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## PULP PRODUCED WITH WOOD FROM *Eucalyptus* TREES DAMAGED BY WIND

Keywords:
Fiber
Nanoindentation
Opacity
Tear index
Tensile index

**ABSTRACT:** Wind may damage eucalyptus trees, especially 24 months after planting, which can reduce wood fiber quality and hinder pulp production. The objective of this study was to evaluate the use of these materials in mixtures with wood from seven-year-old trees to produce pulp. Bleached pulp was produced using 100, 95, 85, 75 and 0% wood from seven-year-old eucalyptus trees, related to cutting age. Wood from two-year-old trees, when trees are most susceptible to damage by wind, completed each treatment. A 5 cm thick disc was taken from breast height (1.3m) on each tree for anatomical and ultrastructural characterization. The seven-year-old wood had lower vessel frequency and fibers with a longer length, higher cell wall fraction, higher modulus of elasticity and hardness, and a lower microfibril angle. Pulp refining decreased the opacity and specific volume, increased air resistance and improved mechanical properties. The addition of two-year-old wood to produce pulp reduced the mechanical properties and opacity, and increased the air resistance of the paper. The proportion of two-year-old wood that can be used in pulp production varied with the clone, parameter, and refining level. However, the pulp produced with 5% wood from two-year-old trees and 95% wood from seven-year-old trees was similar to that with 100% seven-year-old wood. Therefore, 5% two-year-old wood can be used to produce pulp without quality losses.

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## PRODUÇÃO DE POLPA CELULÓSICA COM MADEIRA DE ÁRVORES DE *Eucalyptus* DANIFICADAS PELO VENTO

Palavras chave:
Fibra
Índice de rasgo
Índice de tração
Nanoindentação
Opacidade

**RESUMO:** Árvores de eucalipto de rápido crescimento podem ser danificadas por ventos, principalmente 24 meses após o plantio, mas a baixa qualidade das fibras dessa madeira dificulta a produção de polpa celulósica. O objetivo deste estudo foi avaliar a utilização destes materiais para a fabricação de polpa celulósica em misturas com madeira de árvores de sete anos de idade. Polpa celulósica branqueada foi produzida com 100, 95, 85, 75 e 0% de madeira de árvores de dois clones de *Eucalyptus grandis* x *Eucalyptus urophylla* com sete anos de idade, relacionada com a idade de corte. Madeira de árvores de dois anos de idade, mais susceptíveis a danos por ventos, foi utilizada para completar cada tratamento. Um disco de espessura de 5 cm foi retirado na altura do peito (1,3 m) em cada árvore para a caracterização anatômica e ultra-estrutural. As árvores com sete anos apresentaram maior frequência de vasos, fibras com maior comprimento, fração parede, módulo de elasticidade e dureza e menor ângulo microfibrilar. O refino nas polpas diminuiu a opacidade e o volume específico e aumentou a resistência a passagem do ar e as propriedades mecânicas. A adição de madeira de dois anos de idade na produção de polpa celulósica reduziu a resistência mecânica e opacidade e aumentou a resistência à passagem de ar. A proporção da madeira de dois anos de idade, que pode ser utilizado na produção de polpa celulósica variou com o clone, parâmetro avaliado e intensidade do refino. No entanto, a polpa celulósica produzida com 5% de madeira de dois anos de idade, e 95% de madeira de sete anos de idade, foi semelhante aquela com 100% de madeira de árvores de sete anos de idade. Portanto, cinco por cento de madeira de dois anos de idade pode ser utilizado para a produção de polpa celulósica sem perda de qualidade.

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## INTRODUCTION

In Brazil, the annual volume increment of *Eucalyptus* plantations is approximately 39 $m^3 \cdot (ha \cdot year^{-1})$ (IBA, 2015) with a seven-year rotation period. These growth rates result from climate conditions and investment in tree breeding and silviculture management (CAMPINHOS Jr, 1999; GONÇALVES et al., 2008). The wood from these crops is used for diverse purposes, such as panel production (BAL;BEKTAŞ, 2014), energy (ZANUNCIO et al., 2013a; ZANUNCIO et al., 2013b; ZANUNCIO et al., 2014), lumber (ANANIAS et al., 2014; SEPULVEDA-VILLARROEL et al., 2015; ANDRADE et al., 2016) and cellulose pulp (OKAN et al., 2015; BARBOSA et al., 2016). This generates jobs and taxes for the Brazilian economy, but wind damage may limit the performance of this segment.

Air displacements cause wind damage (MITCHELL et al., 2012; MOORE et al., 2013). In Brazil, wind damage is common in *Eucalyptus* plantations, mainly between 24 and 36 months after planting, affecting up to 20% of trees (CENIBRA, 2014).

