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SPECIFIC GAS PERMEABILITY OF NORMAL AND NANOSILVER-IMPREGNATED SOLID WOOD SPECIES AS INFLUENCED BY HEAT-TREATMENT

Hamid R. Taghiyari^{1,*}, Stavros Avramidis²

ABSTRACT

The effect of heat treatment at 50 and up to 150°C was studied on dowel-shape specimens prepared from beech (*Fagus orientalis*), poplar (*Populus nigra*), and fir (*Abies alba*) wood. Specimens were cut into two diameter sizes (18 and 25 mm) to explore the effect of diameter size on permeability. Separate sets of specimens from each size and species were prepared to be first impregnated with a 200 ppm aqueous nanosilver (NS) suspension to investigate the effect of facilitated heat-transfer on permeability at different temperatures. Specimens were heated in five consecutive steps at 50, 75, 100, 125, and 150°C and for 24 hours in each step. High variance was found in the specific gas permeability between each treatment group, thus indicating probable high fluctuation in settlement of extractives at different spots of a log. Heat treatment only affected gas permeability at the first steps of heating (50 and 75°C), where loss of moisture content resulted in a permeability increase in nearly all species. Consecutive steps of heating up to 150°C did not significantly affect the permeability in either normal or NS-impregnated specimens.

Keywords: Beech, poplar, fir, longitudinal permeability, wood-modification.

INTRODUCTION

Wood is a unique material that has helped humans over centuries develop their culture, civilization, and community. However, there are some inherent drawbacks such as dimensional instability, biological degradation, and combustion, to name a few; moreover, the natural regeneration of trees may not cover the increasing needs for wood. Therefore, it is frequently modified by engineering processes to gain stiffness or more homogeneous physical and mechanical properties (Papadopoulos 2012). Heat treatment (thermal modification) of wood is generally considered the most commercially used engineering process (Hill 2006). Effect of heat treatment from various perspective is quite elaborated during the past decades (Ayata *et al.* 2017, Salman *et al.* 2017). However, little research has been done as to the effects of heat treatment on permeability as an important physical property in solid wood species (Poonia *et al.* 2016). Therefore, a primary objective of the present project was to find out the effects of heat treatment at different temperatures on gas permeability in some hardwood and softwood species. Over the past two decades, nano-materials have been used to improve quality in many materials, including wood and wood composites (Ismita and Lokesh 2017, Muñoz and Moya 2018). In this connection, low thermal conductivity coefficient of wood (Taghiyari *et al.* 2013) makes heat-treatment process rather lengthy, especially in those treatments where the medium is not water or vapor. Different metal and mineral nano-fluids with enhanced thermal conductivity coefficients and dispersed metallic nanoparticles (Majidi 2016, Matinise *et al.* 2016, Pethig 2017, Suganya *et al.*

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2017) were applied in wood and wood-composites with an aim to accelerate heat transfer to the inner parts of specimens in air medium (Ghorbani *et al.* 2012, Esmailpour *et al.* 2017). Therefore, as a secondary objective in the present research project, separate sets of specimens were prepared to be first impregnated with silver nano-suspension and to be heat-treated along with un-impregnated specimens. Comparison between the un-impregnated and nanosilver-impregnated specimens would eventually indicate if nanosilver would have any significant impact on gas permeability in different wood species, including hardwood and softwood species.

MATERIALS AND METHODS

Specimen procurement and preparation

Two commercial hardwoods and one softwood were chosen based on their importance in various industrial applications in Iran, namely, beech (*Fagus orientalis*), poplar (*Populus nigra*), and fir (*Abies alba*). Cylindrical specimens of 30 mm in length parallel to the tree main axes and of two diameters, specifically, 18 and 25 mm were cut from the mature wood area of beech and fir log sections, and from both mature and juvenile sections of poplar. All specimens were clear and free of any defects. A total of 20 specimens were produced (2 diameters \times 10 replicates) for each species which were randomly distributed into two groups, namely, nanosilver-impregnated (NSI) and control (C); totally, 80 specimens. The side-surface of each cylindrical specimen was covered by silicon adhesive to restrain air flow along the longitudinal axis. A separate set of specimens (40 specimens) were cut for mass-loss measurements. Mass-loss (ML) specimens were not covered with silicon adhesive.

Gas permeability measurements

Different methods have so far been used to determine permeability in wood and wood composites (Poonia *et al.* 2016). Longitudinal gas permeability measurements were carried out by an USPTO-patented apparatus equipped with an automatic-time-measurement device with millisecond precision (Taghiyari *et al.* 2012). The falling-water volume-displacement method was used to calculate specific longitudinal gas permeability values based on the microstructure porosity of wood (Avramidis and Mansfield 2005, Shi 2007).

