardwoods. In Brazil, some researches have searched to extend the use of alternative tropical hardwoods species and optimize their adhesion quality with traditional adhesives, by means of new formulations (Bohn 1995; Nascimento et al. 2002; Zangiácomo 2003; Zangiácomo and Lahr 2002). The adhesion quality of the adhesive, i.e. mechanical stability and bond-durability, is directly affected by its compatibility with the wood substrate characteristics which affects the adhesive penetration into the wood surface. The adhesion process involves physical, chemical and structural of wood properties density, porosity, water content and buffer capacity; and adhesive wetting and viscosity between others (Follrich et al. 2007). Consequently, some cares as the wood surface preparation before the adhesive application, the application methods of the adhesives, the applied pressure at the glued joints, have be taken (Forest Products Laboratory 1999).

No studies involving quaruba cedar (*Vochysia* spp.) wood glued joints were found in the literature. However, Zangiácomo (2003) studied glued laminated wood of *Erisma uncinatum* Warm, which presents similar anatomical characteristics to quaruba cedar and appertains to the same botanical family, (*Vochysia* spp.) and found good results for strength and stiffness properties when bonded with a commercial resorcinol adhesive at pressure of 0.8 and 1.2 MPa.

The resorcinol adhesive is one of the most used for structural glued wood products. Nevertheless, although to guarantee a good bonding with high mechanical strength and bond-durability under weathering conditions, the resorcinol presents high costs, reaching around 30% of the total cost of the glued laminate wood production. For this reason, glued laminate wood is less competitive than other materials such as concrete and steel for structural applications (Melo and Mantilla Carrasco 2004).

In order to reduce the resorcinol adhesive costs, some formulations have appeared to increase its viability by using of dilutions and mixtures with other less expensive adhesives (Grigsby and Warnes 2004; Nascimento et al. 2002; Szücs et al. 1998; Vrazel 2002). In this context, the tannin-based adhesives represent a good option in the market and they have been widely used because of its excellent environmental appeal due to extraction generally be carried from the residue exploitation such as barks. Moreover, some authors states that the addition of tannin to resorcinol adhesives in presence of paraformaldehyde catalyst increases the mechanical strength of wood glued joints even to humidity and temperature variations, the two most important environmental factors affecting the adhesion quality (Grigsby and Warnes 2004; Pizzi 1994).

Several adhesive formulations have been developed, but in Brazil the works involving strength tests of the alternative tropical wood glued materials after exposure to weathering conditions are scarce. Thus, the present work aims to evaluate the strength of resorcinol and resorcinol-tannin adhesives used in quaruba cedar wood (*Vochysia* spp.) glued joints before and after exposure to simulated conditions of internal and external services. The choice of specie is justified by the abundance and low price of queruba cedar wood in the regional market, and also by its good mechanical and machining properties. Therefore, the objectives were:

(1) To verify the adhesion quality and the integrity of the quaruba cedar wood glued joints with the resorcinol and resorcinol-tannin adhesives;

(2) To verify the effect of the curing temperature and methanol content in the adhesion quality of these adhesives;

(3) To verify the strength of the bondline of the wood glued joints before and after exposure to weathering simulated conditions.

Material and Methods

Material Preparation

Commercial boards of Quaruba Cedar Wood (*Vochysia* spp.) with dimensions 450 x 30 x 2.5 cm (length x width x thickness) were obtained from local market in Rio de Janeiro City, Rio de Janeiro State, Brazil. After to reach the moisture content equilibrium, the wood boards were cut to performer the quality adhesion tests of wood glued joints and then the samples were conditioned at 20 ± 2^{o}C and 65 ± 3% relative humidity in climate room until stable weight.

The quaruba cedar wood glued joints were bonded with three adhesives types: resorcinol; resorcinol-tannin (90:10) and resorcinol-tannin (80:20). The resorcinol adhesive, commercial type, was provided by Borden Química Indústria e Comércio Ltda, Curitiba City, Paraná State, Brazil and the powdered black wattle (*Acacia mearnsii* De Wild) tannin-based adhesive, commercially named Phenotan M, was supplied by TANAC S.A, Montenegro City, Rio Grande do Sul State, Brazil. A solution of tannin-based adhesive was prepared at the proportion 1:1 (tannin:water). The catalyst paraformaldehyde was added to all adhesives (proportion 1:5) and mixed during 5 minutes. For all adhesives, a quantity of 300 g m^{-2} was applied to the wood face.

Two curing temperatures of 25 and 60^{o}C and two methanol contents (0 and 10% - based on the adhesive weight) were evaluated. The wood glued joints were pressed by an apparatus adapted to universal testing machine at a pressure of 1 MPa for 5 hours.

Therefore, a factorial design was used in this project. The three factors chosen in the experimental design were adhesive type (3 levels: resorcinol, resorcinol-tannin (90:10) and resorcinol-tannin (80:20)), curing temperature (2 levels: 25 and 60^{o}C) and methanol content (0 and 10%) which resulted in a total of 12 treatment combinations. The performance of quaruba cedar wood glued joints was compared to quaruba cedar solid wood by using a total of 20 samples.

Four measurements were performed in order to evaluate the adhesion quality: tensile strength (TS), shear strength (SS), shear strength after weathering simulated conditions ($SS_{weathering}$) and delamination testing. For tensile strength measurements were used 12 replications for each treatment combination resulting in a total of 144 observations. For shear strength measurements were used 20 replications for each treatment combination where 10 replications were tested before and 10 after exposure to weathering simulated conditions, respectively, which resulted in a total of 120 observations for each condition. The delamination testing was performed for the three best treatments found in the shear strength measurements before and after weathering simulated conditions.

Determination of Tensile Strength

The tensile strength testing measured the force necessary to rupture the quaruba cedar wood glued joints by means of the stress applied perpendicular to the grain and to the plane of the bondline. Wood glued joints samples of 6.4 x 5 x 5 cm with 2.54 cm diameter holes were prepared and tensile strength determined according to the ABNT NBR 7190.1997 standard.