Losses from wind may impact the entire production chain. Harvesting wood with a smaller diameter increases operation costs (HIESL et al., 2015; SPINELLI et al., 2009) and new plantations start earlier. Trees broken by the wind have lower fiber quality because of their younger age (RAMÍREZ et al., 2009), hindering their use in the pulp and paper industry (PIRRALHO et al., 2014; SEVERO et al., 2013). Thus, this wood is used mainly for power generation (GUERRA et al., 2014).

The use of wood from wind damaged trees to produce pulp and paper can potentially reduce financial losses caused by winds. The adverse effects of poorer quality wood from young trees may be offset by blending them with that of older trees, but the optimum proportion of each wood type is unknown.

The objective of this study was to characterize the anatomy and ultrastructure of the wood and assess the pulp quality from two *Eucalyptus grandis* × *Eucalyptus urophylla* clones made with mixtures of wood from two and seven-year-old trees.

## METHODOLOGY

### Biological Material

Wood from two *Eucalyptus grandis* × *Eucalyptus urophylla* clones was obtained from trees harvested at two (wind damage age) and seven years of age (normal harvest age), from Belo Oriente, Minas Gerais State, Brazil, 42°22'30 S and 19°15'00 W. Three trees per clone and age were harvested (12 trees in total). A 5 cm thick disk was removed from each tree at breast height (1.3 m), for anatomical and ultrastructural characterization. Finally, one meter long logs were taken at 0, 25, 50, 75, and 100% of the merchantable stem length, for pulp production.

### Anatomical characterization

A wood sample (1.5 x 1.5 x 1.5 cm) was cut from each breast height disc. This sample was taken from halfway between the pith and the bark. The slides (JOHANSEN, 1940) and the macerated material (FRANKLIN,1945) were prepared from this sample. The microscopic description of the wood was done according to the International Association of Wood Anatomists (IAWA, 1989). The cell wall thickness of the fibers was calculated with the equation 1 and the cell wall fraction using the equation 2, where: CWT= cell wall thickness ($\mu$m); FW = fiber width ($\mu$m); LD=Lumen diameter ($\mu$m); C.W.F.= Cell wall fraction (%).

$$C.W.T = \frac{(F.W. - L.D.)}{2} \quad [1]$$

$$C.W.F. = \left(\frac{(2 \times C.W.T.)}{F.W.}\right) \times 100 \quad [2]$$

### Microfibril angle measurement

The microfibril angle of the S2 layer was determined using the same sample used for anatomical characterization. After saturation, the sample was cut with a microtome in the tangential plane, in 10 $\mu$m thick sections, which allows for the cutting of fibers longitudinally (half-fibers) (LENEY, 1981). These fibers were macerated in glacial acetic acid and hydrogen peroxide 35 volume (2:1 ratio) at 55° C for 24 hours. Next, the fibers were washed in distilled water and temporary slides were prepared to measure the microfibril angle.

The microfibril angle was measured by polarized light microscopy (LENEY, 1981), using an Olympus BX 51 microscope, adapted with a rotary stage, graduated from 0° to 360°, and connected to the image analysis program, Image Pro-plus. The image was magnified 200 times and 20 fibers were analyzed per wood sample.

### Nanoindentation

The nanoindentation used in wood science and technology is a technique to determine the mechanical properties of the fiber and middle lamella. To perform these tests, a sample (1.5 × 1.5 × 1.5 cm) was removed from the opposite position to that used for anatomical characterization.

From this sample, a 3 × 3 × 3 mm new sample was made and embedded in epoxy resin solution to determine the modulus of elasticity and hardness of the S2 layer of the fiber and of the middle lamella. The nanoindentation was performed in a TriboIndenter Hysitron TI-900®. The maximum applied load was 100 μN for 60 seconds, with discharge performed in 20μN/s. The modulus of elasticity was determined according to the equation 3, where: MOE= modulus of elasticity (GPa) according to manufacturer's instructions, vi= 0.07; vm= 0.35, and Ei= 1140 GPA (MUÑOZ et al., 2012). The reduced modulus (Er) was obtained from the load-displacement curve, from the initial unloading slope, wherein, the elastic response was generated (MUÑOZ et al., 2012).

$$MOE = \left(1 - vm^2\right) \times \left(\frac{1}{Er} - \frac{1 - vi^2}{Ei}\right)^{-1} \quad [3]$$

Hardness was determined by the maximum load supported by the specimen divided by the contact area, according to the equation 4, where: H=hardness (GPa); Pmax=maximum load of nanoindenter penetration; and A=Projected contact areas at maximum load.

$$H = \frac{Pmax}{A} \quad [4]$$

## Characterization of pulp produced

The wood pulping process was calibrated to produce pulp with a kappa number 18 ± 0.5. The pulping was carried out using 600 g of dry wood, 25.3% sulfidity, liquor-to-wood ratio of 4:1, and cooking temperature of 170°C and residence time of 60 minutes. The effective alkali and yield are shown in Table 1.

