Mokchae Konghak 35(2) : 29~38, 2007

Radial and Circumferential Variations in Hygroscopicity and Diffusion Coefficients within a Tree Disk*1

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ABSTRACT

This study was undertaken to investigate the variation of equilibrium moisture content (EMC) in transverse direction and three different directional (longitudinal, radial, and tangential) linear movements, and diffusion coefficients within a tree disc of Korean red pine (*Pinus densiflora*). The EMC gradually increased in heartwood from pith. Therefore, the chemical components might differ even in heartwood and the radial variation in EMC might have a close relationship with the cellulose content within a cross section. The specific gravity increases gradually from pith and the porosity has not direct influence on the variation of EMC within a tree disk. Both the radial and tangential diffusion coefficients exhibited clear trend of increase from pith. The EMC change (*ΔEMC*) and tangential diffusion coefficient were close to be axisymmetrical but others were deviated from axisymmetry. The diffusion coefficient decreases with decreasing an activation energy and specific gravity. The diffusion coefficient increased with increasing *ΔEMC* and hygroscopicity of wood might be inversely proportional to the activation energy. The *ΔEMC* may depend on the chemical constituents of cellulose, hemicellulose and lignin. As the number of sorption sites and sorption capacity of wood increase, therefore, it might be assumed that the hygroscopicity of wood increases while activation energy decreases. Modeling physico-mechanical behavior of wood, the variations should be considered to improve the accuracy.

Keywords : tree disk, heterogeneity, hygroscopicity, diffusion, linear movement

1. INTRODUCTION

Wood is an ecological building material and does no harm to nature system. However, it is a highly heterogeneous material with variations in the physico-mechanical and anatomical properties both between trees and within a tree, which result in much difficulty in engineering analysis. The intra-tree variations can be described in three directions : radial, tangential and longitudinal. Most properties in radial direction gradually vary from pith to bark but the

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pattern in longitudinal direction is irregular and depends on the species.

In most cases of modeling for estimating the physico-mechanical behaviors, wood is usually assumed to be homogeneous spatially because it is cumbersome to measure them. As the dimension of a wood member increases, the heterogeneity within a member will increase. Therefore, wood of large dimension will exhibit more complex pattern of performance such as distortion. The behavior of wooden products will be understood deeply when the spatial variation of wood properties is known.

In recent, some researchers have investigated the radial and axial variations in wood density, shrinkage and ring width (Kärki 2001; Koga and Zhang 2004). The inter-tree variation in balsam fir was relatively smaller than the intra-tree variation. Much of the intra-tree variation is due to the radial variation. Similar to most of the previous studies, these researches were assumed that the radial variation would be axisymmetric and there were no circumferential variations. Constant *et al.* (2002) studied the variations of green moisture content in sessile oak whose results showed that the radial variation was not axisymmetric. Constant *et al.* (2003) studied warping of plywood and the results of heterogeneous model were more realistic than those of homogeneous model, especially for displacement shape.

Diffusion coefficient is important to understand the rate of moisture content change and its spatial variation within a wood member with the fluctuation of atmospheric conditions in an environment to which it is exposed. However, there are very few researches on the radial variation in diffusion coefficients except for a report of Koumoutsakos and Avramidis (2002). They investigated the difference in diffusion coefficients between heartwoood and sapwood of western hemlock and western red cedar. A comparison of heartwood and sapwood in the logitudinal direction revealed that sapwood had a higher diffusion coeffcient, while it did not give a clear trend for the radial and tangential directions.

In a literature review, most researches focused only on the difference of wood properties between heartwood and sapwood or between juvenile wood and mature wood (Zobel and Sprague 1998). There are few studies on the radial variation as well as the circumferential variation in wood physical properties.

This study was undertaken to investigate the radial and circumferential variations of equilibrium moisture content (EMC), linear movement, and diffusion coefficient in the longitudinal, radial and tangential direction within a tree disc of Korean red pine. The main purpose of this work is not to measure the true diffusion coefficients but to study the degree of their variation within a stem, which result in the apparent diffusion coefficients.

