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CERNE, vol. 19, núm. 2, abril-junio, 2013, pp. 315-321
Universidade Federal de Lavras
Lavras, Brasil

PRODUCTION OF PLYWOOD PANELS FROM *Pinus taeda* USING VENEERS OF DIFFERING DENSITIES AND PHENOL-FORMALDEHYDE RESIN WITH HIGH AND LOW MOLECULAR WEIGHTS

Graciela Ines Bolzon de Muniz[1], Setsuo Iwakiri[1], Lívia Cássia Viana[2],
Mário Andrade[3], Cristiane Weber[4], Vanessa Coelho Almeida[2]

(received: March 24, 2010; accepted: January 25, 2013)

ABSTRACT: This study aimed to evaluate the bonding quality of plywood panels from *Pinus taeda* using low and high molecular weight phenol-formaldehyde resin and veneers from three different density classes. The experiment consisted of six treatments, each of which produced three panels (replicates). Tests were conducted to evaluate glue line strength to shear stress after two boiling cycles and after 24 hours of cold water immersion. Also determined was the percentage of defects in wood samples. Results indicated that the density classes being assessed differed statistically. However, no significant difference was found between panels produced with high and panels produced with low molecular weight resin as to the mean values of glue line strength, whether subjecting them to two boiling cycles or after 24 hours of cold water immersion. Interactions between different density classes and adhesive formulations were found not significant either. Low molecular weight resin (BPM) and panels produced with higher density veneers were found to have better behavior, regarding both bonding strength and percentage of defects. It was concluded that the bonding quality of plywood panels from *Pinus taeda* was satisfactory after using different densities of veneer and also high and low molecular weight phenolic resins. All treatments were found to comply with minimum requirements established in European standard EN 314-1/1993, which addresses bonding quality of plywood panels.

Key words: Plywood panels, *Pinus taeda*, veneers, phenol-formaldehyde.

PRODUÇÃO DE PAINÉIS COMPENSADOS DE *Pinus taeda* COM LÂMINAS DE DIFERENTES DENSIDADES E RESINA FENOL-FORMALDEÍDO COM ALTO E BAIXO PESO MOLECULAR

RESUMO: *Neste trabalho, objetivou-se avaliar a qualidade da colagem de painéis compensados de Pinus taeda, produzidos com resina fenol-formaldeido de alto e baixo peso molecular, e lâminas de três diferentes classes de densidades. O experimento foi organizado em seis tratamentos, e para cada tratamento foram produzidos três painéis (repetições). Os ensaios de resistência da linha de cola aos esforços de cisalhamento foram realizados após dois ciclos de fervura e após 24 horas de imersão em água fria. Determinou-se, também, a porcentagem de falhas na madeira. Os resultados indicaram que as classes de densidade são estatisticamente diferentes entre si. Entretanto, não houve diferença significativa entre os valores médios de resistência da linha de cola dos painéis produzidos com resina de alto e baixo peso molecular, tanto para os painéis submetidos aos dois ciclos de fervura, quanto para os submetidos ao ensaio após 24 horas em água fria. A interação entre as classes de densidade das lâminas e as formulações do adesivo, igualmente, não foi significativa. A resina de baixo peso molecular (BPM) e os compensados produzidos com as lâminas de maior densidade apresentou melhor comportamento, tanto para resistência quanto para a porcentagem de falha na madeira. Conclui-se que a qualidade de colagem dos painéis compensados de Pinus taeda produzidos com lâminas de densidades diferentes e com resinas fenólicas de alto e baixo peso molecular foi satisfatória. Todos os tratamentos atendem às exigências mínimas da norma européia EN 314-1/1993, que trata da qualidade da colagem de painéis compensados.*

Palavras-chave: Painéis compensados, Pinus taeda, lâminas, fenol-formaldeído.