Determination of Shear Strength

The shear strength testing measured the strength of the quaruba cedar wood glued joints to shearing stresses parallel to the grain or the force per unit area sheared, at failure (Landrock 1985). Wood glued joints samples were prepared (Figure 1) and shear strength measured according to the ASTM D 905.1994 standard. Shear strength properties of quaruba cedar solid wood were measured according to the ASTM D 143.1994 standard. After, the failure evaluation of the wood glued joints was performed following the ASTM D 3110.1994 standard. Also, the moisture content and density of samples were determined.

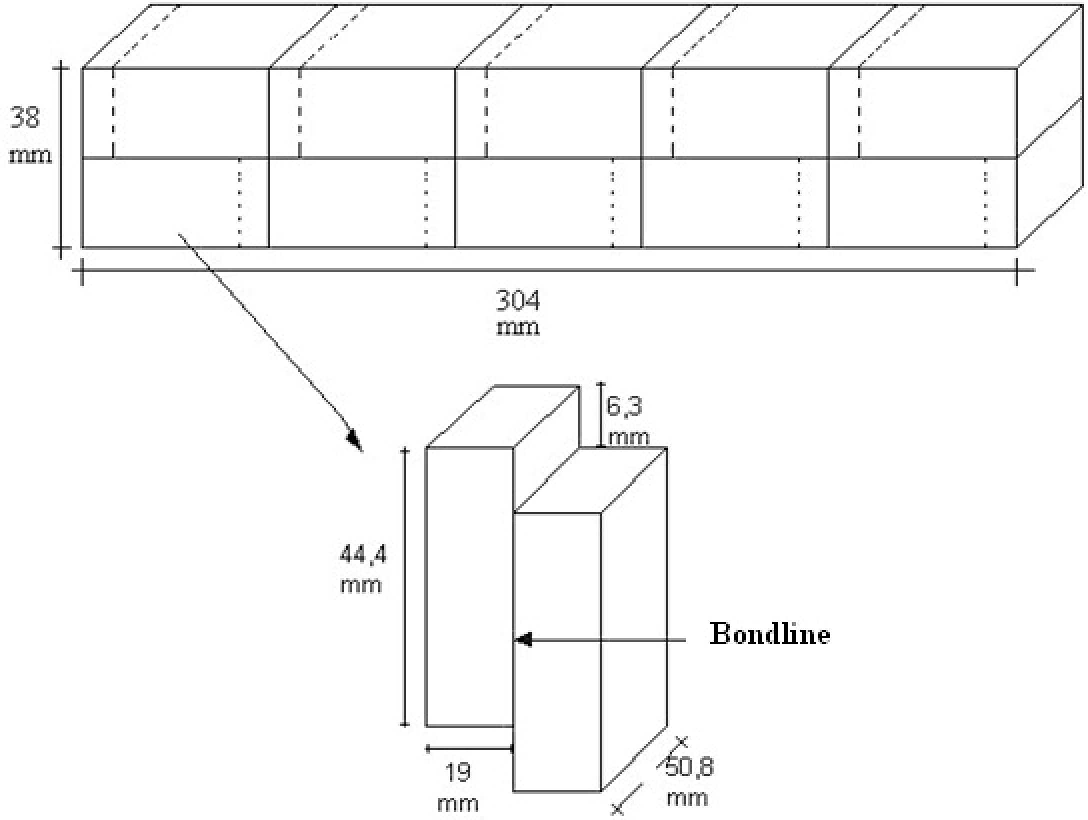


Figure 1. Dimension samples for shear strength measurement of quaruba cedar wood glued joints, according to ASTM D 905.1994 standard.

Determination of Shear Strength after Exposure to Weathering Simulated Conditions

Wood glued joints used for this test were prepared as previously mentioned in the last paragraph. To simulate the weathering conditions, it was chosen the procedure B from ASTM D 1183.1994 standard with addition of water immersion as specified in Table 1. This test was performed at two cycles. After, the shear strength variation values were calculated as follows:

$$\Delta_{ss} = [(SS_{weathering} - S)/SS] \text{ x } 100\ (\%)$$

Where: Δ_{ss} : shear strength variation as a result of exposure to the test conditions, percentage. SS : shear strength value before exposure at weathering simulated conditions, MPa. $SS_{weathering}$: shear strength value after exposure at weathering simulated conditions, MPa.

Table 1. Procedure used to simulate the weathering conditions for the quaruba cedar wood glued joints.

Exposure	Period (hours)	Temperature (°C)	Relative Humidity (%)
Exterior	48	60 ± 3	Inferior to 30
	48	38.5 ± 2	85 to 90
	48	23 ± 1	Water immersion
	8	-18 ± 2	About 100
	64	38.5 ± 2	85 to 90

Delamination Testing

Three wood blocks (with 8 veneer sheets of 19 mm thickness per block) of 330 x 76 x 152 mm (length x width x thickness) were pressing to glue the joints and after samples were cut at dimensions of 76 x 76 x 152 mm. The delamination test was performed following the ASTM D 1101.1994 standard. The Procedure A described by this standard was modified to adapt it to our laboratory conditions. Therefore, the samples were immersed in water at 18-27°C in autoclave under 508 mmHg vacuum and hold it for 25 minutes. After, the vacuum was released and a pressure of 270 kPa applied for three hours. Finally, the samples were dried at 67°C for 22 hours. This cycle was performed three times.

Results and Discussion

Tensile Strength

Table 2 shows the results of analysis of variance (F values) for tensile strengths (TS) property. Table 3 presents the results obtained for TS property of quaruba cedar wood glued joints and solid wood. TS values for solid wood was higher than those found for wood glued joints, however statistical analysis showed the solid wood samples presented higher density values ($D_{12\%}$) than those of wood glued joints (Table 2). Therefore, to consider the impact of sample density on the tensile strength, the ratio $TS/D_{12\%}$ was used. Nonetheless, none treatment reached the solid wood values for TS. Exceptionally, the wood glued joints bonded with resorcinol at 25°C and 0% methanol content presented TS values close to solid wood (Table 3).