**TABLE 1** Effective Alkali, total yield, screened yield and reject yield of pulping

| Treatments | Clone A | | | | |
|---|---|---|---|---|---|
| | T1 | T2 | T3 | T4 | T5 |
| Effective alkali (%) | 17.0 | 16.7 | 16.7 | 16.6 | 16.0 |
| Screened yield (%) | 50.4 | 50.2 | 50.3 | 50.0 | 49.6 |
| Reject yield (%) | 0.03 | 0.02 | 0.02 | 0.03 | 0.03 |
| Total yield (%) | 50.4 | 50.2 | 50.3 | 50.0 | 49.6 |
| Treatments | Clone B | | | | |
| | T1 | T2 | T3 | T4 | T5 |
| Effective alkali (%) | 15.7 | 15.4 | 15.4 | 15.3 | 14.7 |
| Screened yield (%) | 50.7 | 50.3 | 50.1 | 50.5 | 49.8 |
| Reject yield (%) | 0.02 | 0.03 | 0.04 | 0.03 | 0.03 |
| Total yield (%) | 50.4 | 50.2 | 50.3 | 50.0 | 49.6 |

Pulp made with 100% (T1); 95% (T2); 85% (T3) and 75% (T4) of wood from seven-years-old trees and 100% wood from two-years-old trees (T5).

Bleaching was carried out to obtain pulp with brightness 90% ISO ± 1. The pulps were bleached by sequence OD(EP)D. In this sequence, "O" represents delignification with oxygen, "D" a stage with chlorine dioxide, and "(EP)" represents a stage with sodium hydroxide and hydrogen peroxide.

This sequence and conditions at each stage are used in pulp mills. The oxygen delignification (O stage) was run at 10% consistency, 100°C, 60 min, 700 kPa pressure, 20 kg NaOH/odt pulp and 20 kg $O_2$/odt pulp. The first chlorine dioxide stage (D) was carried out at 90°C for 120 minutes, 10% consistency, end pH between 2.5 to 3.0 and kappa factor of 0.23. The hydrogen peroxide stage (EP) was carried out at 80°C for 120°C and at 10% consistency. The second dioxide stages (D) was carried out at 80°C for 120°C, at 10% consistency and end pH was between 4.5 and 5.0.

Samples were refined at 0, 500, 1500, and 3000 revolutions in the PFI mill. The pulping was carried out using wood from seven-year-old trees in proportions of 100, 95, 85, 75, and 0%, supplemented by wood from two-year-old trees.

The pulp produced from different mixtures of wood from two and seven-year-old trees was analyzed according to the "Technical Association of Pulp and Paper Industry- TAPPI" (Table 2).

**TABLE 2** Physical, mechanical and optical characterization of pulp produced

| Test | Norma |
|---|---|
| Refining in PFI mil | T248 sp-08 |
| Paper sheets for tests | T205 sp-06 |
| Schopper Riegler degree - °SR | T452 om-08 |
| Brightness | T452 om-08 |
| Opacity | T1214 sp-07 |
| Resistance to air passage | T536 om-07 |
| Tear Resistance | T414 om-04 |
| Tensile index and stretch | T494 om-06 |

## Statistical analysis

The variance homogeneity (Bartlett's test at 5% significance) and normality were performed (Shapiro-Wilk test at 5% significance). The means obtained in the anatomical characterization were analyzed by t-test at 5% probability and those of pulp characterization were subjected to Scott-Knott at 5% probability.

## RESULTS AND DISCUSSION

The wood anatomical composition and mechanical properties of the S2 cell wall layer and middle lamella varied between clones and ages of the same clone (Table 3).

**TABLE 3** Anatomical and ultrastructural characterization of *Eucalyptus* grandis x *Eucalyptus* urophylla clones with two and seven years old

