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Original Article

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Wood Permeability in *Eucalyptus grandis* and *Eucalyptus dunnii*

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ABSTRACT

The objective of this study was to evaluate the flow of air and water in *Eucalyptus grandis* and *Eucalyptus dunnii* wood. Wood was collected from four trees aged 37 years in an experimental plantation of the Federal University of Lavras, Brazil. Planks were cut off the basal logs to produce specimens for air and water permeability testing. Results indicated that the longitudinal permeability to air and water of *E. grandis* wood were, on average, 5% and 10% higher, respectively, than that of *E. dunnii* wood. *E. grandis* and *E. dunnii* wood showed neither air nor water flow in the test for permeability transversal to the fibers, and longitudinal permeability to air exceeded that to water by approximately 50 fold in both species.

Keywords: air flow, water flow, longitudinal permeability, transverse permeability.

1. INTRODUCTION

Eucalyptus grandis occupies one of the largest planted areas in Brazil. This species presents high productive and technological potential and its wood is used in the pulp and paper industry, for the production of fiber panels and agglomerates, in the manufacture of furniture, as firewood and in sawmills (IBÁ, 2015; Lopes et al., 2011; Soares et al., 2003; Souza et al., 2004). *Eucalyptus dunnii* has been considered a silvicultural alternative for companies in the south and southeast regions of Brazil, mainly because of its rapid growth, uniformity of stands, tree shape, and frost tolerance (Florsheim et al., 2009). Among its applications, it presents adequate performance for pulp and paper, sawn lumber for structural purposes, engineering wood products, and floors.

However, difficulties in the processing and use of these wood species have been verified due to their low permeability, which directly affects chip impregnation in chemical pulping, preservative treatment, bonding, water absorption, panel finishing and, mainly, the quality of drying (Lehringer et al., 2009; Taghiyari et al., 2010; Tarmian & Perré, 2009).

According to Kamke & Lee (2007) and Siau (1971), permeability is a physical property related to the ease with which fluids are transported through a porous medium under differential pressure, indicating the magnitude of flow in the material and varying according to a range of factors such as chemical and anatomical characteristics, flow direction and type of fluid, among others.

In wood, diameter, frequency and distribution of vessels, fiber length, and type of pit affect permeability, as well as the deposition of extractives, which may cause partial or total occlusion and become a barrier to liquid or gas flow (Alzate, 2004; Comstock, 1970; Lepage, 1986; Lehringer et al., 2009). Regarding flow direction, Pokki et al. (2010) observed that wood permeability is of great variability, and the longitudinal-to-transverse permeability ratio is high. The explanation for this lies in the structure and orientation of the vessels, which facilitate longitudinal flow and play a major role in the movement of liquids (Ahmed & Chun, 2009).

Depending on the type of fluid that moves through the wood, permeability also presents different magnitudes. Silva et al. (2010) reported that the higher the fluid viscosity, the lower the flow and permeability. Liquid-phase permeability to water is lower than gas-phase permeability due to viscosity; permeability to atmospheric air in wood is 55 times higher than that to water at the same temperature (Siau, 1984). Permeability to liquids was initially determined in 1963, and the apparatus developed for its measurement still serves as the basis for the development of experimental instruments. It basically comprises manometers, a vacuum reservoir, a sample holding compartment, a burette to hold fluid, hoses, stoppers, and interconnected conical seals (Siau, 1984). Gas permeability was first determined in 1969, and the equipment used to measure it is similar to that used for liquid permeability, utilizing flowmeters instead of burettes.

Despite the relevance of studies on wood permeability, currently, one of the greatest problems is the absence of norms and standardized equipment for its determination. In short, information on air and water flow in wood is scarce, especially in fast growing species such as *Eucalyptus*.

In this context, the aim of this study was to evaluate the air and water flow in *Eucalyptus grandis* and *Eucalyptus dunnii* wood.

2. MATERIAL AND METHODS

2.1. Vegetal material and preparation of specimens

Wood from an experimental plantation belonging to the Federal University of Lavras (UFLA) located in the municipality of Lavras, Minas Gerais state, southeastern Brazil, was used in this study. Two *Eucalyptus grandis* and two *E. dunnii* trees, aged 37 years, planted at 3.0 × 2.0 m spacing were selected, felled, and sectioned. A central board was obtained from the first log (4.0 m in length; 70.0 cm of mean diameter) of each tree. The central planks were planed and cut into battens for chemical and anatomical characterization and permeability determination. The specimens for anatomical characterization and chemical analysis were planed and sectioned in 12 smaller pieces measuring 50 × 30 × 20 mm for each treatment.