A significant interaction between adhesive type and curing temperature as well as adhesive type and methanol content was observed for TS property at a probability level of 0.01 (Table 2). No significant differences were found between adhesive types bonded at 60°C curing temperature while wood glued joints showed higher TS values when bonded with resorcinol adhesive at 25°C as compared with other adhesive at the same temperature (Figure 2A). The strength of the resorcinol-tannin adhesive had a tendency to diminish with an increase of the tannin proportion from 10 to 20% at 25°C curing temperature. The resorcinol adhesive had a reduced strength when bonded at 60°C curing temperature (Figure 2A). No significant differences were found between adhesives types for 0% methanol content while for 10% methanol, the strength of wood glued joints for TS decreased with addition of 20% tannin adhesive (Figure 2B).

Table 4 presents the results for strength qualitative analysis of quaruba cedar wood glued joints. These results show that the majority of samples for all treatments failed completely or partially in the wood which show good adhesion for all adhesives types. However, the majority of the treatments had low or regular strengths – compared to wood characteristic value of 2.26 MPa. Also, the wood glued joints bonded with all adhesives for both temperatures and 0% methanol content as well as those bonded with resorcinol adhesive at 25% curing

Table 2 . Results of the analysis of variance (F values) for tensile and shear strengths of quaruba cedar wood glued joints.

Source of variation	TS	$D_{12\%\ TS}$	SS	$D_{12\%\ SS}$	$SS_{weathering}$
T X Solid Wood	-	7.44**	-	3.82**	-
Adhesive	4.10*	-	1.64^{NS}	-	3.01^{NS}
Temperature	4.67*	-	58.25**	-	147.71**
Methanol	7.71*	-	1.16^{NS}	-	0.20^{NS}
Adhesive*Temperature	10.52**	-	6.83**	-	17.90**
Adhesive*Methanol	5.01**	-	7.07**	-	11.90**
Temperature*Methanol	2.43^{NS}	-	1.49^{NS}	-	21.40**
Adhesive*Temperature*Methanol	0.33^{NS}	-	7.04**	-	2.37^{NS}

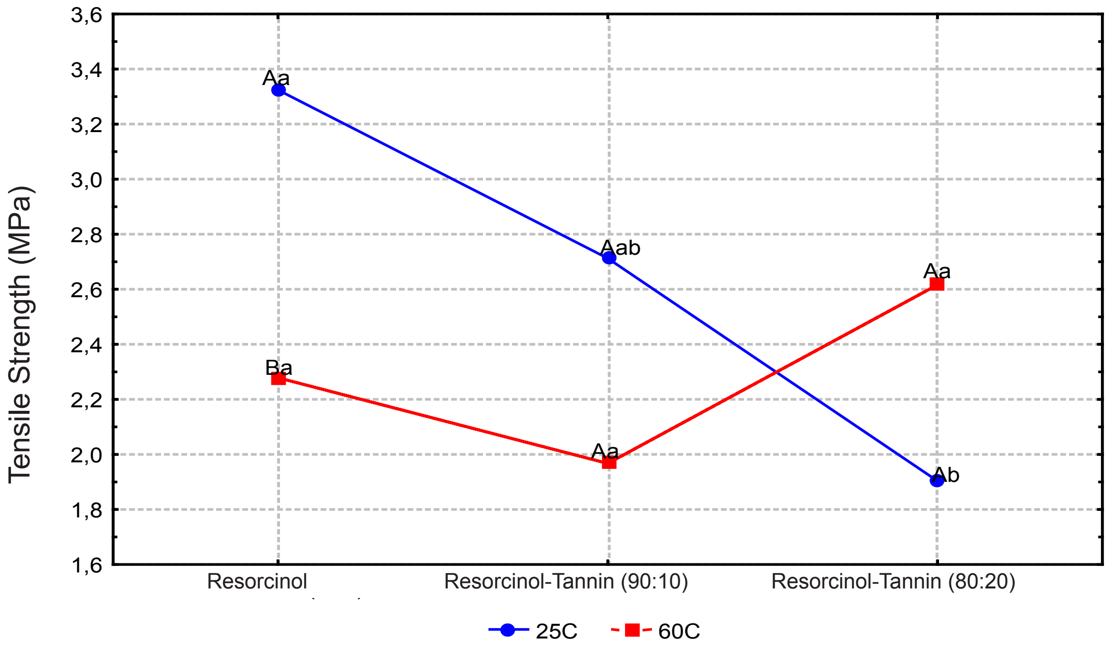
T x Solid Wood: contrast between treatment (wood glued joints) and solid wood. TS: tensile strength. $D_{12\%\ TS,\ SS}$: density average value at 12% moisture content for TS and SS, respectively. *SS*: shear strength before exposure to weathering simulated conditions. $SS_{weathering}$: shear strength after exposure to weathering simulated conditions.
* Significant at 0.05 probability level.
** Sgnificant at 0.01 probability level.
^{NS} Not significant.

Table 3. Results obtained for tensile strength average values of quaruba cedar wood glued joints and solid wood.

Adhesive	**Curing Temperature (˚C)**	**Methanol Content (%)**	**TS (MPa)**	**$D_{12\%}$ (g cm^{-3})**	**TS/ $D_{12\%}$ (MPa cm^3 g^{-1})**
Resorcinol	25	0	3.4	0.56	6.0
		10	3.3	0.60	5.5
	60	0	2.2	0.58	3.7
		10	2.4	0.57	4.2
Resorcinol-Tannin (90:10)	25	0	3.0	0.56	5.3
		10	2.5	0.56	4.4
	60	0	2.0	0.54	3.8
		10	1.9	0.58	3.3
Resorcinol-Tannin (80:20)	25	0	2.7	0.56	4.9
		10	1.1	0.62	1.8
	60	0	3.0	0.63	4.7
		10	2.3	0.56	4.0
Means			**2.5**	**0.58**	**4.3**
Solid Wood			**3.8**	**0.63**	**6.1**

TS: tensile strength average values. D12%: density average value at 12% moisture content. TS/D12%: ratio tensile strength per density at 12% moisture content.