| CL. | Ag. | F.L. (mm) | F.W. (µm) | L.D. (µm) | C.W.T. (µm) | C.W.F. (%) | Diâm. (µm) | Freq. (pores·mm$^{-2}$) | Alt. (µm) | Larg. (µm) | Microfibrilangle (°) | Moe of S2 layer (Gpa) | Hardness of S2 layer (Gpa) | Moe of m.l. (Gpa) | Hard. of m.l. (Gpa) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 2 | 0.822$^{14.7}$ a | 17.62$^{13.2}$a | 10.47$^{16.6}$ b | 3.57$^{17.3}$ a | 40.96$^{16.3}$ a | 109.6$^{14.5}$ a | 11.1$^{12.5}$ a | 306.4$^{18.1}$a | 7.64$^{16.8}$ a | 10.88$^{6.6}$ b | 11.0$^{6.9}$ a | 0.256$^{6.9}$ a | 6.12$^{7.7}$ a | 0.301$^{7.3}$ a |
| | 7 | 1.01$^{17.5}$ b | 16.97$^{13.2}$a | 7.45$^{16.1}$a | 4.73$^{17.5}$b | 55.83$^{15.5}$ b | 112.5$^{15.1}$ a | 9.5$^{12.1}$ b | 315.6$^{17.5}$ a | 7.12$^{17.5}$ a | 9.35$^{6.7}$ a | 16.5$^{7.9}$ b | 0.310$^{7.1}$ b | 6.28$^{7.3}$ a | 0.306$^{7.6}$ a |
| B | 2 | 0.831$^{13.9}$ a | 18.76$^{14.3}$a | 11.93$^{16.4}$ b | 3.41$^{16.4}$ a | 36.63$^{16.2}$ a | 91.64$^{13.1}$ a | 12.1$^{11.7}$ a | 226.3$^{17.2}$ a | 8.53$^{17.2}$ a | 9.56$^{7.5}$ b | 11.6$^{7.0}$ a | 0.266$^{7.3}$ a | 7.13$^{7.2}$ a | 0.299$^{6.9}$ a |
| | 7 | 1.03$^{13.8}$b | 18.41$^{12.3}$a | 9.63$^{17.4}$a | 4.18$^{15.9}$ b | 46.25$^{11.4}$ b | 110.6$^{13.6}$ b | 9.5$^{11.4}$b | 235.5$^{17.4}$a | 8.12$^{16.5}$ a | 9.02$^{6.2}$ a | 15.9$^{7.2}$ b | 0.305$^{6.5}$ b | 7.22$^{7.1}$ a | 0.313$^{7.9}$ a |

CL. = Eucalyptus grandis × Eucalyptus urophylla clone; Ag.= *Eucalyptus grandis* × *Eucalyptus urophylla* age in years F.L.=Fiber length; F.W.=Fiber width; L.D.=Lumen diameter; C.W.T.= Cell wall thickness; C.F.R.=Cell Wall Fraction; Ves. Diam.= Vesssel diameter; Freq.=Vessel Frequency; Moe of m.l.= Moe of middle lamella; Hard. of m.l.= Hardness of middle lamella. Means followed by the same letter vertically per parameter does not differ by the t-test at 5% probability. Values in superscript represent the coefficient of variation.

Fibers from two-year-old trees had higher microfibril angle and smaller length and wall fraction in both clones, characteristics common at the beginning of cambial activity (DONALDSON et al., 2008; PANSHIN; DE ZEEUW, 1980; LIMA et al., 2014). This agrees with a greater cell wall fraction with increasing age of *Eucalyptus grandis* × *Eucalyptus urophylla* and *Eucalyptus globulus* (QUILHO et al., 2006; RAMÍREZ et al., 2009) and reduction of microfibril angle in *Eucalyptus grandis* (LIMA et al., 2014).

Pore frequency decreased 14.41 and 21.48% with increasing age from two to seven years old in the A and B clones, respectively. The highest growth rate and auxin concentration in the trees during the first years may have influenced cambial activity and increased pore frequency (PANSHIN; DE ZEEUW, 1980; NUGROHO et al., 2012; LEAL et al, 2003). The pores are important during pulping (PIRRALHO et al., 2014) for reagent penetration into the wood. Finally, the height and width of the rays were similar in the wood between the two and seven-year-old trees of both clones.

A lower microfibril angle results in better arrangement of these structures, increasing the mechanical resistance per unit area, and thus, the hardness (LI et al., 2014). In addition, a higher cell wall fraction increases the modulus of elasticity of the fiber S2 layer (GINDL et al., 2004; MUÑOZ et al., 2012). The fibers are the principal constituents of pulp and paper and, therefore, they have to present good mechanical properties (PIRRALHO et al., 2014). Finally, increasing age did not affect the mechanical properties of the middle lamella.

The Schopper Riegler (°SR) degree during refining had a higher gain for clone B (Figure 1). For both clones, the addition of wood from two-year-old trees increased the Schopper Riegler (°SR) degree (Figure 1). This showed that smaller fibers with lower cell wall fractions have a better fit between them, reducing void spaces and increasing resistance to the passage of water. Similar results have been reported for *Corymbia citriodora, Pinus contorta* and *Pinus sylvestris* (SABLE et al., 2012; SEVERO et al., 2013).