Three measurements were taken for each specimen and the superficial permeability coefficient (k_g) was then calculated using Equation 1 and Equation 2. The k_g values were then multiplied by the viscosity of air ($\mu=1,81 \times 10^{-5}$ Pa s) for the calculation of the specific permeability ($K=k_g \mu$) (Siau 1995).

Nano-Silver (NS) impregnation process

A 200 ppm aqueous dispersion of silver nanoparticles was produced using an electrochemical technique. The size range of silver nanoparticles was 20-80 nm and the pH of the suspension was 6-7. Two kinds of surfactants (anionic and cationic) were used in the suspension as stabilizer and the concentration of the surfactants was three times the nano-silver particles. Empty-cell impregnation process (Rueping method) was carried out in a 3 bar pressure vessel by Mehrabadi Industrial-Machinery Mfg. Co. (Ltd.). After the impregnation process, all specimens were kept under ambient conditions for three months to dry so that the hygromechanical behavior of wood would not affect the permeability measurement (Figuerola *et al.* 2012). The k_g of NSI specimens was re-measured before the heat-treatment process.

Heat-Treatment process

All 80 specimens (C, NSI, and ML) were randomly arranged in a laboratory convection oven for the 24-hour thermal treatment that was carried out at consecutive steps of 50, 75, 100, 125, and 150°C. After each step, specimens were carefully examined by a magnifying glass for possible macroscopic cracks; microscopic cracks caused by heat treatment are inevitable of solid wood (Hill 2006). After each of the above-mentioned heating steps, gas permeability of the specimen was measured after being cooled off on a bench top. Also, adhesive was checked after each step, and if necessary replaced after each step to make sure no air flow through lateral directions. ML specimens were weighed with a digital scale in the intervals to measure ML trend.

Statistical analysis

Statistical analysis was conducted using SAS software program, version 9.2 (2010). Two-way analysis of variance (ANOVA) was performed to discern significant difference at the 95% level of confidence. Grouping was then made between treatments using the Duncan's multiple range test. Regression and hierarchical cluster analysis, including dendrogram and using Ward methods with squared Euclidean distance intervals, was carried out by SPSS/18 (2010). Surface and contour plots were made by Minitab software, version 16.2.2 (2010).

RESULTS AND DISCUSSION

Specific gas permeability was significantly higher in poplar sapwood specimens in comparison to other treatments, including poplar heartwood (Figure 1). With regard to poplar heartwood, the higher permeability in poplar sapwood was attributed to lower extractive settlements in the cell and vessel cavities of sapwood poplar (Taghiyari *et al.* 2010), leaving them unobstructed for the passing of fluids. With regard to beech specimens, this was attributed to vessels with larger diameter as well as simple perforation of vessels in poplar wood. Fir specimens had the lowest permeability in comparison to other wood species. This low permeability was attributed to the small size of pit openings in tracheids of softwood species in comparison to the size of vessels in hardwood species. Any fluids should therefore make their way through small pit openings that connect adjacent tracheids.

Permeability measurement at the first step (ambient temperature) demonstrated that specimen size did not have any increasing or decreasing effect on specific gas permeability. Moreover, high within-group variance was observed in specimens of the same treatment. It can therefore be concluded that in the studied solid wood species, concentration of extractives at scattered locations of wood would make permeability vary from one spot to the other. Moreover, extractive would be apt to settle down at points of constrict along the vessels in hardwoods (Imamura 1989, Taghiyari *et al.* 2010). However, measurement of the amount of extractives in each specimen should be carried out, and correlation between the permeability and extractive content of each single specimen be found, before making any firm and final conclusion in this regard. In order to test this hypothesis in a different way, specimens with both sizes were prepared from medium-density fiberboard (MDF) the permeability of which is not dependent on vessel, but its porous structure. Permeability values of MDF were 0,038 and 0,037 ($\times 10^{-13} \text{ m}^3 \text{ m}^{-1}$) for sizes 18 and 25 mm, respectively. There was no statistical difference between the two values.

Impregnation with nanosilver suspension did not significantly change permeability values in any of the diameters and species. In most of the treatments, permeability increased at the first heating step (50°C), where the highest weight losses occurred (Figure 2). This was attributed to the loss of a major part of moisture content, making vessels and pit openings unobstructed because of shrinkage, for the transfer of fluid. The highest increase in permeability were observed in beech specimens; this can be attributed to higher density of this species, making shrinkage higher than the other two species (poplar and fir). Permeability values showed no particular fluctuations in the further heating steps in most of the treatments. This indicated that thermal degradation up to 150°C do not have a significant impact on permeability. This was in agreement with the nearly constant weight loss values after the second heating step (Figure 2). Impregnation with nanosilver suspension only showed an increasing

trend in beech specimens with 25 mm in diameter; other species and sizes demonstrated no significant difference in permeability between the normal and NS-impregnated specimens. It can therefore be concluded that the facilitated heat-transferring property in the NS-impregnated specimens are not so effective on permeability of small-sized specimens.