1 INTRODUCTION

Brazil has a long-established tradition in the production and export of plywood panels made from pinewood. Even with the drop in international demand for plywood as verified in recent years, Brazilian exports of *Pinus* plywood reached 1,544,000 m^3 in 2007, attaining a sales value of US$476 million. In the same year, exports

[1]Forest Engineer, Professor PhD in Forest Engineering – Universidade Federal do Paraná/UFPR – Departamento de Engenharia e Tecnologia Florestal – Av. Lothário Meissner, 900, Jardim Botânico – 80.210-170 – Curitiba, PR, Brasil – gbmunize@ufpr.br, setsuo@ufpr.br
[2]Forest Engineer, PhD Candidate in Forest Engineering – Universidade Federal do Paraná/UFPR – Departamento de Ciências Florestais – Av. Lothário Meissner, 900, Jardim Botânico – 80.210-390 – Curitiba, PR, Brasil – licvianna@hotmail.com
[3]Chemical Engineer - Hexion Química Ind. e Com. Ltda – Rua Cyro Correa Pereira, 2525 – CIC – 81.460-050 – Curitiba, PR, Brasil – mario.andrade@hexion.com
[4]Forest Engineer, MSc Candidate in Forest Engineering – Universidade Federal do Paraná/UFPR – Av. Lothário Meissner, 900, Jardim Botânico – 80.210-170 – Curitiba, PR, Brasil – criswef@yahoo.com.br

of plywood made from tropical timber reached 419,000 m^3, with a sales value of US$221 million (ASSOCIAÇÃO BRASILEIRA DA INDÚSTRIA DE MADEIRA PROCESSADA MECANICAMENTE - ABIMCI, 2008). In the 90s, tropical timber started to be replaced with timber from *Pinus taeda* and *Pinus elliottii* for production of veneers and plywood panels, with the maturation of nonnative forests in southern Brazil (IWAKIRI et al., 2001). Today, over 70% of plywood panels being produced in Brazil have veneers of these two pinewood species as constituent parts.

Typically, variables involved in production of multilaminated plywood panels relate to two sets of factors: raw materials (wood species and resin) and processing conditions (equipment, for instance). According to Baldwin (1995), major factors affecting the bonding process of veneers will vary according to wood, adhesive and bonding conditions. Wood properties such as density, porosity, pH and extractives will affect in different ways the physicochemical processes involved in veneer bonding. Similarly, the choice of adhesive to be used will depend on the end use of the panels. Phenol-formaldehyde adhesive is typically used in manufacture of structural and exterior plywood, on account of being highly resistant to withstand humidity conditions. Also, different compositions concerning molar ratio, molecular weight and incorporation of chemical additives may be adopted to optimize the cost-benefit tradeoffs when bonding veneers (MARRA, 1992).

Vital et al. (2006) reported that, with wood being a heterogeneous raw material and with its properties varying considerably, the characteristics and behavior of wood pieces may differ and, consequently, reflect in the bonding quality of a finished product. High density wood pieces are more difficult to bond together due to their low porosity, and therefore they obstruct the penetration of adhesive and, consequently, the formation of a resistant, high quality glue line (MARRA, 1992; TSOUMIS, 1991). The opposite occurs with low density woods, which may lead to excessive absorption and penetration of adhesive.

Differing characteristics are reported in timber from *Pinus taeda* by several researchers. For juvenile wood, Muniz (1993) found low specific mass, low strength to static bending and axial compression, along with high values of extractives and resin contents. According to Marra (1992), large quantities of extractives are bound to affect wood hygroscopicity, reducing the rate of water loss. And that gives the adhesive greater mobility than is desired which, compounded by pressure and heat, may lead to excessive glue absorption.

This study aimed to evaluate the quality of plywood panels made from *Pinus taeda* using veneers from three density classes and also low and high molecular weight phenol-formaldehyde resin.