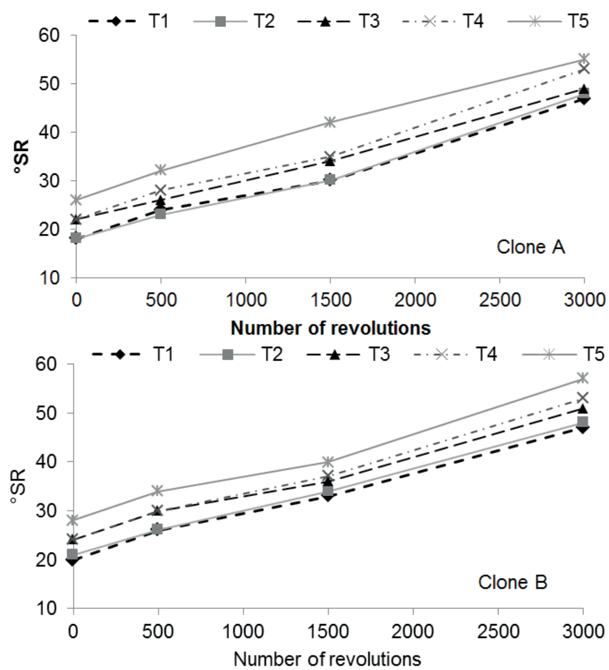


**FIGURE 1** SchopperRiegler (°SR) degree with different number of revolutions during refining in pulps made from wood with two and seven-years-old trees; Pulps were made with 100% (T1); 95% (T2); 85% (T3) and 75% (T4) wood from seven-years-old trees and 100% of wood from two-years-old trees (T5).

The specific volume decreased with refining and increased with the utilization of wood from two-year-old trees (Table 4). The lower cell-wall fraction of wood fibers from two-year-old tress facilitated the arrangement between them, and thereby, reduced the specific volume. This also explained the reduction in the specific volume with refining intensity, because the cell collapse through this technique, improved fiber arrangement and reduced this parameter (BIERMANN, 1996), especially at initial refining levels. The addition of 25% wood from two-year-old trees did not reduce the specific volume of pulp compared with that produced entirely from wood of seven-year-old trees. However, pulp made entirely from the wood of two-year-old trees showed lower values for this parameter.

The utilization and wood from two-year-old trees to produce pulp and the refining increased air resistance (Table 4). Refining induced fiber collapse, improving their arrangement in the paper sheet by reducing empty spaces and increasing air resistance. Wood fibers from two-year-old trees have a lower cell wall fraction and the poorest mechanical properties, and are therefore more fragile (GINDL et al., 2004; MUÑOZ et al., 2012), resulting in a large amount of fines that fill the voids of the paper and hinder the passage of air (SANTOS; SANSÍGOLO, 2007; PIRRALHO et al., 2014). However, the addition of 5% wood from two-year-old trees resulted in pulp with similar values of air resistance as that for pulp produced with 100% wood from seven-year-old trees.

The tear index decreased with the use of wood from two-year-old trees and increased with the refining process (Table 5). Refining increases the contact surface and intensifies the connections between the fibers, but it damaged the fiber and reduces its resistance (ARACRI; VIDAL, 2012; BIERMANN, 1996). Gains in tear index were higher up to 1500 revolutions because of the high number of connections between fibers with little damage to their structure, but with 3000 revolutions, such damage was more intense and reduced the gain in tear index. The gain in the tear index was lower with 3000 revolutions of refining when using 100% wood from two-year-old trees. This is due to the presence of fibers with poorer mechanical properties (MUÑOZ et al., 2012), which broke during the paper production process and explained the reduced tear resistance.

The addition of wood from two-year-old trees resulted in paper more susceptible to tearing (Table 5). However, proportions of up to 5% of this wood did not decrease the tear index, indicating that this wood proportion can be used to produce pulp.

The addition of wood from two-year-old trees decreased the tensile index while refining increased its values for the pulp produced (Table 5). The tensile index depends on the number of inter-fiber connections (SIXTA, 2006; GORSKI et al., 2012). The highest average length and the lowest production of fines in cellulosic pulp from seven-year-old trees guaranteed greater connectivity between the fibers and a higher tensile index (FU et al., 2015). Refining also increases the inter-fiber bonds (BIERMANN, 1996), resulting in a higher tensile index.

Pulp without refining and with 500 revolutions allowed the addition of 15% of the wood from two-year-old trees without affecting its tensile index compared to pulp produced from seven-year-old trees. However, in more severe refining conditions, only pulp produced with up to 5% wood from two-year-old trees showed a similar tensile index to that with 100% wood from seven-year-old trees.