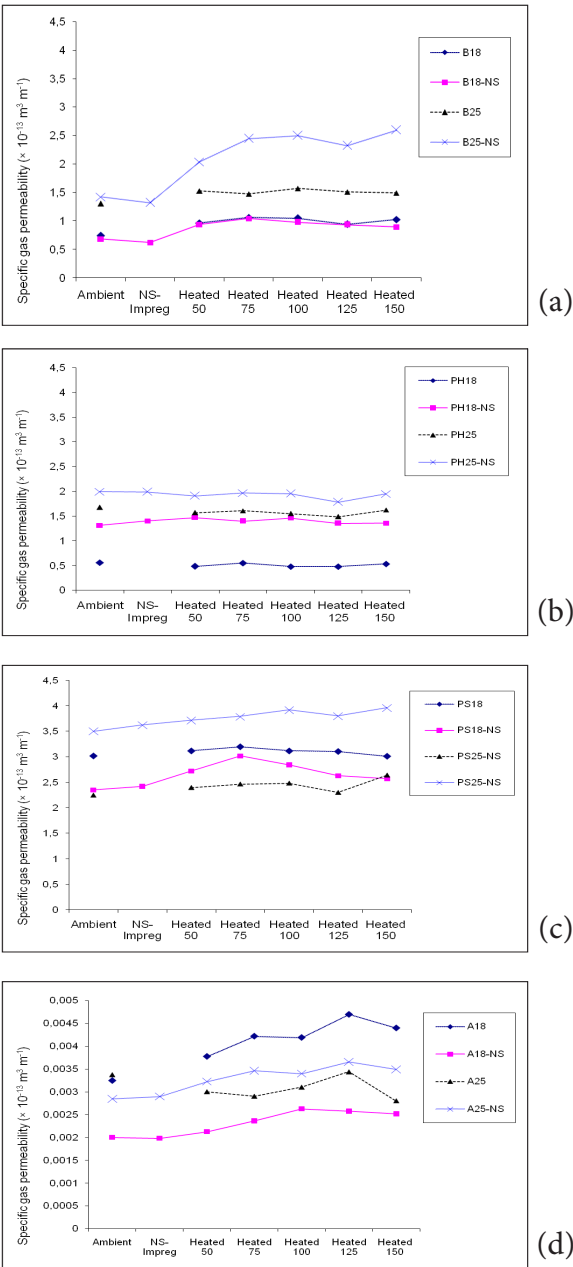


Figure 1: Specific gas permeability values in (a) beech, (b) poplar heartwood, (c) poplar sapwood, and (d) fir wood specimens for the two diameter groups.

(B=Beech; PH=Poplar heartwood; PS=Poplar sapwood; A=Abies fir wood; NS=Nanosilver-impregnated specimens) ($\times 10^{-13} \text{ m}^3 \text{ m}^{-1}$).

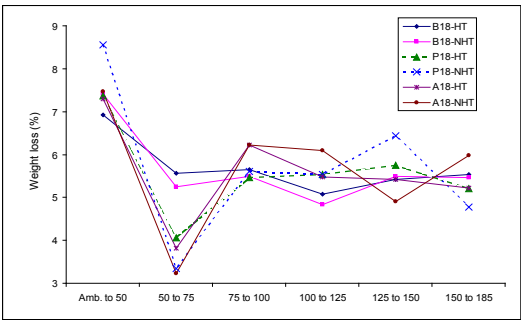


Figure 2: Weight losses (%) caused by thermal treatment in poplar specimens at different stages of heat-treatment.

(B=beech; HT=heat-treated; N=nanosilver-impregnated; P=poplar; A=Abies).

Regression analysis showed high significant R-square between nearly all gas permeability values measured when both the un-impregnated and nanosilver-impregnated specimens were heated at different heating steps versus the permeability value measured at ambient conditions (Table 1 and Table 2).

Table 1: Correlation between the gas permeability of un-impregnated specimens at ambient conditions (unheated) with different stages of heat-treatment in different species.