2 MATERIAL AND METHODS

2.1 Material

Veneers were obtained from trees of *Pinus taeda* around 15 years in age, which had been planted in the region of Palmas, Paraná state. The veneers were peeled using a Finnish Raute lathe to around 2.7 mm in thickness. This lathe type has a programming system that allows grading the veneers into different density groups.

2.2 Veneer preparation for bonding

The Raute lathe was programmed to separate veneers into three distinct density classes, namely Super Hard (SD), Hard (D) and Soft (M). The veneers were dried in a continuous dryer to 6% average moisture content. Once dried, the veneers were cut to a square shape 40 X 40 cm in size. The basic density of the *Pinus taeda* samples was determined according to the method described by Vital (1984). For each density class established by the veneer supplying company, nine replicates were tested.

2.3 Panel production

Once veneers were graded, each plywood panel was produced by bonding together five veneer plies with adhesive made from phenol-formaldehyde resin, using two types of resin produced by Momentive Química, namely a high molecular weight resin (APM) and a low molecular weight resin (BPM). Adhesive preparations consisted of differing parts of phenol-formaldehyde resins, extender (wheat) and water. The APM resin adhesive was formulated with 100.00 parts by weight of resin, 15.00 parts by weight of wheat and 8.00 parts by weight of water, while the BPM resin adhesive was formulated with 100.00 parts by weight of resin, 19.17 parts by weight of wheat and 19.25 parts by weight of water.

The adhesive formulated with APM resin had a solids content of 35.37%, against 35.76% for the adhesive formulated with BPM resin, and both had a viscosity of 5500 cP. The quantity of adhesive used was 360 g/ m^2 (double surface).

The experiment was laid out into six treatments, considering each density class and resin type. Three panels were produced per treatment (replicates), as illustrated in Table 1.

Table 1 – Experimental design for production of plywood panels.

Tabela 1 *– Delineamento experimental para produção dos painéis compensados.*

Treatment	Density class (DBM)	Resin	Num. of panels
T1	Super Hard (> 0.550 g/cm³)		3
T2	Hard (0.350-0.550 g/cm³)	APM	3
T3	Soft (< 0.350 g/cm³)		3
T4	Super Hard (> 0.550 g/cm³)		3
T5	Hard (0.350-0.550 g/cm³)	BPM	3
T6	Soft (< 0.350 g/cm³)		3

Where: DBM = basic density of each respective class.

The average assembly time was 20 minutes. During prepressing, the panels were subjected to a specific pressure of 10 kgf/cm² for five minutes. The pressing temperature was 140°C for all treatments. The total pressing time for the panels produced with APM resin was seven minutes, out of which four and a half had a specific pressure of 12 kgf/cm² while two and a half had a specific pressure of 10 kgf/cm². As for the panels produced with BPM resin, the total pressing time was nine minutes, in which six minutes had a specific pressure of 12 kgf/cm² and three minutes had a specific pressure of 10 kgf/cm².

2.4 Tests of glue line strength

After panels were acclimatized, 10 test pieces were removed from each panel, to a total of 30 test pieces per treatment, in preparation for glue line strength testing to shear stress. Out of this total, 15 pieces were subjected to two 4-hour boiling cycles, with rest intervals in a forced air oven at a temperature of 60 ± 3°C, for 16 to 20 hours. The remaining 15 pieces were subjected to cold water immersion (20 ± 3°C) for 24 hours, for subsequent tests.

The testing methodology followed standard EN 314-1 (EUROPEAN STANDARD, 1993a), documenting rupture strength and percentage of defects. In all test pieces, shear force was applied to the central glue line portion of the panels.

Once sheared, the test pieces were subjected to analysis for the percentage of wood defects. Values found were compared with bonding requirements established in standard EN 314-2 (EUROPEAN STANDARD, 1993b), which correlates mean values of tensile strength with mean values of defect percentage.