The results for paper stretch (%) were similar to those for the tensile index with decreasing values as wood from two-year-old trees was added (Table 5). High values for stretch depend on fiber length and low fine production, allowing a greater number of connections between the fibers and greater paper stretch (SABLE et al., 2012; SEVERO et al., 2012). The refining process increased the inter-fiber connections and the stretch values for both clones, with higher gains at up to 1500 revolutions. The addition of up to 15% wood from two-year-old trees, the age with a higher wind damage, did not reduce the pulp stretch.

The refining and addition of wood from two-year-old trees reduced the opacity of the pulp produced (Table 6). Opacity is related to the ability of light to penetrate the paper (Sixta, 2006) with higher values showing lower passage of visible light. The wood fibers from seven-year-

**TABLE 4** Specific volume and air resistance with different levels of revolution during the refining of wood pulps made with wood from two and seven-years-old trees of E. grandis × E. urophylla

| Clone | Treatment | Specific volume ($cm^3 \cdot g^{-1}$) | | | | Air resistance($s \cdot (100\ cm^3)^{-1}$ | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Revolutions during the refining | | | | Revolutions during the refining | | | |
| | | 0 | 500 | 1500 | 3000 | 0 | 500 | 1500 | 3000 |
| A | T1 | $2.15^{4.2}$Aa | $1.64^{3.8}$Ba | $1.35^{3.6}$Ca | $1.16^{2.4}$ Da | $0.95^{10.3}$ Aa | $2.26^{11.5}$ Ba | $6.76^{12.6}$ Ca | $46.9^{9.8}$ Da |
| | T2 | $2.12^{4.1}$ Aa | $1.65^{4.1}$ Ba | $1.37^{2.6}$Ca | $1.19^{2.3}$ Da | $1.13^{11.2}$ Aa | $2.33^{11.2}$ Ba | $6.55^{12.4}$ Ca | $48.9^{10.0}$ Da |
| | T3 | $2.12^{3.9}$ Aa | $1.69^{3.9}$ Ba | $1.32^{2.5}$ Ca | $1.18^{2.1}$ Da | $3.26^{12.4}$Ab | $11.9^{11.8}$Bb | $26.9^{11.1}$Cb | $59.3^{9.6}$Db |
| | T4 | $2.14^{4.0}$ Aa | $1.68^{3.9}$ Ba | $1.29^{3.1}$ Ca | $1.16^{2.7}$ Da | $4.11^{11.6}$ Ac | $13.9^{11.3}$Bb | $42.9^{10.8}$Cc | $93.6^{10.6}$Dc |
| | T5 | $1.96^{3.9}$Ab | $1.49^{4.1}$Bb | $1.20^{3.3}$Cb | $1.10^{2.2}$Db | $7.6^{10.8}$Ad | $18.7^{12.5}$Bc | $60.6^{11.6}$Cd | $186.9^{10.2}$Dd |
| B | T1 | $2.12^{4.1}$ Aa | $1.58^{4.1}$Ba | $1.30^{2.9}$ Ca | $1.15^{2.3}$ Da | $1.13^{12.6}$Aa | $3.45^{13.5}$ Ba | $8.56^{13.4}$ Ca | $53.6^{11.5}$ Da |
| | T2 | $2.10^{4.5}$ Aa | $1.54^{3.9}$ Ba | $1.36^{2.8}$ Ca | $1.13^{2.3}$ Da | $1.29^{12.9}$Aa | $3.59^{14.5}$ Ba | $8.88^{11.1}$ Ca | $54.2^{10.5}$ Da |
| | T3 | $2.13^{3.6}$ Aa | $1.57^{3.6}$ Ba | $1.35^{2.8}$ Ca | $1.15^{2.2}$ Da | $4.69^{12.4}$Ab | $14.5^{12.1}$Bb | $36.8^{10.2}$Cb | $65.9^{10.3}$Db |
| | T4 | $2.08^{4.2}$Aa | $1.58^{4.1}$ Ba | $1.32^{2.6}$ Ca | $1.14^{2.5}$ Da | $5.45^{12.5}$Ab | $18.9^{11.2}$Bc | $56.1^{10.7}$Cc | $100.9^{11.5}$Dc |
| | T5 | $1.94^{4.0}$Ab | $1.42^{3.8}$Bb | $1.22^{2.7}$Cb | $1.14^{2.6}$ Da | $8.13^{12.1}$ Ac | $26.8^{12.4}$Bd | $89.7^{11.3}$Cd | $225.6^{10.6}$Dd |

Pulps were made with 100% (T1); 95% (T2); 85% (T3) and 75% (T4) wood from seven-years-old trees and 100% wood from two-years-old trees (T5). Means followed by the same capital letter per line and lower case letter per column did not differ between them by the Scott-Knott test at 5%. Values in superscript represent the coefficient of variation.

