STUDY ON THE LONGITUDINAL GAS PERMEABILITY OF JUVENILE WOOD AND MATURE WOOD

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The present study is aimed at longitudinal gas permeability measurement of juvenile wood and mature wood of the two most important poplar clones in Iran. Longitudinal gas permeability for juvenile wood of P. deltoides was $1.50 \times 10^{-13}$, and for its mature wood was $28.18 \times 10^{-15}$ ($m^3 \ m^{-1}$). As for P. euroamericana, values were $0.16 \times 10^{-13}$ and $13.74 \times 10^{-15}$ ($m^3 \ m^{-1}$) for juvenile and mature woods, respectively. The higher extractive content in juvenile wood in comparison with mature wood varies significantly among different clones; the maximum extractive content was measured to be 3.4% in juvenile wood of P. euroamericana, while the minimum (0.3%) was observed in mature wood of P. deltoides. A negative relationship is obvious between gas permeability values and extractive content. Vessel diameter in juvenile woods of both species tends to be lower than mature woods; maximum and minimum vessel diameters were observed in mature wood (67.3 μm) and juvenile wood (54.5 μm) of P. deltoides. Although vessel diameter has a great impact in gas permeability, in the present study no clear relationship was found between them. Therefore, the low permeability in the mature wood of P. euroamericana may be rooted in the intense settlement of extractives in the heartwood.

KEY WORDS: extractive content, juvenile wood, longitudinal gas permeability, mature wood, poplar, porous materials, vessel diameter

1. INTRODUCTION

Poplar belongs to the Salicaceae family. Apart from natural species we can take benefit of special capabilities of poplar hybrids and clones. In the meantime, the world of wood industries faced a new problem having used fast-growing trees because in their first years of growth, the trees produce juvenile wood, a zone of wood extending outward from the pith. During this early growth period, the characteristics of the wood produced from year to year in each successive growth ring change markedly. During a "transition" period from 5 to 20 years of age, characteristics of the wood produced gradually improve until they become relatively constant. This material is known as mature wood. All trees have juvenile wood, but it had little significance when the timber supply was primarily old-growth trees grown in natural forest conditions. In these trees, the juvenile wood core was small because early growth was suppressed by competition from surrounding trees. Additionally, the percentage of juvenile wood in the total volume was small because larger trees were harvested. Now, improved trees grown on intensively managed plantations reach saw-timber size and are harvested at a younger age (Dickmann, 2006). Because
diameter growth is generally greatest during the years juvenile wood is produced, the juvenile wood core may be a very significant part of the harvest.

As to the fact that many characteristics of juvenile wood differ from mature wood (Anon., 1998), the question may arise as to what extent they may differ. If the difference is statistically nonsignificant and can only be considered as a trend, that would cause no problem. But in most cases, there is a significant difference between specific characteristics in juvenile and mature woods. Since permeability is one of the most important characteristics of wood, having great impact on its utilization in different industries (such as wood preservation, wood drying, pulp, and paper), the present study is aimed at the permeability measurement of juvenile wood and mature wood of two of the most important poplar clones in Iran that have shown great compatibility with climate variability and are cultivated vastly all over Iran. It is to be noted that these two clones show suitable growth rates and have the capability to be used in different industries (Anon., 2008).

Heartwood has less extractive content, and extractive content increases with tree height (Woo et al., 2005). Permeability is different in sapwood and heartwood, as well as in different tree heights, and shows significant correlation with extractive content. Decrease in permeability toward the crown is probably due to an increase in extractive content. Koch (1996), Flynn (1995), and Rice and D’Onofrio (1996) also reported that a decrease in permeability is generally due to a more extractive content as well as blockage of vessel perforations (vessel openings) and pits. It has been proved that extractive content and pitch deposits block the way through which fluid passes along wood. Furthermore, concentration of extractive content and pitch deposits is not the same in different parts of trees. Ward (1986) reported $230 \times 10^{-13}$ for mature wood and $1.9 \times 10^{-13}$ (m$^3$ m$^{-1}$) for juvenile wood of poplar. Perng et al. (1985) reported $3.9 \times 10^{-13}$ for mature wood and $2.8 \times 10^{-13}$ (m$^3$ m$^{-1}$) for juvenile wood of poplar. Avramidis and Mansfield (2005) also reported an average permeability of $22,940 \times 10^{-13}$ for mature wood and $1,950 \times 10^{-13}$ (m$^3$ m$^{-1}$) for juvenile wood of six poplar clones.