2.2. Wet chemistry

Chemical characterization was performed in wood obtained from the specimens, ground, sieved, and retained in 60 mesh in accordance with the recommendations of the following norms: NBR14853 (ABNT, 2010b) for total extractive content, NBR7989 (ABNT, 2010a) for lignin, and NBR13999 (ABNT, 2003) for mineral components. The holocellulose content was obtained by difference, using the percentage in relation to the other components.

2.3. Wood anatomy

For anatomical characterization, specimens with well-oriented rings were sectioned in cubic samples with nominal dimensions of 20 × 20 × 20 mm (microscopic analysis) and analyses of the diameter of vessel pits and vessel-ray pitting were conducted using specimens measuring 5 × 5 × 5 mm. The preparation of specimens, histological cuts, staining, and assembly of the slides followed the recommendations of COPANT (1974) and Johansen (1940). The method described in Franklin (1945) adapted by Berlyn & Miksche (1976) was used to prepare the material macerated from wood fragments.

Microscopic anatomical characterization was performed according to the methodology established in IAWA (1989), with the aid of an optical microscope with magnification of 100x, a camera coupled and connected to a computer, and the Image ProPlus software.

Thirty measurements were performed for each anatomical character, namely: frequency (number.mm^{-2}), length (μm) and diameter (μm) of vessels; frequency (number.mm^{-1}), length (μm) and width (μm) of rays, length (μm), width (μm) and cell wall thickness of fibers, and lumen diameter (μm).

2.4. Electronic microscopy

A scanning electron microscope (LEO EVO 40 XVP) was used to measure the pit diameters of the cell walls of the vessels and ray-vessel elements. Prior to the test, the specimens of each species had their radial longitudinal surfaces flattened using a sliding microtome and were oven dried at 70 °C for 1 hour and kept in a container with silica until test time. Specimen surface was covered with approximately 20 nm of gold using a gold evaporator apparatus (Sputtering - Bal-Tec), and the scanning electron microscopy images were obtained and measured in the LEO EVO 40 XVP device.

2.5. Permeability tests

For longitudinal and transverse permeability tests, the battens were initially transformed into a cylindrical shape with a diameter of 2.0 cm according to the Baraúna (2010) methodology. After this procedure, the cylindrical sections were cut into 50 mm long specimens for the permeability tests, yielding 48 specimens per initial specimen for each direction (longitudinal and transverse to the fibers).

Specimens were conditioned in a climatic chamber at a temperature of 20 °C ± 3 °C and relative humidity of 65% ± 5% until mass stabilization. After the acclimatization stage, the specimens were waterproofed on the lateral surface with low-flow epoxy structural adhesive. To cure the adhesive, the specimens were packed into the same climatic chamber until stabilization.

The wood permeability tests were conducted according to the methodology described in Silva (2007), adapted by Baraúna (2010), in an experimental permeameter for liquids and gases, using distilled water as fluid and atmospheric air from a pump. The initial pressure was based on the average monthly pressure of the test site, referenced in Brasil (1992).

Wood permeability to air according to Darcy's law was determined by Equation 1:

$$K_{ar} = \frac{Q \times L \times P}{A \times \Delta P \times \overline{P}} \qquad (1)$$

where: K_{ar} = air permeability, $cm^3.cm^{-1}.atm^{-1}.s^{-1}$; L = length in the direction of flow, cm; P = initial pressure, atm; A = sectional area of the specimen, cm^2; ΔP = differential between initial and final pressure, atm; $\overline{P}$ = arithmetic mean between initial and final pressure, atm; Q = flow obtained in the rotameter, $cm^3.s^{-1}$.

Permeability to water was also determined based on Darcy's Law using Equation 2:

$$K_L = \frac{V \times L}{t \times A \times \Delta P} \qquad (2)$$

where: K_L = permeability to distilled water, $cm^3.cm^{-1}.atm^{-1}.s^{-1}$; V = volume of the drained liquid, cm^3; L = length in the direction of flow, cm; t = time of liquid flow, s; A = cross-sectional area, cm^2; ΔP = differential between initial and final pressure, atm.