The experiment was laid out in a completely randomized design consisting of three replicates, in a 2 x 3 factorial arrangement, including two resin types (APM and BPM) and three different veneer densities (SD, D and M). Effects included in the model were tested at a nominal significance level (α) of 5%. Levels of factor Resin (R), if found significant, were compared by the Student's t test (α = 5%), while levels of factor Density (D) were compared by the *Scott-Knott* test (α= 5%).

3 RESULTS AND DISCUSSION

3.1 Basic density

Table 2 provides mean values of basic density for veneers from *Pinus taeda* according to three classes.

Table 2 – Mean values of basic density for the three classes of veneers.

Tabela 2 *– Valores médios da densidade básica das lâminas para as três classes.*

Class	DB (g/cm³)	CV (%)
SD	0.604 a	8.60
D	0.397 b	13.97
M	0.342 c	8.12
Overall mean	0.444	28.70

Where: SD = super hard; D = hard; M = soft; DB = basic density; CV = coefficient of variation. Means followed by the same letter do not differ statistically by the *Tukey* test at the 5% probability level.

In examining Table 2, a significant difference was found between the density classes of *Pinus taeda*. The mean value of basic density for class SD (super hard) was higher than for class D (hard) which, in turn, was higher than for class M (soft), demonstrating grading efficiency by the laminating lathe used by the veneer supplier.

The mean value of basic density found here for *Pinus taeda* was 0.444 g/cm³. Walker (1993) points to density values between 0.38 and 0.70 g/cm³ as being ideal for lamination processes. Iwakiri et al. (2002c) evaluated production feasibility for plywood panels, using *Pinus taeda* at age 20 years, with a mean basic density of 0.480 g/cm³. Rigatto et al. (2004) found a mean density of 0.390

g/cm³ for *Pinus taeda* at age 12 years. Nisgoski (2005) found mean values of basic density ranging from 0.332 g/cm³ to 0.372 g/cm³ in a study with *Pinus taeda* at ages 10 and 14 years respectively.

3.2 Glue line strength to shear stress

Table 3 gives the analysis of variance summary for shear testing after two boiling cycles (2 cycles) and 24 hours in cold water, as a function of the tested variables.

Table 3 – Analysis of Variance Summary (ANOVA).

Tabela 3 – *Resumo da Análise de Variância (ANOVA).*

Source	DF	Mean Square (p-value)	
		2 cycles	24 hours
Resin (R)	1	2.980 (p=0.491)	2.105 (p=0.689)
Density (D)	2	28.173 (p=0.030)	53.454 (p=0.040)
R x D	2	4.062 (p=0.521)	1.141 (p=0.914)
Error	12	5.897	12.566
CV (%)		21.62	24.87

The mean values found for the two shear testing conditions are expressed as kgf/cm² and are illustrated in Tables 4 and 5.

Table 4 – Mean values of shear strength, after the boiling cycles and cold water immersion tests, as a function of resin type.

Tabela 4 *– Valores médios de resistência ao cisalhamento, após os testes de ciclos de fervura e de imersão em água fria, em função dos tipos de resina.*

Resin	Mean	
	2 cycles (kgf/cm²)	24 hours (kgf/cm²)
APM	10.83 a	13.91 a
BPM	11.64 a	14.57 a
Overall CV (%)	21.62	24.87

Where: APM = high molecular weight; BPM = low molecular weight; CV: coefficient of variation.

Table 4 data reveal no statistically significant difference between the mean values found for panels made with high molecular weight resin and panels made with low molecular weight resin, whether in the boiling cycle or in the cold water immersion testing.

Table 5 – Mean values of shear strength, after the boiling cycles and cold water immersion tests, as a function of density class.

Tabela 5 – *Valores médios de resistência ao cisalhamento, após os testes de ciclos de fervura e de imersão em água fria, em função das classes de densidade.*

Density	Mean	
	2 cycles (kgf/cm²)	24 hours (kgf/cm²)
SD	13.39 a	17.43 a
D	11.25 a	13.82 b
M	9.06 b	11.51 b
CV (%)	21.62	24.87

Where: CV: coefficient of variation. Means followed by the same lowercase letter in a column do not differ by the *Scott-Knott* test, at the 5% nominal significance level.

