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Statistical Modeling of Weight and Dimensions Changes of *Paulownia fortunei* and *Pseudotsuga menziesii* Sapwood

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ABSTRACT

Wood is the primary raw material used to manufacture pulp, although other raw materials can be used. For economic and environmental reasons, chemical and semi-chemical pulp mills must employ some procedures to keep the balance between chemical consumption and effluent production. Therefore, the absorption of neutral and alkaline liquors in the longitudinal, radial and tangential directions of Paulownia (*Paulownia fortunei*) and Douglas fir (*Pseudotsuga menziesii*) sapwood was investigated in this research to study two important factors, namely chemical penetration and cooking time. For this purpose, non-defect specimens with dimensions of 2×2×2cm were prepared and their lateral surfaces were coated by epoxy resin glue to study the absorption in each direction. The results showed that the absorption in the longitudinal direction was more than other directions. It was high in Douglas fir wood but neutral liquor had less absorption rate than alkaline liquor; while both of the shrinkage and the swelling were high in the tangential direction and their rates were low in Paulownia wood. Alkaline liquor caused more shrinkage and swelling than neutral liquor. In addition, a sigmoid-type model was appropriately fitted for the relation between “test time, specimen weight changes” and “test time, specimen dimensions changes”.

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INTRODUCTION

With advancing technology and increasing wood applications, it is more important to understand the wood structure and characteristics. The permeability is one of the wood structural features that limits its use in various applications [19]. It is a very variable feature dependent on the wood anatomical structure [1, 19, 22]. In addition, it is different in three orthotropic directions of wood, so that the permeability in the longitudinal direction is much more than two other directions [9, 19]. In addition to the orthotropic feature, wood is a highly heterogeneous material. It means that occurrence of any kind of abnormality and defect in wood can affect its permeability behavior [22]. In general, the fluid transfer process in wood is influenced by many factors such as cutting pattern, anatomical characteristics, moisture content and liquid (fluid) features [5, 7]. The microscopic structure of hardwoods and softwoods is not simple and the transport processes in cells and among cells of wood are often very complicated. For example, the interconnecting pits provide one of the main pathways for the flow of liquid between cells, and their structure and distribution affect the penetration of liquid in wood [17]. In this regard, various mathematical models of the liquid transport in wood have been carried out [2, 3, 4, 15, 16, 18, 19, 20, 21]. The influence of wood structure, as for its permeability and impregnability, has been summarized in the works of Siau [19, 20], Hansmann et al. [6], Usta [24], Lehringer et al. [8] and others.

The sapwood permeability of both softwoods and hardwoods are generally much higher than heartwood one with 3 to 144 and 1 to 1302 times, respectively [1]. Perré and Karimi [14] reported that the permeability of both sapwood and heartwood, and the number of active vessels in the fluid transfer is decreased with increasing of the sample length in *Fagus orientalis* wood. Omidvar and Omrani [12] observed that the amounts of absorption and

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penetration depth in the tangential flow are greater than radial one. This functional characteristic of wood plays a major role in the wood preservation, composite, wood polymer and pulp production [19]. It is a very important feature that has a major role in the paper industry. Paper industry is one of the greatest industrial consumers of water in the world and since it uses several chemical to produce paper from wood, its effluent is one of the main sources of environmental pollutant. Therefore, chemical penetration into wood structure and its rate determines the product quality, process performance, environmental problems, etc. [10]. In addition, the anatomical characteristics of different wood species and the permeability in different directions of wood influence on the use of different processes for the production of desired pulp, of which the penetration rate, fiber length and cell wall thickness are so important.

This research is based on the assumption that placing the wood samples in neutral liquor and alkaline liquor caused different permeability, shrinkage and swelling in the longitudinal, radial and tangential directions of Paulownia and Douglas fir wood specimens and there is a relation between test time and the changes of specimen weight and dimensions.

MATERIAL AND METHODS

Samples preparation:

The lumbers with 1m length and 7cm thickness from Paulownia (*Paulownia fortunei*) and Douglas fir (*Pseudotsuga menziesii*) sapwood were prepared and placed in a hangar to air dry for 2 to 3 weeks. Then, 84 non-defect specimens with dimensions of 2×2×2cm (longitudinal×radial×tangential) were prepared from each species. The lateral surfaces of specimens were coated by epoxy resin glue to limit the penetration in other directions. The prepared specimens were place in a hangar for 1 week. At the end, the specimens were weighed by a digital scale with an accuracy of 0.0001g and their dimensions were measured by a digital caliper with an accuracy of 0.01 mm. The experiment was performed in 3-stages nested design [11].