2. MATERIALS AND METHODS

2.1 Specimen Procurement

Disks at breast height from five trees of Populus deltoides (69/55) and five trees of Populus × euroamericana (cv. I-214) were harvested from the research site belonging to the Forestry and Watershed Organization of Gilan province. It is to be noted that these clones have shown great compatibility with climate variability and are cultivated vastly in Iran. All trees were 22 years old. Geographical specifications of the region are as follows: the altitude is 10 meters below see level and 15 meters above Caspian sea level; and 49° and 57° eastern longitude and 37° 19’ northern latitude. The soil was comprised of alluvial settlements and silty loam having a neutral pH to somewhat alkaline. The average annual precipitation is 1.186 mm, and the average annual temperature is 17.5°C; averages for maximum and minimum temperatures are 26.6 and 8.6°C, respectively. The distinction of juvenile wood from mature wood was based on fiber length fluctuations from pith to bark. Transition from juvenile to mature wood took place at the age of 10–12 years (Taghiyari et al., 2008).

2.2 Gas Permeability Specimen

The longitudinal gas permeability measurement was done by an apparatus designed and built by the authors based on the microstructure porosity of wood. All gas permeability specimens were cylindrical, 18 mm in diameter and 50 mm in length. They were free from any knots, checks, and splits. The specimens were kept in a conditioning chamber to reach an MC level of 12%. Both ends of each specimen were trimmed using sharp cutter blades. Furthermore, all around each specimen was covered by silicon adhesive to prevent airflow through the radial and tangential directions. Ten specimens were cut randomly at scattered locations (five from juvenile and five from mature wood, Fig. 1). Measurements were made using the falling water displacement volume method per the instructions of Siau (1995). The connection between the specimen and holder of the apparatus was made fully airtight.

Three measurements were taken for each specimen. A superficial permeability coefficient was then calculated using Siau’s equations (Siau, 1995) [Eqs. (1) and (2)]. The superficial permeability coefficients were then multiplied by the viscosity of air ($\mu = 1.81 \times 10^{-5}$ Pa s) for the calculation of their specific permeability ($K = \kappa \mu$).

$$K_g = \frac{V_d C L (P_{atm} - 0.074Z)}{tA(0.074Z)(P_{atm} - 0.037Z)} \times \frac{0.760}{1.013 \times 10^6} \text{mHg} \quad (1)$$

$$C = 1 + \frac{V_d(0.074\Delta Z)}{V_d(P_{atm} - 0.074Z)} \quad (2)$$

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The circle that indicates transition zone of juvenile wood to mature wood.

Diameter of the specimens is 18 mm in scattered form in the juvenile and mature wood of disks where there is no checks or knots.

FIG. 1: Position of juvenile wood and mature wood in the disk and location of sampling

where:

\[ k_g = \text{longitudinal specific permeability, m}^3/\text{m} \]
\[ V_d = \pi r^2 \Delta z \quad [r = \text{radius of measuring tube (m)}, \text{m}^3] \]
\[ C = \text{correction factor for gas expansion as a result of change in static head and viscosity of water} \]
\[ L = \text{length of wood specimen, m} \]
\[ P_{\text{atm}} = \text{atmospheric pressure, m Hg} \]
\[ \bar{z} = \text{average height of water over surface of reservoir during period of measurement, m} \]
\[ t = \text{time, s} \]
\[ A = \text{cross-sectional area of wood specimen, m}^2 \]
\[ \Delta z = \text{change in height of water during time t, m} \]
\[ V_r = \text{total volume of apparatus above point 1 (including volume of hoses), m}^3 \]

2.4 Vessel Diameter

For the vessel diameter, five blocks of 2 × 2 × 2 cm from juvenile wood and five from mature wood of each tree were taken and kept in distilled water for 48 h. Transverse sections of 20–25 μm in thickness were cut by a Jung Heidelberg slicing microtome. The sections were stained with safranin and then dehydrated in a graded series of ethanol (50%, 75%, and 96%), and then in xylol to make them ready to be mounted on microscopic slides. The measuring procedure covered all vessels from spring wood to summer wood. Each vessel was measured in the radial as well as tangential directions (Fig. 2).