Species (ambient)	Heated (50°C)	Heated (75°C)	Heated (100°C)	Heated (125°C)	Heated (150°C)
Beech	0,644 **(+)	0,628 **(+)	0,688 **(+)	0,658 **(+)	0,486 *(+)
Poplar (sapwood)	0,662**(+)	0,667**(+)	0,777**(+)	0,668**(+)	0,722**(+)
Poplar (heartwood)	0,945**(+)	0,938**(+)	0,924**(+)	0,926**(+)	0,913**(+)
Fir	0,897**(+)	0,786**(+)	0,813**(+)	0,673**(+)	0,627**(+)
** Correlation is significant at the 1 % level (2-tailed) (+) Positive correlation					

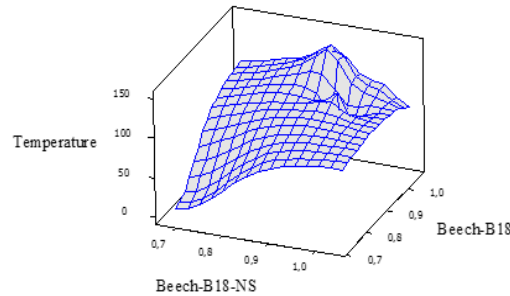
Table 2: Correlation analysis between the gas permeability of nanosilver-impregnated specimens at ambient conditions with different stages of nanosilver-impregnation and heat-treatment in different species.

Species (ambient)	Nanosilver Impregnation	Heated (50°C)	Heated (75°C)	Heated (100°C)	Heated (125°C)	Heated (150°C)
Beech	0,850**(+)	0,646**(+)	0,659**(+)	0,702 **(+)	0,729**(+)	0,559**(+)
Poplar (sapwood)	0,859**(+)	0,816**(+)	0,817**(+)	0,831**(+)	0,808**(+)	0,843**(+)
Poplar (heartwood)	0,633**(+)	0,856**(+)	0,862**(+)	0,850**(+)	0,839**(+)	0,805**(+)
Fir	0,714**(+)	0,831**(+)	0,831 **(+)	0,818**(+)	0,794**(+)	0,833**(+)
** Correlation is significant at the 1 % level (2-tailed) (+) Positive correlation						

The highest R-square values were found in poplar heartwood. The trends in poplar heartwood showed a rather constant value and no particular fluctuation observed as the temperature increased from 50 to 150°C; this can imply that heat-treatment up to 150°C cannot significantly affect permeability in poplar heartwood and therefore high R-square was observed.

Surface plots of un-impregnated and nanosilver-impregnated of different sizes and species versus the heat-treatment steps showed a steady increase in permeability values as the temperature increased (Figure 3a, Figure 3b). Only at higher temperatures of about 125 and 150°C were some inconsistencies observed. The fluctuations in permeability values that occurred at the higher temperatures in Figure 1a, Figure 1b, Figure 1c, Figure 1d) caused the inconsistencies against the normal trend. High and statistically significant R-squares that were found by fitted-line plots also approve that in small size specimens, heat treatment at temperatures up to 150°C cannot significantly affect the permeability values (Figure 4a, Figure 4b).

a. Surface Plot of Temperature vs Beech-B18; Beech-B18-NS



b. Surface Plot of Temperature vs Fir-B18; Fir-B18-NS

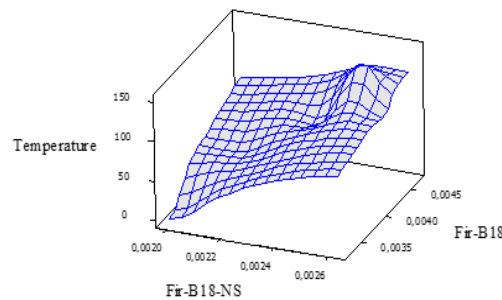


Figure 3: Surface plots of un-impregnated and nanosilver-impregnated (a) beech and (b) fir specimens size 18. (B=beech; N=nanosilver-impregnated).

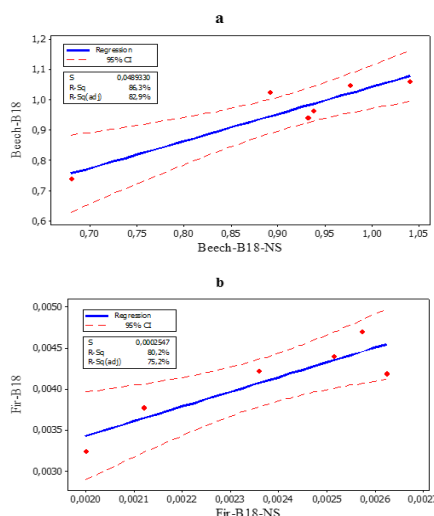


Figure 4: Fitted-line plots of un-impregnated and nanosilver-impregnated beech (a) and fir (b) specimens size 18. (B=beech; N=nanosilver-impregnated).

CONCLUSIONS

High variance in specific gas permeability values exists in specimens cut from the same position of tree. This can be attributed to high fluctuation of extract settlement at different location spots of a tree.

In small size specimens, specific gas permeability values are not dependant on the diameter of specimens.

Loss of moisture content can significantly increase permeability.

Thermal degradation up to 150°C does not significantly affect specific gas permeability in beech, poplar, and fir wood.

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