Moisture content determination:

In order to determine the moisture content, 12 specimens were selected from each species and placed in the oven with temperature of 103±2˚C for 24 hours. Then, the specimens were weighed again and their moisture contents (dry basis) were calculated by using following equation:

$$\text{Moisture Content (\%)} = \frac{W_1 - W_2}{W_2} \times 100 \qquad (1)$$

In equation (1), W_1 and W_2 are specimen air and oven dried weight, respectively.

Absorption and dimensions changes test:

Twelve specimens were considered from each direction to determine the absorption and dimensions changes in neutral (distilled water, pH=7) and alkaline liquors (0.1 Normality (N) sodium hydroxide solution, pH≈13). In order to prepare 0.1N sodium hydroxide solution, 1g pure sodium hydroxide was brought to the volume of 250 ml by adding distilled water. Potassium di-hydrogen phosphate/di-Sodium hydrogen phosphate and potassium chloride/sodium hydroxide solutions were used for neutral liquor and alkaline liquor as buffer solution, respectively.

Glass containers were prepared with dimensions of 30×15×10cm. The plastic granules were used to avoid the specimens contact with the containers floor. Then, 250ml neutral and alkaline liquors were poured into the separated containers and only 2 mm of specimens were placed into the liquors. The specimen's dimension and absorption change were measured in the regular time distances (i.e. 5, 15, 35, 60, 90, 125, 165, 210, 260 and 315 minutes).

At the end of test, the specimens were placed in oven with temperature of 103±2˚C for 24 hours and then, they were weighed again. The specimen absorption, shrinkage and swelling were calculated by using following equations:

$$\text{Absorption (\%)} = \frac{W_{secondary} - W_{initial}}{W_{initial}} \times 100 \qquad (2)$$

In equation (2), $W_{initial}$ and $W_{secondary}$ are specimen before and after test weight, respectively.

$$\text{Shrinkage (\%)} = \frac{V_{secondary} - V_o}{V_{secondary}} \times 100 \qquad (3)$$

In equation (3), V_O and $V_{secondary}$ are specimen oven dried and after test volume, respectively.

$$\text{Swelling (\%)} = \frac{V_{secondary} - V_{initial}}{V_{initial}} \times 100 \qquad (4)$$

In equation (4), $V_{initial}$ and $V_{secondary}$ are specimen before and after test volume, respectively.

Advances in Environmental Biology, 8(12) July 2014, Pages: 440-444

RESULTS AND DISCUSSION

Absorption and dimensions changes:

The moisture content of Paulownia and Douglas fir woods were 8.437% and 10.429% in average, respectively.

Since the desirable time for pulping is low, the absorption, shrinkage and swelling of Paulownia and Douglas fir woods were measured after placing them in neutral liquor and alkaline liquor for 315 minutes. The results have shown in the fig. 1.

As shown in fig. 1(a), the absorption in the longitudinal direction was more than other directions. The reason of this difference is probably that the penetration in the longitudinal direction occurs through the cell holes, which are relating to the longitudinal elements such as vessels in hardwoods and tracheids in softwoods [19]. The tangential direction had more absorption than radial one; but this different was not tremendous. This can be probably related to the tangential dimensional change due to parallel orientation of micro-fibrils along the axis of cell wall. In addition, it was low in Paulownia wood; despite it has spongy and porous tissue compared to Douglas fir. Filling the vascular elements of Paulownia with tylose can be probably its reason [12]. Neutral liquor had less absorption rate than alkaline liquor and the difference between the absorption rate of radial and tangential directions was obvious in the neutral liquor compared to alkaline liquor. The reason can be expressed that the swelling and dissolving features of sodium hydroxide are high [13].

In addition, it was found that the difference between the shrinkage and swelling was very low, as shown in figures 1(b) and 1(c). However, the shrinkage and swelling of Paulownia samples was low. This can be probably in relation to its less absorption than Douglas fir. Their rates were more in tangential direction than radial one. The most commonly used explanation is the occurrence of wood rays in the radial direction. The existence of wood rays is supposed to have a restraining effect on the shrinkage in the radial direction [23].

The difference between the shrinkage and swelling rates of radial and tangential directions was high in Paulownia wood. This can be probably due to the existence of filled vessels with tylose and surrounding by longitudinal parenchyma with long branches, in addition to the existence of impenetrable wood rays. In addition, alkaline liquor caused more shrinkage and swelling than neutral liquor and similar to the absorption, the difference between the shrinkage and swelling rates of radial and tangential directions was obvious in neutral liquor compared to alkaline liquor.