2.6. Data analysis

Data was statistically assessed by means of descriptive analysis, with determination of mean values of the chemical and anatomical properties and permeability of wood according to species with their respective coefficients of variation.

3. RESULTS AND DISCUSSION

The mean values and the coefficients of variation of the chemical properties, anatomical features, and permeability of *Eucalyptus grandis* and *Eucalyptus dunnii* wood are presented in Table 1.

The wood of *E. grandis* and *E. dunnii* trees evaluated in this study did not present air and water flow in the test for permeability transversal to the fibers. Similar findings were reported by Baraúna (2010) for two Amazonian wooden species (faveira and amapá) and by Silva (2007) for *Pinus elliottii* wood. Kininmonth (1971) reported a relationship between longitudinal and transverse permeability of approximately 10^6 in *Eucalyptus* wood, mainly due to the small pit diameter of this species. Nasroun & Al-Shahrani (1998) considered cell wall thickness as a significant factor influencing the low magnitude of permeability transverse to fibers, whereas Siau (1971) reported extremely low transverse permeability. Moreover, the currently used instruments present limitations in determining low-magnitude liquid and gas flow through wood.

3.1. Influence of chemical composition on wood permeability

Table 1 shows that extractive content was 10% lower and lignin content was 8% higher in *E. grandis* wood compared with those of *E. dunnii* wood. These results are superior to those described in Silva et al. (2005) and Latorraca (1996). However, it is worth noting that, according to Silva et al. (2005), with increased age and enhanced classification, the extractive and lignin contents present a growth trend. Milota et al. (1995) considered that higher extractive content became a barrier to flow,

Table 1. Mean values of the chemical and anatomical properties and permeability of *Eucalyptus grandis* and *Eucalyptus dunni* wood.

Properties	*Eucalyptus Grandis*	*Eucalyptus Dunnii*
Total extractives (%)	9.26 (16.6)	10.48 (18.9)
Lignin (%)	27.82 (1.9)	25.74 (1.63)
Holocellulose (%)	61.28 (2.8)	61.72 (3.1)
Mineral components (%)	1.64 (12.9)	2.06 (14.6)
Frequency of vessels (nº.mm^{-2})	13.00 (14.3)	16.10 (18.8)
Length of vessels (μm)	241.60 (19.8)	219.30 (21.1)
Diameter of vessels (μm)	125.50 (13.6)	107.70 (14.7)
Frequency of rays (nº.mm^{-1})	13.83 (18.8)	14.19 (18.1)
Length of rays (μm)	204.04 (23.4)	235.02 (17.0)
Width of rays (μm)	14.41 (15.6)	12.16 (14.5)
Diameter of intervessel pits (μm)	3.12 (20.6)	2.78 (23.1)
Diameter of ray-vessel pits (μm)	5.39 (14.8)	4.59 (15.6)
Fiber length (μm)	971.22 (14.1)	1003.75(13.8)
Fiber width (μm)	18.51 (17.6)	20.64 (18.9)
Diameter of lumen fiber (μm)	7.69 (26.3)	7.03 (29.3)
Cell wall thickness (μm)	5.70 (20.4)	6.48 (19.8)
Longitudinal permeability to air (cm^3.cm^{-1}.atm^{-1}.s^{-1})	69.24 (24.3)	65.88 (29.7)
Longitudinal permeability to water (cm^3.cm^{-1}.atm^{-1}.s^{-1})	1.47 (55.8)	1.33 (57.5)

() = coefficient of variation (%).

especially of liquids, as can be observed in Table 1, where *E. dunnii* wood presents lower permeability.

E. grandis wood presented a 20% lower mineral content than that of *E. dunnii*, and the values were higher than those found by Rocha (2011), who reported that the amount of inorganic materials in Eucalyptus wood rarely exceed 1.0%.

As for the holocellulose content, the highest means were observed in *E. dunnii* wood. The holocellulose contents of *E. grandis* and *E. dunnii* wood were lower than those found by Silva et al. (2005) and Pereira et al. (2000) for the same species with ages between 10 and 25 years. They affirmed that the holocellulose contents are lower in mature trees compared with those of younger ones.