Despite the statistical similarity found in the mechanical tests in terms of absolute mean values, the BPM resin provided panels with greater shear strength. The low molecular weight of that resin may have favored deeper penetration of adhesive, in contrast with the APM resin, and thus helped form a better quality glue line.

In a study with trees of *Pinus taeda* with a basic density of 0.480 g/cm³, at age 20 years, and using urea-formaldehyde resin adhesive, Iwakiri et al. (2002c) found that the mean values of glue line strength to dry testing for the resulting plywood panels ranged between 10.61 and 14.28 Kgf/cm².

Iwakiri et al. (2001), in studies conducted on six tropical *Pinus* species and using phenol-formaldehyde resin, found that the mean values of glue line strength ranged between 23.38 kgf/cm² (*Pinus caribaea*) and 35.67 kgf/cm² (*Pinus taeda*) after dry testing, against 13.62 kgf/cm² (*Pinus oocarpa*) and 20.10 kgf/cm² (*Pinus chiapensis*), after boil testing.

The different classes of basic density were found to influence the values of glue line strength to shear stress, in both adhesive formulations, as is illustrated in Table 5.

After applying two boiling cycles, it was found that panels made with class SD veneers had a higher mean value of glue line strength (13.39 kgf/cm²) than panels made with class D (11.25 kgf/cm²) and class M (9.06 kgf/cm²) veneers, the first two classes being found statistically similar.

Also, the mean tests revealed that, when subjecting test pieces to shear testing after 24 hours in cold water, the panels produced with SD veneers had greater shear strength and were statistically different from the remaining panels, at a 95% nominal significance level. As for class D and class M panels, no significant differences were found between them.

After working with *Araucaria angustifolia, Pinus taeda* and *Eucalyptus grandis*, the relevant veneers having a specific mass of 0.60 g/cm^3, 0.53 g/cm^3 and 0.70 g/cm^3 respectively, Iwakiri et al. (2006) found that the values of glue line strength to shear stress were not statistically different.

The mean values found in this study are consistent with results found by other authors. Iwakiri et al. (2002a) manufactured plywood panels from *Pinus taeda* at age 20 years and from *Pinus oocarpa* at age 24 years, using phenol-formaldehyde resin. In the boiling test, the mean values of glue line strength ranged between 9.4 and 12.6 kgf/cm^2 for *Pinus taeda*, and between 11.8 and 14.6 kgf/cm^2 for *Pinus oocarpa*.

Using SD veneers (DB = 0.604 g/cm^3) to produce plywood panels helped attain higher values of glue line strength to shear stress. According to literature, the higher the basic density, the lower the porosity of a wood piece and, consequently, the lower its permeability to adhesive, which in turn prevents the formation of a superior quality glue line (MARRA, 1992; TSOUMIS, 1991). However, the interactions between density/porosity and adhesive viscosity under these particular conditions did favor formation of a stronger adhesive bond.

Iwakiri et al. (2002b) evaluated the influence of radial growth in *Pinus taeda* trees on the mechanical properties of plywood panels. The authors found that veneer density increased in the pith-to-bark direction from 0.493 g/cm³ to 0.638 g/cm³, and that static bending and glue line strength properties were significantly lower in panels produced with veneers taken from the pith portion, with low density. Iwakiri et al. (2000) studied composite panels made from veneers of *Pinus elliottii* and *Eucalyptus saligna* and found that panels made with *E. saligna* veneers, with higher density on the covers, resulted in higher values of MOR and MOE in static bending tests, demonstrating the influence of wood density on the mechanical properties of plywood panels.