(A) Interaction Adhesive Type*Curing Temperature



(B) Interaction Adhesive Type*Methanol Content

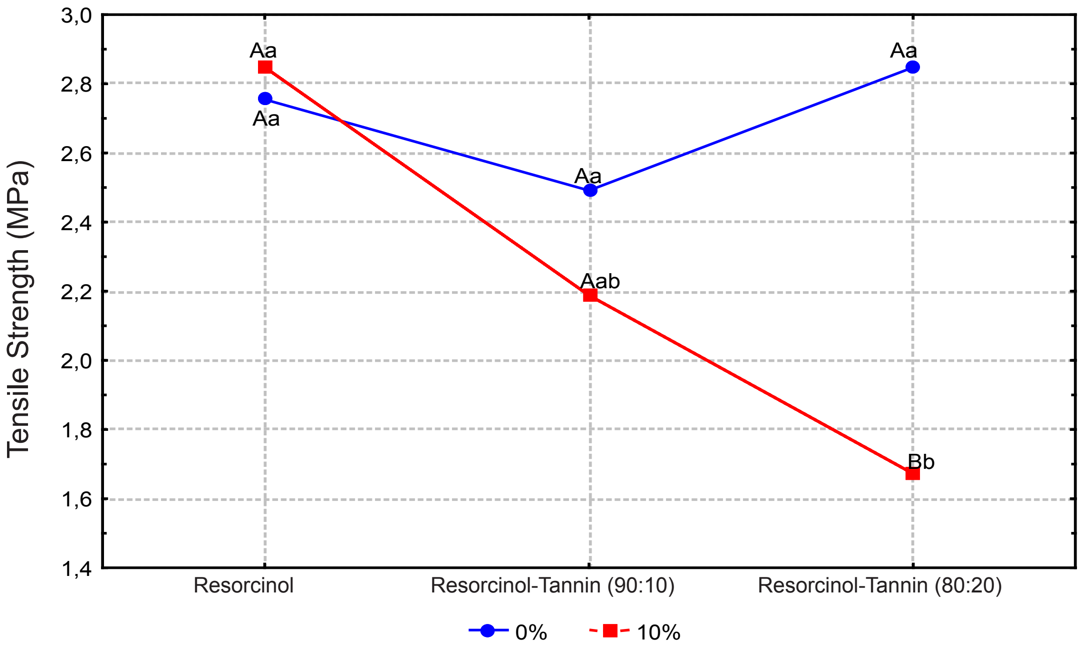


Figure 2. (A) Interaction between adhesive type and curing temperature for tensile strength property. (B) Interaction between adhesive type and methanol content. Means with the same letter are not significantly different at 0.05% probability level. Capital letters: comparison between means of the same adhesive and different curing temperatures and methanol contents for (A) and (B), respectively. Lower case letters: comparison between means of the same curing temperature and methanol content for (A) and (B) at different adhesive types, respectively.

temperature and 10% methanol content had at least 10% of higher strength than solid wood (Table 4).

Shear Strength

Table 5 presents the results obtained for shear strength before and after exposure to weathering simulated conditions and for sample densities at 0 and 12% moisture content. According to Wood Handbook of the USDA Forest Products Laboratory (1999), low moisture contents can cause an excessive adhesive's water absorption which causes problems due to the reduced penetration of the adhesives within the wood. On the other side, woods with high moisture contents can not absorb the adhesive. Therefore, the ideal moisture content for glued woods is situated between 6 and 14%. For this raison, in our study, the wood joints were bonded with a moisture content of 12% (based on the oven-dry of wood sample).

The sample densities at 0 and 12 % moisture contents presented values from 0.54 to 0.60 g cm^{-3} and from 0.53 to 0.58 g cm-3, respectively. These densities contribute to obtain a good adhesion in quaruba cedar wood glued joints. The influence of wood density in the adhesion is more physical than chemical. Really, it directly controls the mechanical adhesion and the adhesive diffusion because high densities generally diminish the amount and/or the size of the pores making difficult the adhesive wetting and penetration as well as a good linkage formation in the interface wood-adhesive. Then, the wood density recommended to glued joints is below of 0.8 g cm^{-3} (Forest Products Laboratory (1999).

According to ASTM D 2559.1994 standard, the wood glued joints employed in structures exposed at external service conditions not must have lower shear strength than solid wood. In our work, the shear strength of wood solid is higher than that of the treatments (Table 5). Nevertheless, statistical analysis showed higher densities for solid wood, which can explain these results (Table 2). Hence, to consider the impact of sample density on the shear strength, the ratio $SS/D_{12\%}$ was used. Consequently, the following treatments reached superior or similar

Table 4. Strength qualitative analysis of quaruba cedar wood glued joints for tensile strength test.

Adhesive	Curing Temperature (˚C)	Failure Type	Methanol Content (%)							
			0				10			
			Strength							
			L	R	H	%	L	R	H	%
Resorcinol	25	Adhesive	0	0	0	0.0	0	0	0	0.0
		Wood	0	4	8	100.0	3	5	2	83.3
		Interface*	0	0	0	0.0	0	0	2	16.7
	60	Adhesive	1	0	0	10.0	0	0	0	0.0
		Wood	2	1	3	60.0	6	3	0	75.0
		Interface	3	0	0	30.0	3	0	0	25.0
Resorcinol-Tannin(90:10)	25	Adhesive	0	0	0	0.0	0	0	0	0.0
		Wood	3	6	1	83.3	8	3	0	91.7
		Interface	0	1	1	16.7	0	1	0	8.3
	60	Adhesive	1	0	2	27.3	1	0	0	8.3
		Wood	5	0	0	45.5	6	2	0	66.7
		Interface	3	0	0	27.3	3	0	0	25.0
Resorcinol-Tannin(80:20)	25	Adhesive	2	0	1	27.3	8	0	0	80.0
		Wood	2	2	3	63.6	1	0	0	10.0
		Interface	0	0	1	9.1	1	0	0	10.0
	60	Adhesive	2	0	0	16.7	0	0	0	0.0
		Wood	2	1	4	58.3	11	1	0	100.0
		Interface	3	0	0	25.0	0	0	0	0.0

L: low strength, next to solid wood characteristic values. R: regular strength, below or next to solid wood average values. H: higher strength than solid wood. * failure at the interface wood-adhesive.

Table 5. Results obtained for shear strength average values before and after exposure to weathering simulated conditions of quaruba cedar wood glued joints and solid wood.