3.2. Wood anatomy controls wood permeability

Regarding wood anatomy, it was possible to observe that the frequency of vessels for *E. dunnii* was superior to that of *E. grandis*, although vessel length and diameter were smaller. These observations are in agreement with those reported by Rocha et al. (2004) and Ahmed & Chun (2009) for *Eucalyptus* wood, considering that smaller vessel diameter is usually accompanied by higher frequency in wood, and that vessel diameter has a closer relation with permeability - a tendency observed for *E. grandis* wood, which was more permeable than *E. dunnii* wood.

The results obtained for the dimensions and frequency of vessels and the length and width of rays of *E. grandis* and *E. dunnii* wood are consistent with those observed by Batista (2012) and Florsheim et al. (2009), who worked with the same species with ages of 18 and 7 years, respectively. Nevertheless, it should be noted that the rays had greater influence on the transverse fluid movement, which was not observed in this study.

Analysis of the characteristics of the fibers revealed that *E. grandis* wood presents smaller fiber length and width and cell wall thickness than *E. dunnii* wood, but greater fiber diameter. The results found for *E. grandis* wood were lower than those obtained by Alzate (2004) and Batista (2012), who also worked with *E. grandis* aged 8 and 18 years, respectively. They observed the following mean values: fiber length between 1030.00 and 1120.00 μm, fiber width from 20.99 to 21.50 μm, lumen diameter from 9.60 to 12.80 μm, and cell wall thickness up to 7.00 μm. Regarding *E. dunnii* wood, only the values for fiber length and cell wall thickness were distinct and superior to those described by Florsheim et al. (2009), who reported mean values of 860.00 and 4.33 μm for the two characteristics, respectively. With respect to lumen diameter, these authors found a mean value of 8.38 μm, higher than that presented in Table 1.

Analysis of the diameter of the intervessel and ray-vessel pits showed that *E. dunnii* wood presented values 10% and 15% lower than those of *E. grandis* wood, respectively. The diameters of intervessel and ray-vessel pits obtained in this study are similar to those reported by Alzate (2004) and Lopes (2013), who found ray-vessel pits with diameter values between 4.45 and 6.25 μm and intervessel diameter measures ranging from 3.00 to 6.10 μm for *Eucalyptus* wood. Ahmed & Chun (2011) highlighted the strong influence of pit diameter on the flow of liquids between cells and on wood permeability, which may explain the higher values for permeability to air and water observed in *E. grandis* wood.

3.3. Wood permeability

Mean values of longitudinal permeability to air and water in *E. grandis* wood were 5% and 10% higher, respectively, compared with those in *E. dunnii*, mainly due to their chemical and anatomical characteristics.

Differences between the permeability of wood to water and air were observed, considering that, according to Siau (1971), the viscosity of water is 55 times higher than that of atmospheric air at 20 °C. In addition, water can bind to wood because of the hygroscopicity of the material, reducing fluid flow. Based on the values of permeability to air and water in *E. grandis* and *E. dunnii* wood (Table 1), the ratio between them obtained in this study for both species was 50:1, close to that of water and air viscosities, whereas Silva et al. (2010) obtained a ratio of 59:1 for *Corymbia citriodora* wood.

In this study, the average permeability values of the investigated wood species were lower than those reported by Pinheiro (2013) for *Eucalyptus urophylla* wood, with mean air permeability of 108.49 $cm^3.cm^{-1}.atm^{-1}.s^{-1}$; however, these values are close to those reported by Baraúna (2010), who found longitudinal permeability to both air and water equal to 64.53 $cm^3.cm^{-1}.atm^{-1}.s^{-1}$ and 2.10 $cm^3.cm^{-1}.atm^{-1}.s^{-1}$, respectively, for amapá wood, an amazon hardwood species.

4. CONCLUSIONS

Based on the results obtained, we conclude that:

- The longitudinal permeability to air and water of *E. grandis* wood was, on average, 5% and 10% higher than that of *E. dunnii*, probably because *E. dunnii* presents higher extractive content and fiber length, as well as smaller vessel and pit diameters;
- *E. grandis* and *E. dunnii* showed neither air nor water flow in the test for permeability transversal to the fibers, and longitudinal permeability to air exceeded that to water by approximately 50 fold in both species.

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