**TABLE 5** Physical, mechanical and optical characterization of pulp produced

| Clone | Treatment | Tear index (mN·m²·g⁻¹) | | | | Tensile index (Nm·g⁻¹) | | | | Stretch (%) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Revolutions during the refining | | | | Revolutions during the refining | | | | Revolutions during the refining | | | |
| | | 0 | 500 | 1500 | 3000 | 0 | 500 | 1500 | 3000 | 0 | 500 | 1500 | 3000 |
| A | T1 | $5.01^{8.9}$Aa | $6.64^{7.2}$ Ba | $10.35^{4.6}$Ca | $12.56^{4.1}$ Da | $25.6^{6.4}$Aa | $44.5^{5.7}$ Ba | $60.4^{5.3}$ Ca | $77.5^{4.2}$ Da | $1.98^{8.2}$Aa | $2.43^{7.5}$Ba | $3.78^{6.9}$ Ca | $4.11^{6.3}$Da |
| | T2 | $5.15^{9.4}$Aa | $6.53^{6.9}$ Ba | $10.09^{4.9}$ Ca | $12.35^{4.2}$ Da | $25.1^{5.9}$Aab | $45.1^{5.6}$ Ba | $59.7^{5.8}$Ca | $77.8^{4.6}$ Da | $1.88^{7.4}$Aa | $2.33^{7.1}$Ba | $3.60^{6.7}$ Ca | $4.00^{7.1}$Da |
| | T3 | $4.63^{10.1}$Ab | $5.95^{6.7}$Ba | $9.78^{4.9}$Cb | $11.15^{4.3}$Db | $25.2^{5.6}$Aab | $44.2^{5.3}$ Ba | $56.6^{4.9}$Cb | $74.1^{4.2}$Db | $1.85^{7.8}$Aa | $2.28^{6.9}$ Ba | $3.69^{6.8}$ Ca | $4.05^{6.8}$ Da |
| | T4 | $4.31^{9.1}$Ab | $5.35^{6.6}$Bb | $9.36^{4.8}$Cb | $10.63^{4.0}$Db | $24.0^{5.9}$Ab | $40.2^{5.4}$ Bb | $54.1^{5.2}$Cc | $72.5^{4.7}$Dc | $1.56^{7.5}$Ab | $2.22^{7.3}$Bb | $3.23^{6.5}$Cb | $3.77^{6.1}$Db |
| | T5 | $3.42^{9.4}$ Ac | $4.85^{7.1}$Bb | $7.75^{4.7}$Cc | $8.12^{4.4}$Dc | $21.5^{6.1}$Ac | $36.5^{6.4}$ Bc | $53.3^{5.3}$Cc | $66.6^{4.1}$Dd | $1.34^{7.4}$Ac | $2.00^{6.8}$Bc | $2.88^{6.4}$Cc | $3.25^{7.2}$Dc |
| B | T1 | $4.56^{8.4}$ Aa | $5.95^{6.8}$ Ba | $9.85^{4.8}$Ca | $11.51^{3.9}$ Da | $25.8^{6.2}$Aa | $45.5^{5.7}$ Ba | $65.2^{4.9}$ Ca | $80.4^{5.1}$ Da | $1.88^{8.0}$Aa | $2.38^{7.4}$ Ba | $3.24^{6.5}$ Ca | $3.79^{6.8}$Da |
| | T2 | $4.43^{7.9}$ Aa | $5.92^{7.1}$ Ba | $9.77^{4.7}$Ca | $11.22^{4.1}$ Da | $25.6^{6.5}$Aa | $45.3^{6.3}$ Ba | $65.8^{5.2}$ Ca | $79.6^{4.7}$ Da | $1.76^{7.5}$ Aa | $2.22^{7.6}$ Ba | $3.09^{6.8}$ Ca | $3.60^{5.8}$ Da |
| | T3 | $4.15^{7.1}$Ab | $5.29^{6.2}$Bb | $8.12^{4.8}$Cb | $9.30^{4.2}$Db | $25.3^{5.9}$Aa | $42.6^{6.1}$Bb | $61.6^{5.4}$ Cb | $76.0^{4.7}$Db | $1.76^{6.8}$Aa | $2.28^{7.5}$ Ba | $3.25^{6.6}$Ca | $3.52^{6.8}$ Da |
| | T4 | $4.00^{7.3}$Ab | $5.11^{6.7}$ Bb | $7.91^{4.5}$Cb | $9.63^{3.7}$Db | $24.8^{6.0}$ Aa | $40.5^{6.1}$Bc | $58.8^{5.2}$Cc | $74.8^{4.8}$Dc | $1.51^{7.1}$Ab | $2.05^{6.5}$ Bb | $3.00^{6.2}$Cb | $3.22^{6.4}$Db |
| | T5 | $3.52^{8.0}$ Ac | $4.52^{6.2}$Bc | $6.43^{4.5}$ Cc | $7.45^{4.3}$Dc | $22.3^{6.1}$Ab | $39.6^{6.2}$ Bc | $56.3^{5.6}$Cd | $73.2^{4.9}$Dd | $1.28^{6.9}$Ac | $1.90^{6.3}$ Bb | $2.66^{6.5}$ Cc | $3.10^{6.7}$Db |