Shear Strength Before Exposure to Weathering Simulated Conditions

Adhesive	Curing Temperature (°C)	Methanol Content (%)	SS (MPa)	MC (%)	$D_{12\%}$ (g cm^{-3})	$D_{0\%}$ (g cm^{-3})	$SS/D_{12\%}$ (MPa cm^{3} g^{-1})
Resorcinol	25	0	10.6	13.0	0.58	0.56	18.2*
		10	10.6	13.1	0.58	0.55	18.3*
	60	0	6.9	10.6	0.58	0.57	11.9
		10	8.4	10.6	0.57	0.55	14.7
Resorcinol-Tannin (90:10)	25	0	10.6	12.6	0.61	0.58	17.4*
		10	9.4	13.0	0.60	0.57	15.6
	60	0	8.7	10.0	0.55	0.56	15.8
		10	9.7	10.2	0.56	0.54	17.3*
Resorcinol-Tannin (80:20)	25	0	10.6	12.9	0.60	0.57	17.7*
		10	10.2	13.0	0.60	0.57	17.0*
	60	0	9.9	10.4	0.58	0.58	17.0*
		10	7.5	11.9	0.54	0.53	13.9
Means			**9.4**	**11.8**	**0.58**	**0.56**	**16.3**
Solid Wood			**11.0**	**12.0**	**0.65**	**-**	**17.0**

Shear Strength After Exposure to Weathering Simulated Conditions

Adhesive	Curing Temperature (°C)	Methanol Content (%)	$SS_{weathering}$ (MPa)	$MC_{weathering}$ (%)	$D_{12\% \, weathering}$ (g cm^{-3})	$D_{0\% \, weathering}$ (g cm^{-3})
Resorcinol	25	0	10.8	10.0	0.58	0.56
		10	11.1	10.3	0.57	0.55
	60	0	5.4	10.2	0.58	0.56
		10	7.6	10.4	0.57	0.54
Resorcinol-Tannin (90:10)	25	0	10.9	10.1	0.57	0.56
		10	9.1	10.3	0.58	0.56
	60	0	7.6	10.1	0.58	0.56
		10	8.9	10.1	0.55	0.53
Resorcinol-Tannin (80:20)	25	0	11.0	10.2	0.56	0.55
		10	9.3	10.1	0.59	0.57
	60	0	9.0	10.1	0.57	0.54
		10	8.1	10.4	0.54	0.54
Means			**9.1**	**10.2**	**0.57**	**0.55**

SS, $SS_{weathering}$: shear strength average values before and after exposure to weathering simulated conditions, respectively. MC, $MC_{weathering}$: moisture content of samples for shear strength tests before and after exposure to weathering simulated conditions, respectively. $D_{12\%, 0\%:}$ density average value at 12% and 0% moisture content for SS, respectively. $SS/D_{12\%:}$ ratio shear strength per density at 12% moisture content. $D_{12\%, 0\% \, weathering}$: density average value at 12% and 0% moisture content for $SS_{weathering}$, respectively. * attained the solid wood values.

values to solid wood: resorcinol adhesive at 25°C curing temperature for both methanol contents; resorcinol-tannin (90:10) at 25°C with 0% methanol content and at 60°C with 10% methanol content; and resorcinol-tannin (80:20) for all combinations, in exception at 60°C curing temperature with 10% methanol content. The treatment mean for shear strength before and after exposure to weathering simulated conditions had similar values demonstrating a good performance of wood glued joints even in extreme temperature and humidity conditions.

A significant double interaction for shear strength before weathering simulated conditions (SS) was observed between adhesive type and curing temperature as well as adhesive type and methanol content at a probability level of 0.01. Also, a significant triple interaction was observed between adhesive type, curing temperature and methanol content at a probability level of 0.01 (Table 2). Wood glued joints without methanol had high SS when bonded at 25ºC curing temperature independently of adhesive type (Figure 3A). A positive relationship was observed at 60ºC curing temperature with an increase of black wattle tannin adhesive in methanol absence (Figure 3A). For treatments with 10% methanol content, a significant difference was observed between resorcinol-tannin (90:10) and resorcinol-tannin (80:20) adhesives at 60ºC temperature (Figure 3B). Indeed, the SS was reduced with the increase of tannin proportion in the adhesive formulation. Also, the methanol reduced the SS of the resorcinol and resorcinol-tannin (80:20) adhesives with the curing temperature increase from 25 to 60ºC (Figure 3B).

Shear Strength After Exposure to Weathering Simulated Conditions

Statistical analysis for the shear strength after exposure to weathering simulated conditions ($SS_{weathering}$) revealed a significant interaction between adhesive type and curing temperature; adhesive type and methanol content; and curing temperature and methanol content at a probability level of 0.01 (Table 2). The $SS_{weathering}$ of wood glued joints bonded with resorcinol adhesive presented a significant reduction at 60ºC curing temperature while other adhesives were not significantly affected by the curing temperature (Figure 4A). The resorcinol and resorcinol-tannin (80:20) adhesives had the $SS_{weathering}$ increased and decreased, respectively, with