2.5 Statistical Analysis

A statistical analysis was conducted using SAS software program, version 9.1. A two-way analysis of variance (ANOVA) was performed to conclude the significant difference at a 99% confidence level.

3. RESULTS

3.1 Longitudinal Gas Permeability

The average longitudinal specific gas permeability of *Populus deltoids* (69-55) is \( 1.50 \times 10^{-13} \) (m³ m⁻¹) for juvenile wood and \( 28.18 \times 10^{-13} \) (m³ m⁻¹) for mature wood; whereas the averages for *Populus × euroamericana* (cv. 1-214) show \( 0.17 \times 10^{-13} \) (m³ m⁻¹) for juvenile wood and \( 13.75 \times 10^{-13} \) (m³ m⁻¹) for mature wood. The statistical analysis shows a significant difference between the permeability of juvenile and mature wood of
these two clones, as well as these two clones with each other. Figure 3 shows the permeability amount in juvenile and mature wood of the two clones measured in the present study.

3.2 Extractive Content

The results of the extractive analysis are shown in Fig. 4. The statistical analysis show a significant difference at an $\alpha$ level of 1% between juvenile wood of *P. deltoides* and *P. × euroamericana*, as well as between mature wood of *P. deltoides* and *P. × euroamericana*. The extractive content of the juvenile wood in *P. × euroamericana* was the greatest (3.4%), whereas in the mature wood of *P. deltoides* was the lowest (0.3%) (Table 1).

3.3 Vessel Diameter

The results of vessel diameter are shown in Fig. 5. Statistical analysis shows a significant difference between juve-

![Graph showing permeability values](image)

**FIG. 3:** Permeability values ($\times 10^{-13}$ m$^3$ m$^{-1}$) for juvenile wood and mature wood in *P. deltoides* and *P. × euroamericana*.
TABLE 1: Comparison between different variables measured in the present study: permeability \((10^{-13} \text{ m}^3 \text{ m}^{-1})\), extractive content \((\% \)) , vessel diameter \((\mu m)\)

<table>
<thead>
<tr>
<th>Kind of wood</th>
<th>Permeability ((10^{-13} \text{ m}^3 \text{ m}^{-1}))</th>
<th>Extractive content ((%))</th>
<th>Vessel diameter ((\mu m))</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>P. deltoides</em> mature**</td>
<td>28.18</td>
<td>0.3</td>
<td>67.3</td>
</tr>
<tr>
<td><em>P. ×euroamericana</em> mature</td>
<td>13.75</td>
<td>0.35</td>
<td>61.6</td>
</tr>
<tr>
<td><em>P. deltoides</em> juvenile</td>
<td>1.5</td>
<td>0.75</td>
<td>54.5</td>
</tr>
<tr>
<td><em>P. ×euroamericana</em> juvenile</td>
<td>0.17</td>
<td>3.4</td>
<td>57.4</td>
</tr>
</tbody>
</table>

*Populus
**Wood
***Diameter

FIG. 4: Extractive content \((\%)\) of juvenile wood and mature wood for *P. deltoides* (69/55) and *Populus × euroamericana* (cv. I-214)

FIG. 5: Vessel diameter \((\mu m)\) of juvenile wood and mature wood for *P. deltoides* (69/55) and *Populus × euroamericana* (cv. I-214)
nile wood and mature wood in both clones; but no significant difference was observed between *P. deltoides* (69/55) and *P. × euroamericana* (cv. 1-214). Vessel diameter in mature wood of *P. deltoides* was the highest (67.3 μm) and in juvenile wood of *P. deltoides* was the lowest (54.5 μm) (Table 1). No significant difference was seen between the two clones.

A summary of the three variables measured in the present study is shown in Table 1.