3.3 Wood defects

Table 6 provides mean values of tensile strength combined with mean values of defect percentage, according to standard EN 314-2 (EUROPEAN STANDARD, 1993b). This standard correlates the two above parameters, allowing a closer analysis of bonding conditions.

Table 6 – Bonding requirements.

Tabela 6 – *Requisitos da colagem.*

Glue Line Strength to Shear Stress	
Tensile Strength – TR (kgf/cm^2)	Split or Defect in Wood (%)
$2.04 \leq TR < 4.08$	≥ 80
$4.08 \leq TR < 6.12$	≥ 60
$6.12 \leq TR < 10.2$	≥ 40
$10.2 \leq TR$	No requirement

Source: EN 314-2 (EUROPEAN STANDARD, 1993b).

The mean values of defect percentage in the test pieces, using both types of adhesive (APM and BPM) and subjecting the pieces to boil and cold water tests are given in Table 7.

Table 7 – Mean values of wood defect percentage, after the boiling cycles and cold water immersion tests, as a function of resin type.

Tabela 7 – *Valores médios de porcentagem de falhas na madeira, após os testes de ciclos de fervura e de imersão em água fria, em função dos tipos de resina.*

Resin	Percentage of wood defects	
	2 cycles	24 hours
APM	64.22 (10.83)	51.00 (13.91)
BPM	79.33 (11.64)	68.33 (14.57)

Where: APM = high molecular weight; BPM = low molecular weight. In brackets are kgf/cm² values.

Mean values of defect percentage ranged from 51.00% to 79.33%, the highest values being found for panels made with BPM resin, as with values of tensile strength, confirming the superiority of that resin.

An analysis of the values established in standard EN 314-2 (EUROPEAN STANDARD, 1993b), in Table 6, which correlates the minimum value of defects with strength to shear stress, reveals that both APM and BPM resin panels met said requirements, in both test conditions. Results of tensile strength were above 10.2 kgf/cm^2, which is the threshold value after which there are no requirements as to percentage of defects.

In contrasting the mean values found of tensile strength and percentage of defects with the combined values established in standard EN 314-2 (EUROPEAN STANDARD, 1993b), as provided in Table 6, it was found that all plywood panels complied with the above standard, in both test conditions (Table 8).

Table 8 – Mean values of defect percentage, after the boil cycles and cold water immersion tests, as a function of density class.

Tabela 8 – *Valores médios de porcentagem de falhas na madeira, após os testes de ciclos de fervura e de imersão em água fria, em função das classes de densidade.*

Density	Percentage of wood defects	
	2 cycles	24 hour
Super hard	61.83 (13.39)	50.50 (17.43)
Hard	88.17 (11.25)	74.00 (13.82)
Soft	65.33 (9.06)	54.50 (11.51)

In brackets are kgf/cm² values.

Panels produced with class D veneers had the highest percentage of wood defects (88.17% and 74.00%), with a tensile strength of 11.25 Kgf/cm^2 for the boiling test against 13.82 Kgf/cm^2 for the cold water immersion test.

The defect percentage was overall high, indicating good quality glue line. The bond between adhesive and wood and the strength of the adhesive/wood interface are at least equal to or higher than the strength of the wood itself.

4 CONCLUSIONS

Results found in this study led to the following conclusions:

• Both the APM resin and the BPM resin derived panels that comply with standard EN 314-2 (EUROPEAN STANDARD, 1993b);

• The mean values found in this study of glue line strength to shear stress were, for the most part, higher than the minimum requirement set in standard EN 314-2 (EUROPEAN STANDARD, 1993b);

• Although the differences between values were not found significant, the low molecular weight resin (BPM) proved superior in bonding quality;

• The percentages of wood defects were overall higher when low molecular weight resin (BPM) was used, indicating a higher degree of penetration;

• Basic density was found to influence bonding, in which the higher the density of the core veneers, the higher the mean values of glue line strength to shear stress found in finished panels.

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