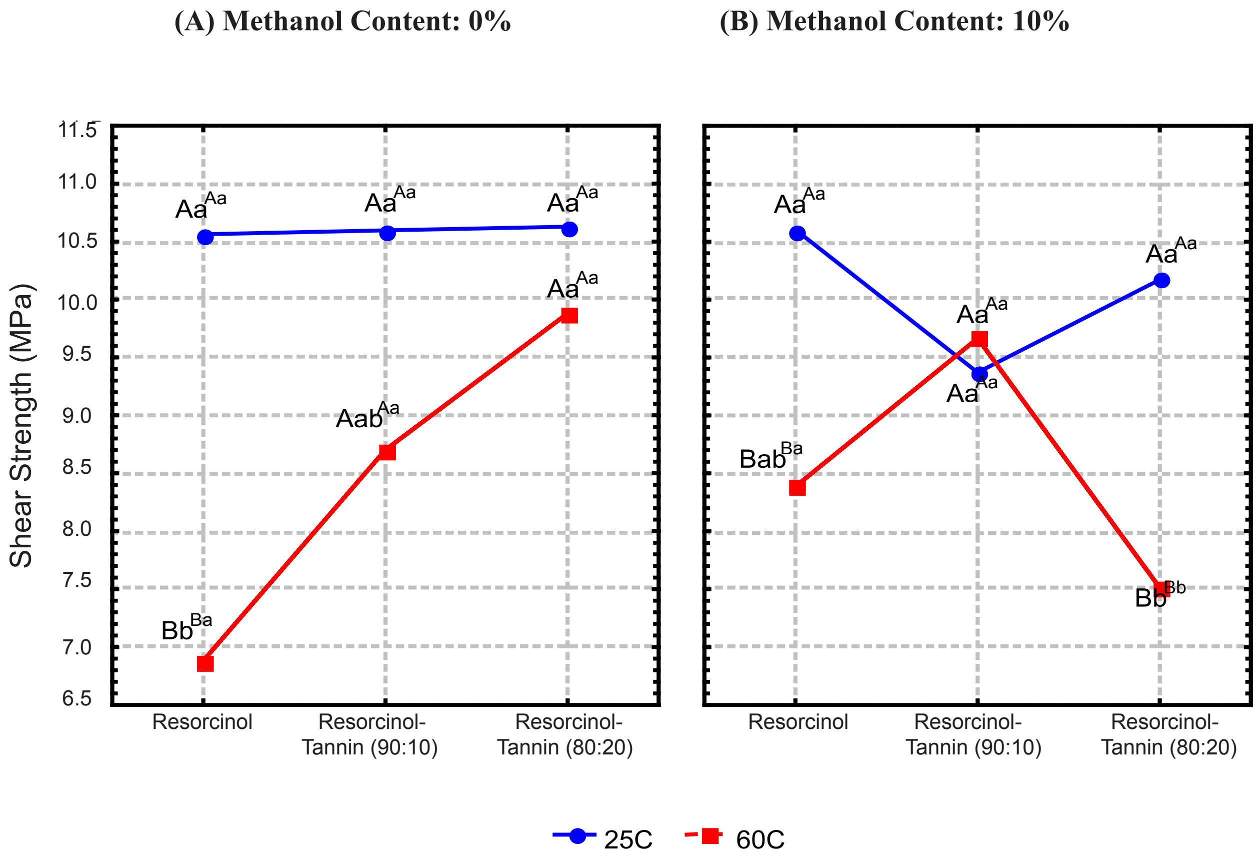
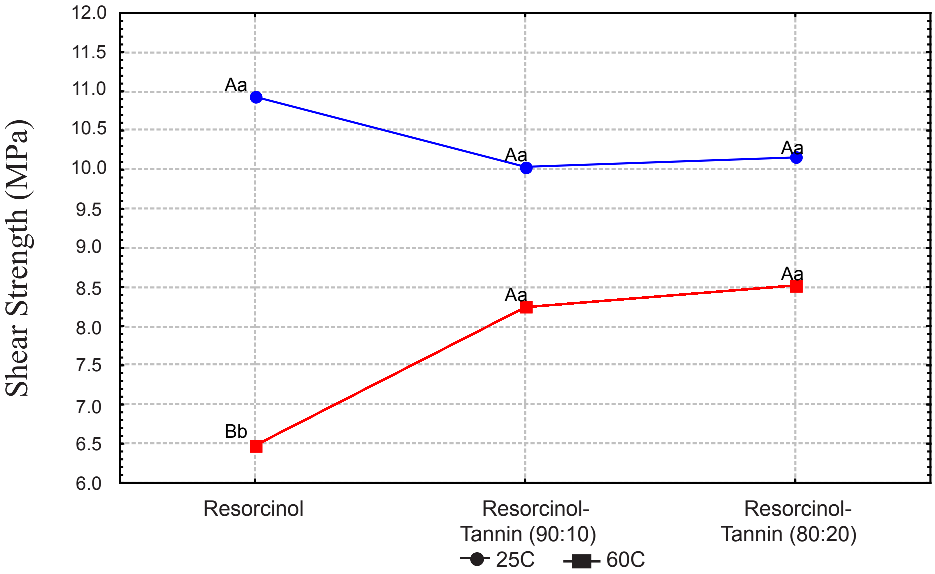


Figure 3. Interaction between adhesive type, curing temperature and methanol content for shear strength before weathering simulated conditions. Means with the same letter are not significantly different at 0.05% probability level. Capital letters: comparison between means of the same adhesive and methanol content, and different curing temperatures. Lower case letters: comparison between means of the same curing temperature and methanol content, and different adhesives. Superscript capital letters: comparison between means of the same adhesive and curing temperature, and different methanol contents.

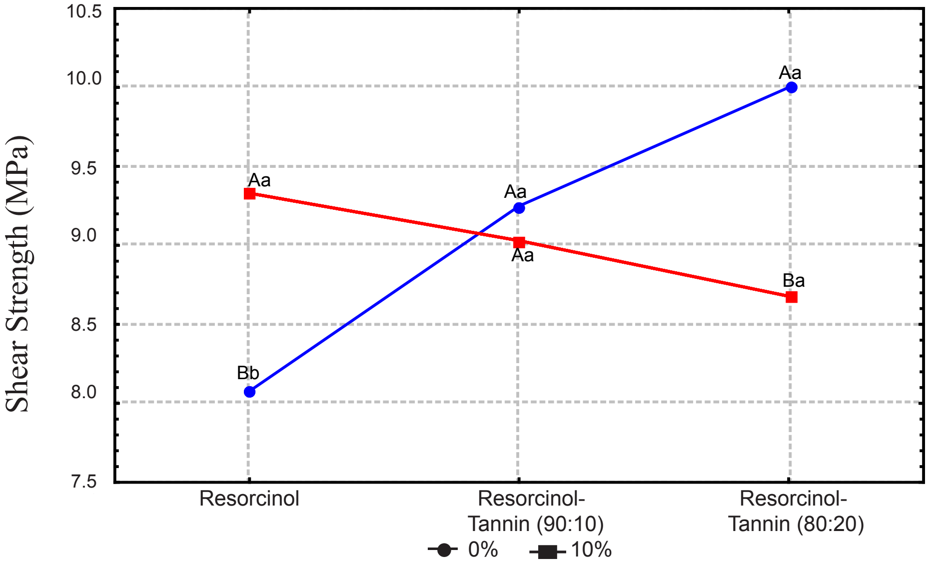
a 10% methanol content (Figure 4B). The wood glued joints bonded with adhesives at 25°C curing temperature had higher $SS_{weathering}$ for both methanol contents when compared to results at 60°C temperature (Figure 4C). Also, $SS_{weathering}$ property was improved for adhesives cured at 60°C in presence of methanol while $SS_{weathering}$ diminished with methanol addition to adhesive at 25°C curing temperature (Figure 4C).