Pulps were made with 100% (T1); 95% (T2); 85% (T3) and 75% (T4) wood from seven-years-old trees and 100% wood from two-years-old trees (T5). Means followed by the same capital letter per line and lower case letter per column did not differ between them by the Scott-Knott test at 5%. Values in superscript represent the coefficient of variation.

old trees presented a greater cell wall fraction and better mechanical properties, this fiber type presents greater resistance to collapse, resulting in paper with a higher void volume (Sixta, 2006). Thus, the transition of light between these void spaces and the fiber cell wall causes transition and light scattering, preventing its passage through the paper and increasing opacity (BIERMANN, 1996; ANJOS et al., 2014). The reverse occurred with refining, where the fibers collapsed, reducing paper opacity.

The mechanical property values increased and the paper opacity decreased with refining process improvements. It is necessary to reach an optimal point for acceptable values for these parameters, because printing and writing paper need high mechanical properties and opacity values (BIERMANN, 1996; ANJOS et al., 2014; SEVERO et al., 2013).

The proportion of wood from young trees damaged by wind that can be used to produce pulp varied according to parameters, genetic material, and refining intensity. However, pulp properties did not change with the use of up to 5% wood from two-year-old trees. Thus, this proportion is suggested for use with wind-damaged trees in pulp production, without quality losses.

## CONCLUSION

The wood from two-year-old *Eucalyptus* trees had a higher vessel and fiber frequency with lower length, cell wall fraction, modulus of elasticity and hardness, and a higher microfibril angle. In pulp production, up to 5% of this wood can be mixed with wood from seven-year-old trees without quality losses. The use of wood from two-year-old trees reduced the tensile, tear, and stretch indexes, and increased paper opacity and resistance to air. The refining process increased tear and tensile indexes, air resistance and stretch, and decreased opacity. Refining is important and thus should be considered before using wood from young wind damaged trees to produce pulp.

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**TABLE 6** Opacity (%) at different levels of revolution during the refining in pulps made with wood from two and seven-years-old trees of Eucalyptus grandis × E. urophylla

| Clone | Treatment | Revolutions during the refining | | | |
|---|---|---|---|---|---|
| | | 0 | 500 | 1500 | 3000 |
| A | T1 | $84.8^{1.32}$ Aa | $80.7^{1.27}$ Ba | $77.5^{1.45}$ Ca | $72.3^{1.49}$ Da |
| | T2 | $84.2^{1.35}$Ab | $80.2^{1.53}$ Ba | $77.8^{1.23}$ Ca | $72.7^{1.39}$ Da |
| | T3 | $84.8^{1.13}$Ab | $80.4^{1.13}$ Ba | $77.4^{1.28}$Ca | $72.8^{1.75}$ Da |
| | T4 | $84.3^{1.02}$Ab | $81.3^{1.18}$ Ba | $78.5^{1.45}$ Ca | $73.6^{1.24}$Db |
| | T5 | $82.6^{1.89}$ Ac | $78.7^{1.10}$Bb | $75.8^{1.54}$Cb | $70.3^{1.58}$Dc |
| B | T1 | $80.5^{1.77}$ Aa | $78.3^{1.35}$ Ba | $75.4^{1.48}$ Ca | $72.1^{1.89}$ Da |
| | T2 | $80.6^{1.74}$ Aa | $78.6^{1.43}$Ba | $76.3^{1.24}$ Ca | $72.8^{1.11}$ Da |
| | T3 | $81.0^{2.11}$ Aa | $78.1^{1.25}$ Ba | $76.2^{1.45}$ Ca | $70.1^{1.32}$Db |
| | T4 | $78.1^{1.56}$Ab | $77.6^{1.36}$Bb | $76.1^{1.33}$ Ca | $70.6^{1.27}$Db |
| | T5 | $78.4^{1.34}$Ab | $75.8^{1.67}$ Ac | $74.3^{1.65}$Cb | $70.4^{1.89}$Db |

Pulps were made with 100% (T1); 95% (T2); 85% (T3) and 75% (T4) wood from seven-years-old trees and 100% wood from two-years-old trees (T5). Means followed by the same capital letter per line and lower case letter per column did not differ between them by the Scott-Knott test at 5%. Values in superscript represent the coefficient of variation.


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