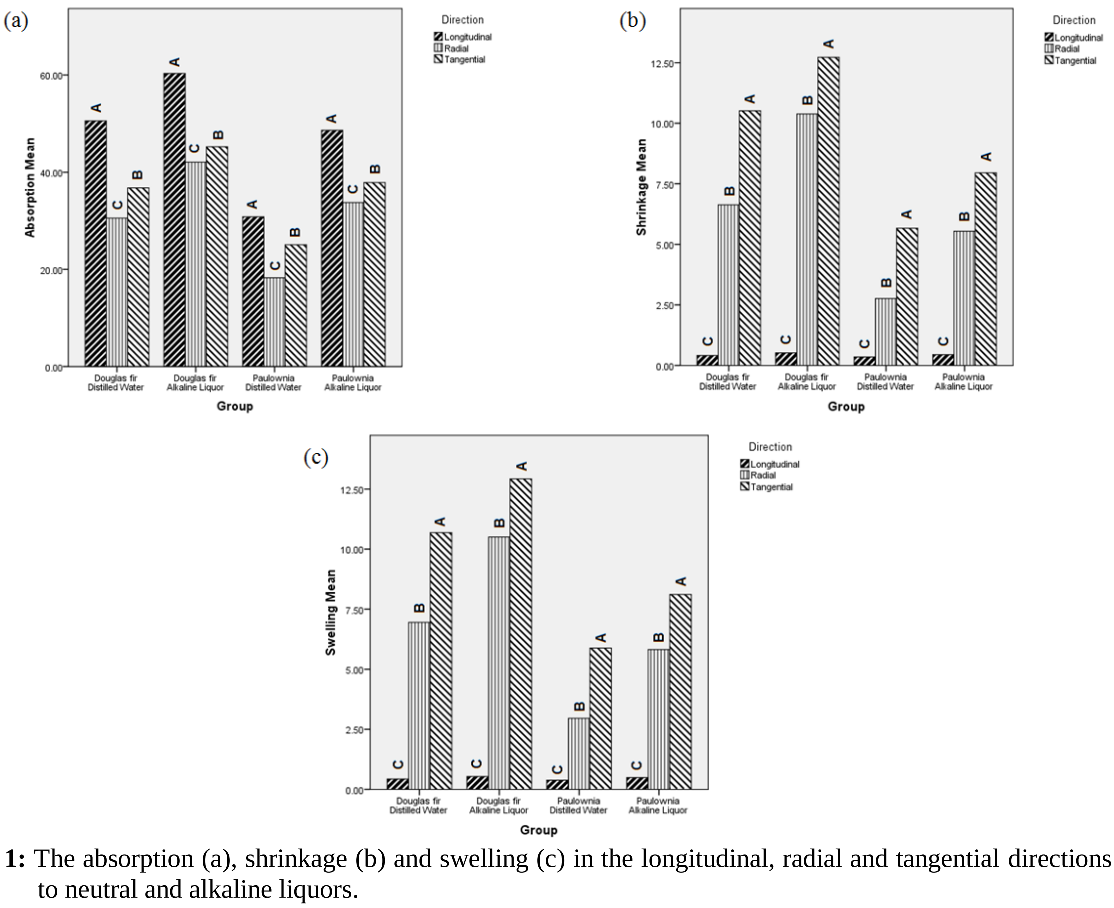

Fig. 1: The absorption (a), shrinkage (b) and swelling (c) in the longitudinal, radial and tangential directions due to neutral and alkaline liquors.