Figure 5A shows the average quaruba cedar wood failure percentage for the SS test while Figure 5B presents the results for $SS_{weathering}$ test. The ASTM D 3110.1994 standard demands a wood failure minimum value of 60%, lower values indicate a poor adhesion quality and vice versa. Before exposure to weathering simulated conditions, at 60°C curing temperature, only the resorcinol did not reach the minimum values required by the ASTM D 3110.1994 standard (Figure 5A). At 25°C curing temperature in methanol presence, the wood

(A) Interaction Adhesive Type*Curing Temperature



(B) Interaction Adhesive Type*Methanol Content



(C) Interaction Curing Temperature* Methanol Content

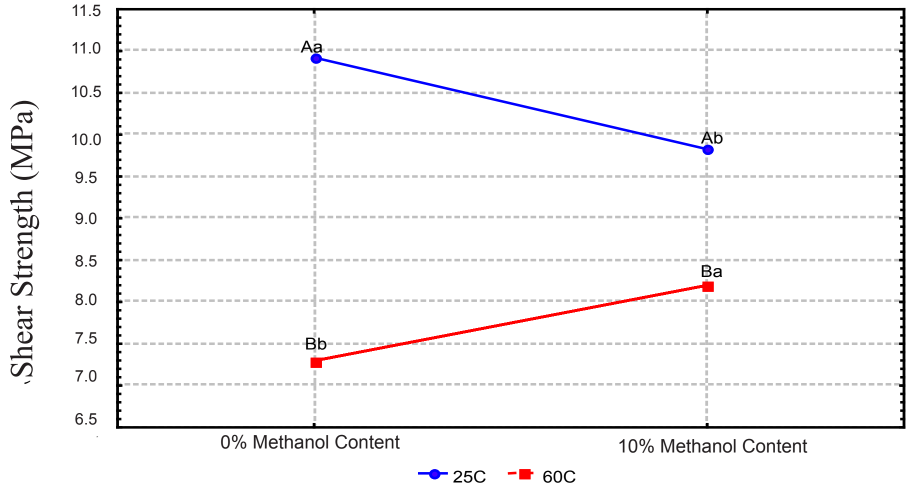
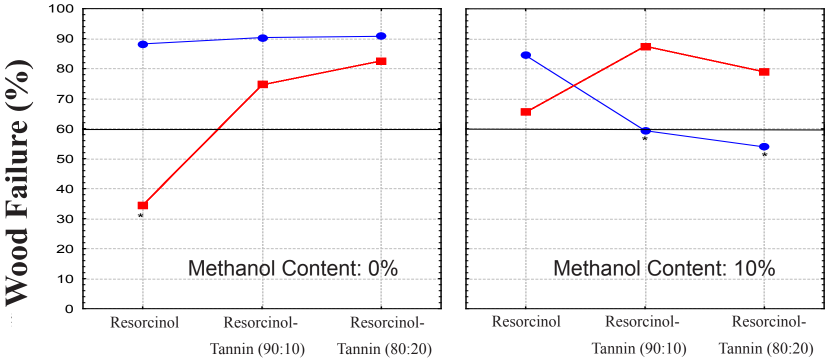


Figure 4. (A), (B) and (C) Interactions between adhesive type and curing temperature; adhesive type and methanol content; and curing temperature and methanol content, respectively, for shear strength after exposure to weathering simulated conditions. Means with the same letter are significantly different at 0.05% probability level. Capital letters: comparison between means of the different curves. Lower case letters: comparison between means of the same curve.

(A) Before weathering simulated conditions



B) After weathering simulated conditions

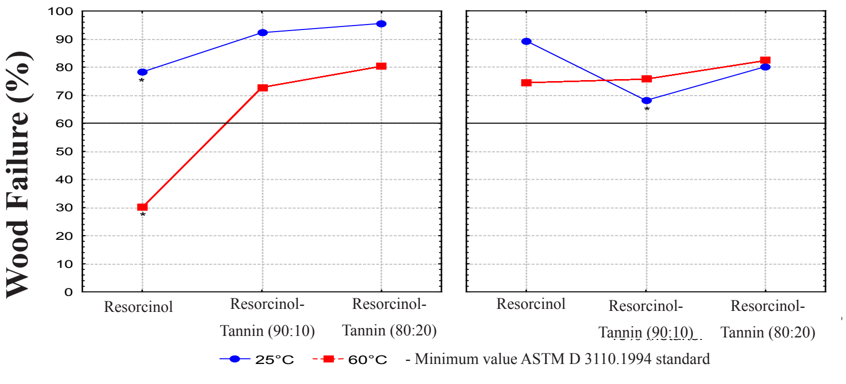


Figure 5. Average quaruba cedar wood failure percentage for shear strength before and after exposure to weathering simulated conditions for (A) and (B), respectively. * Did not reach the requirements of the ASTM D 3110.1994 standard.

failure percentage decreases with an increase of tannin (Figure 5A). After exposure at weathering simulated conditions, the resorcinol adhesive in methanol absence for both curing temperatures and the resorcinol-tannin (90:10) at 25ºC with 10% methanol content did not reach the $SS_{weathering}$ minimum values required by the ASTM D 3110.1994 standard (Figure 5B). To respect the ASTM D 3110.1994 standard, no samples with zero values are permitted, which were observed for resorcinol (0% methanol content) and resorcinol-tannin (90:10) (10% methanol content) adhesives, both cured at 25ºC (Figure 5B). Also, for resorcinol adhesive, the methanol improved the adhesion strength at 60ºC and the wood failure percentage for this adhesive reached the standard values before and after exposure to weathering simulated conditions (Figures 5A and B). This fact occurred because the methanol reduces the viscosity and gel time of the resorcinol adhesive improving its flow and absorption properties, and consequently its adhesion quality (Pizzi 1994).