4. DISCUSSION

In all cases, the permeability of juvenile wood is far below that of mature wood; causes can be rooted in more extractive content, tyloses, and pitch deposits that may block the pits and vessel perforations (Woo et al., 2005; Koch, 1996; Flynn, 1995; Rice and D’Onofrio, 1996; Ward, 1986). Extractives have a significant impact on the permeability of wood, although they make up only a small percentage of the total chemical composition of it. Ward (1986) indicated that the blockage of pits and openings is due to extractives and tyloses on the way of fluid transfer. Vologdin et al. (1979) also noticed that permeability increased progressively with the removal of extractives (phenolics). Furthermore, Perre and Karimi (2002) reported that permeability increases significantly as the length of specimens is shortened. Error bars in Fig. 3 imply that the concentration of extractives varies in different parts of a tree and therefore permeability values would also vary significantly. Putting permeability values and extractive contents of juvenile wood and mature wood of these two clones in one single figure can show us the reverse relationship between them (Fig. 6).

Comparison between the extractive content of the present study for 22-year-old trees with those of previous studies at the age of 18 that were cut and cultivated from the same site but four years earlier (Mahdavi Feizabadi, 2003) shows that in *P. deltoides*, not much difference in extractive content was made during the four last years of growth. But in *P. × euroamericana*, a comparison with previous studies that was done on 18-year-old trees of the same inhabitant (Rasooli Garmaroudi, 2002) shows a great difference. This difference is most probably made by the process of changing sapwood to heartwood. Therefore, if the end utilization needs to have high permeability or low extractive content, trees of *P. × euroamericana* should be cut before the age of about 18 years.

Statistical analysis showed a significant difference between the vessel diameter of juvenile wood and mature wood in both clones. However, no significant difference was found between vessel diameters of juvenile woods or mature woods of the two clones. Poiseuille’s law of viscous flow, which applies to gases through hardwood vessels, proves there is a positive relationship between the permeability value and the fourth exponent of the radius of capillary (radius of vessels) [Eq. (3)] (Siau, 1971).

$$k_L = \frac{n \pi R^4}{8\eta} \times 1.013 \times 10^6$$

where

FIG. 6: Reverse relationship between longitudinal gas permeability \((10^{-13} m^3 m^{-1})\) and extractive content (%)
Longitudinal Gas Permeability in Poplar

\[ k_L = \text{longitudinal permeability, cm}^3 \text{ (fluid) cm}^{-1} \text{ atm}^{-1} \text{ s}^{-1} \]

\[ 1 \text{ atm} = 1.013 \times 10^6 \text{ dyne cm}^{-2} \]

\[ R = \text{radius of vessels, cm} \]

\[ n = N/A = \text{number of vessels per cm}^2 \text{ of cross section} \]

\[ \eta = \text{viscosity of fluid, (dyne sec) cm}^{-2} \]

The fourth exponent of the radius implies that a slight increase or decrease in the value of the vessel radius may have a high impact on the value of permeability, although statistical methods do not show a significant difference. Putting all this information together, we may conclude that theoretically the juvenile wood of both clones should have nearly the same permeability values based on an insignificant difference between their vessel diameter; but practical measurement showed a great difference. Therefore, we can come to the conclusion that the extractive content between these two plays a more important role in the value of longitudinal gas permeability. Figure 7 shows all three factors of longitudinal gas permeability, extractive content, and vessel diameter together.

5. CONCLUSION AND FUTURE WORK

The permeability of juvenile wood is always less than that of mature wood in sound wood. The reasons for this may be rooted in several factors such as blockage of vessels by more extractive content, tyloses, and pitch deposits in juvenile wood, as well as less vessel diameter in juvenile wood. Regarding the insignificant difference between vessel diameter in the juvenile wood of \textit{P.deltoides} and \textit{P. \times euroamericana}, the high difference between the permeabilities of these two may be traced to their difference in extractive content.

Juvenile wood of \textit{P. \times euroamericana}, especially in its older ages, tends to have an extra amount of extractives and therefore is prone to have very low permeability. Consequently, it is not recommended for industries where permeability is important.

Due to the smallness of the specimens, it was not possible to measure the extractive content in each single one. Still, the corresponding author is working on the extractive measurement in every single specimen to find out the regression equation between gas permeability and extractive content.

ACKNOWLEDGMENT

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FIG. 7: Comparison among permeability (\( \times 10^{-13} \text{ m}^3 \text{ m}^{-1} \)), extractive content (%), and vessel diameter (\( \mu \text{m} \)) in juvenile wood and mature wood of \textit{P. deltoides} and \textit{P. \times euroamericana}

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