Advances in Environmental Biology, 8(12) July 2014, Pages: 440-444

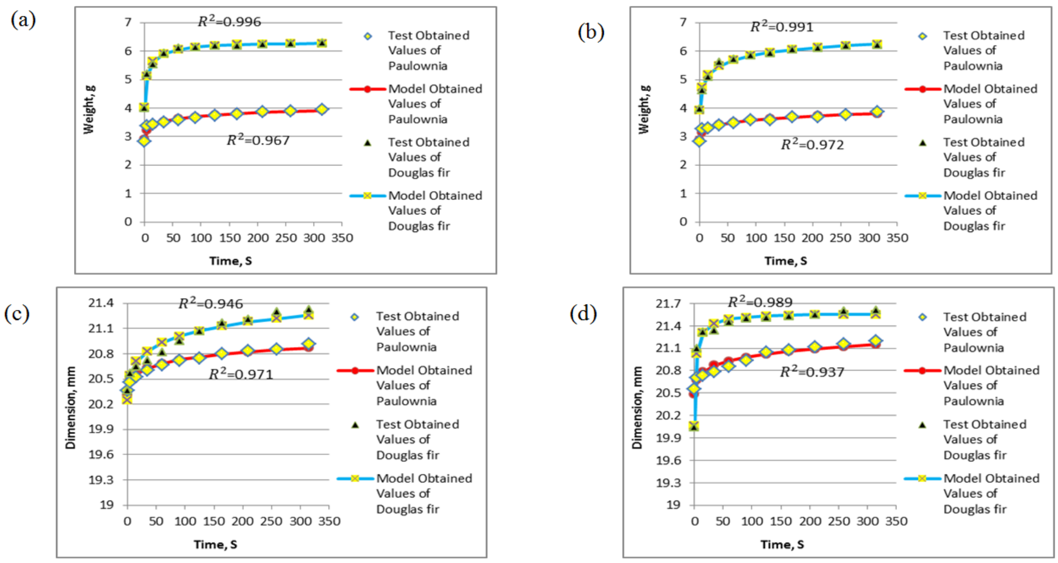

Fig. 2: Weight changes in the radial (a) and tangential directions (b), and dimensions changes in the radial (c) and tangential directions (d) due to alkaline liquor.

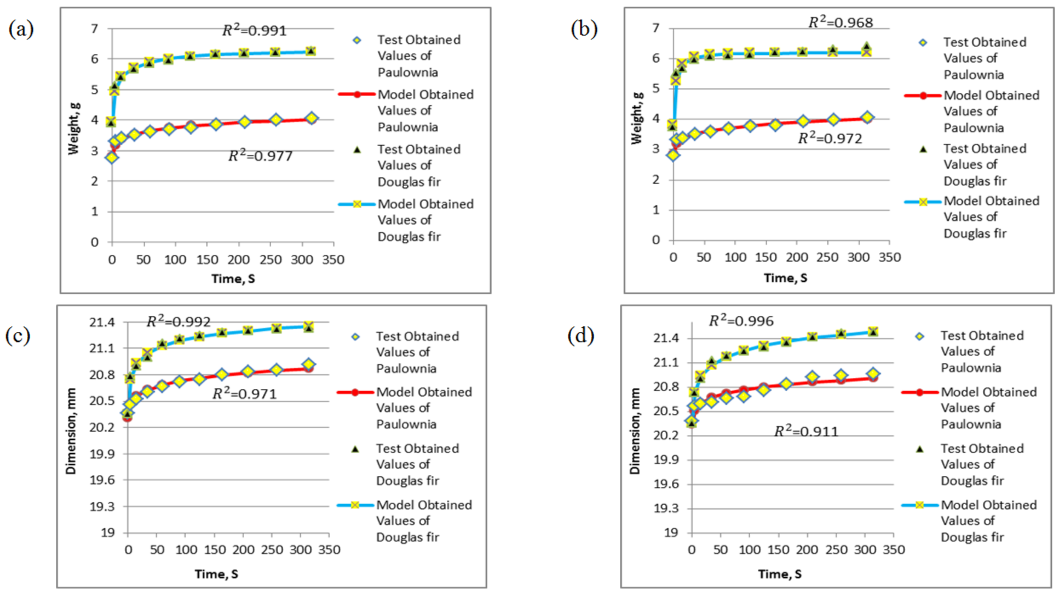

Fig 3: Weight changes in the radial (a) and tangential directions (b), and dimensions changes in the radial (c) and tangential directions (d) due to neutral liquor.

Modeling of weight and dimensions changes:

By investigation on different statistical models, it was found that the sigmoid-type models had better fitting for the relation between test time and the changes of specimen weight and dimensions. The non-linear sigmoid curves have different types and among them, the following model was used to show the mentioned relation:

$$y = a(1 - e^{-cx^b}) \quad (5)$$

In equation (5), *x* and *y* are test time and specimen maximum weight or dimensions. The parameters *a*, *b* and *c* are constant parameters. The accuracy of equation (5) for the relation between "test time, specimen weight changes" and "test time, specimen dimensions changes" have shown in the figures related to radial and tangential directions (i.e. figures 2 and 3).

Conclusions:

The results showed that the direction change had important effects on the absorption, shrinkage and swelling behaviors of wood. The absorption in the longitudinal direction was more than other directions; but contrary to the shrinkage and swelling, there was not tremendous difference between absorption rate of the radial and tangential directions. However, the tangential direction had more absorption than radial one. Due to tylose effects, the absorption, shrinkage and swelling in Paulownia wood were less than Douglas fir one. Alkaline liquor caused more absorption, shrinkage and swelling than neutral liquor and the difference between the absorption, shrinkage and swelling rates of radial and tangential directions was obvious in neutral liquor compared to alkaline liquor. The obtained observations showed that Paulownia wood is not suitable for the processes that need a good material penetration in wood, such as papermaking. In addition, by attention to stability and reliability of the sigmoid model (5) for different conditions and both changes of weight and dimensions with respect to test time, it is recommended to use this model for similar studies.

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