For the resorcinol-tannin (90:10) adhesive, although the comparison between means of the strength not to show influence of the curing temperature or methanol content, a better quality of adhesion was verified through the percentage of wood failure and in comparison with the solid wood, for treatments at 25ºC without methanol – before and after exposure to weathering simulated conditions, and at 60°C with methanol, as show the Figures 5A and B as well as the $SS/D_{12\%}$ values presented in Table 5. For the resorcinol-tannin (80:20) adhesive, the best results were found for the treatments without methanol for both temperatures and with methanol at 60ºC (Table 5).

The best performance of resorcinol-tannin adhesives compositions at 60ºC when compared to resorcinol adhesive is due to optimum curing conditions of the black wattle tannin at high temperatures. Second Mori et al. (2002), curing optimum pick for black wattle tannin is situated between 126 and 216ºC.

The quality of wood glued joints was also evaluated by the shear strength variation (ΔSS). The results obtained for ΔSS are showed in the Figure 6. The resorcinol adhesive with 0 and 10% methanol contents and the resorcinol-tannin (90:10) without resorcinol, all cured at 60ºC, had the highest loss of strength after weathering simulated conditions (Figures 6A and B).

The weak strength of resorcinol adhesive at 60°C can be explained by its pre-curing before to penetrate

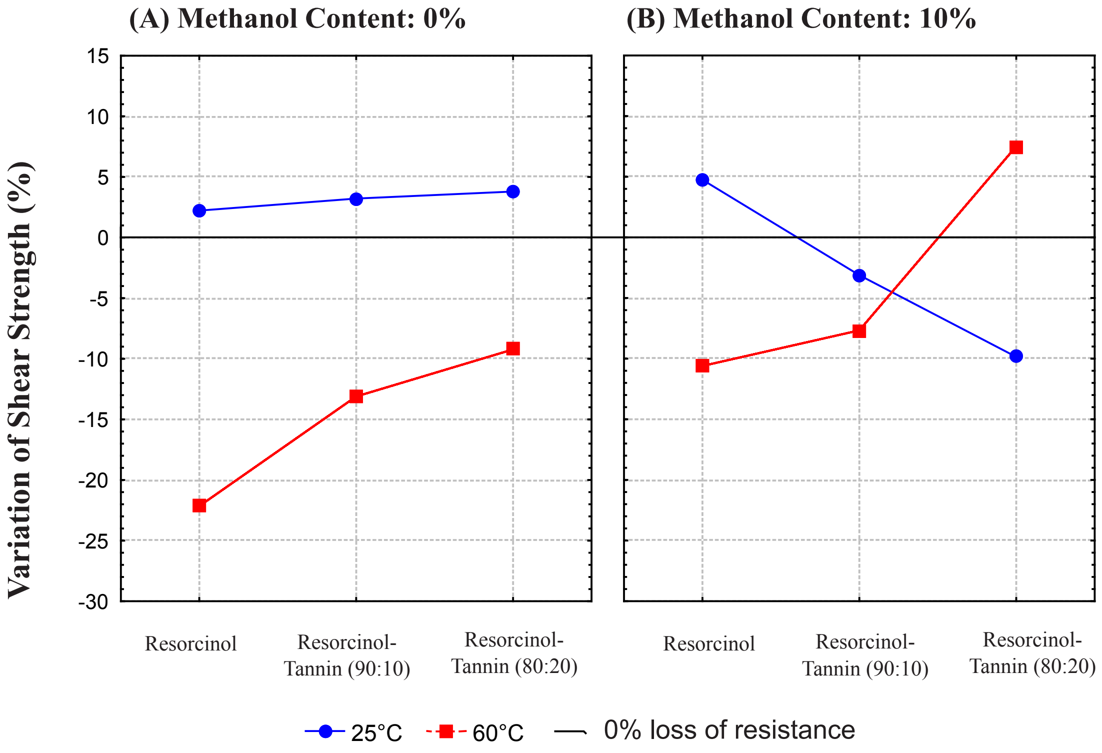


Figure 6. Variation of shear strength before and after exposure to weathering simulated conditions for quaruba cedar wood glued joints.

in the wood and to produce a good anchorage within wood. Our results are in agreement with the statement of Pizzi (1994) which mentions that the resorcinol cure at room temperature presents more advantages because the humidity is liberated gradually from the adhesive layer, inducing to the minimum stresses in the glued joint. As consequence, the adhesive layer can present a similar water loss to wood, which allows that the bondline resists at extreme humidity cycles.

Delamination Testing

The three best treatments chosen for the delamination test were: (1) resorcinol adhesive bonded at 25°C with 10% methanol content; (2) resorcinol-tannin (80:20) bonded at 25°C without methanol; and (3) resorcinol-tannin (90:10) bonded at 25°C without methanol. The delamination percentages were compared with the values required by the ASTM D 2559.1994 standard which expects delamination average values inferior to 8% for hardwoods. None treatment attained the standard values. The high delamination rate can be explained by the characteristics of the quaruba cedar wood. According to IPT (2003) quaruba cedar wood presents a tendency to deformations and cracks which can be worsted during drying process causing collapse in the thicker wood pieces. In our study, these phenomena were not observed during the shear strength test probably due to small size of the samples.

Conclusions

The results found in the present study allow to draw the following conclusions:

1. Only the quaruba cedar wood glued joints bonded with resorcinol adhesive at 25°C curing temperature without methanol present high tensile strength, with values similar to solid wood.
2. Wood glued joints bonded at 25°C curing temperature present the highest shear strength values even after the exposition to weathering simulated conditions.
3. The methanol improves the adhesion of the resorcinol adhesive for both curing temperatures and of the tannin-based adhesives at 60°C.
4. The tannin-based adhesives have a good adhesion at 60°C curing temperature while the resorcinol adhesive presented a poor adhesion at the same conditions.
5. The delamination of quaruba cedar wood glued joints were extremely elevated.
6. It is recommended the use of resorcinol-tannin (80:20) adhesive cured at 25°C without methanol due to lower price and good performance.
7. All adhesives bonded at 25°C and also the tannin-based adhesives bonded at 60°C with 10% methanol content can be used in external service conditions for quaruba cedar. However, the quaruba cedar wood glued joints can be used only in conditions where there are little variations of temperature and humidity.

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