2. MATERIALS and METHODS

2.1. Preparation of Materials

The Korean red pine (*Pinus densiflora*) for the test specimen comes from Gangwon province located at the eastern part of Korea. The log diameter and number of annual rings were shown in Table 1. Several disks (5 cm thick) were consecutively cut from the bottom of a log with little growth eccentricity, which were visibly free of reaction wood. The radio frequency vacuum (RF/V) drying of the samples was carried out in a laboratory kiln (Kang and Lee 2004). After the RF/V drying, drying defects were visually evaluated and three tree disks with no defects were selected as the test specimens of the longitudinal, radial and tangential direction.

Table 1. Diameter and number of annual rings of Korean red pine

Species	Length (cm)	Diameter (cm)		Annual rings	
		Bottom	Top	Bottom	Top
Korean red pine	185	80	70	70	65

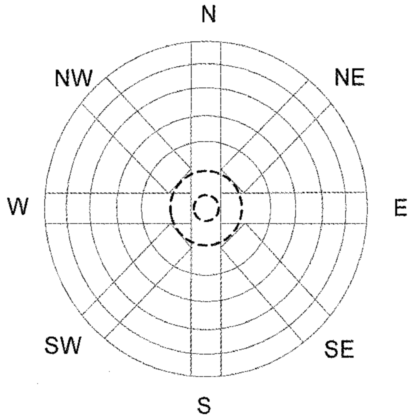


Fig. 1. Specimens for measuring variations of physical properties.

As shown in Fig. 1, each tree disk was cut in the four directions and seven bar samples with cross section of 5 × 5 cm were obtained from one tree disc. For the diffusion experiment, the specimen of 1 cm thickness along the longitudinal, radial and tangential direction were cut successively and numbered from the bar specimen.

2.2. Sorption Measurement

The four edges of each specimen were coated twice using paint with pigments to provide unidirectional movement of moisture. All the specimens were conditioned to reach equilibrium at 27°C and relative humidity (RH) 60% in a conditioning chamber.

Measurement was repeated with two replications for each experimental run for both adsorption and desorption. Specimens were exposed at a constant temperature of 27°C during the test. For adsorption measurements, the specimens were exposed to RH 90%. When their weight did not show any change after successive measurements of several days, equilibrium was assumed. Once an adsorption test was completed, the humidity of chamber was changed to RH 60% for desorption measurements.

Specimens were weighed periodically during sorption. The time interval was relatively short time at early stage of sorption since sorption rate was high, and it was increased at later stages of sorption due to a decreased sorption rate.

The apparent diffusion coefficient was obtained from the real half time as (Siau and Avramidis 1996)

$$D = \frac{0.2a^2}{t_{0.5}} \quad (1)$$

where D is the diffusion coefficient for average moisture content in square meters per second, a the thickness of the specimens in meter. The EMC and dimensional movement were measured with the same specimen for sorption. The reference weight of the wood sample was determined by oven drying method.

After obtaining the test results, the contours were prepared in order to visualize the variability in physical properties within a tree disk as shown in Fig. 2.

3. RESULTS and DISCUSSION

3.1. Average Physical Properties

Average values of specific gravity, EMC, linear movement coefficient (LMC) and diffusion

Table 2. Average physical properties of Korean red pine (L=longitudinal, R=radial, T=tangential)

Physical properties				Average
Specific gravity				0.53 ± 0.04
EMC (%)	RH 90%			15.5 ± 1.2
	RH 60%			9.7 ± 0.6
	△EMC			5.8 ± 0.7
LMC ($m\ m^{-1}\ MC\%^{-1}$)	R			0.155 ± 0.031
	T			0.327 ± 0.038
Diffusion coefficient ($m^2\ s^{-1}$, × 10^{10})		Adsorption	L	3.37 ± 1.76
			R	1.15 ± 0.42
			T	0.79 ± 0.47
		Desorption	L	4.50 ± 2.99
			R	1.92 ± 0.56
			T	1.72 ± 0.72

coefficient were listed in Table 2. The differential transverse linear movement that represents the ratio of tangential LMC to radial one resulted in 2.1. It usually ranges from 1.5 to 2.5 depending on species.

Moisture diffusion in wood is a function of the hygroscopic gradient of bound water and the vapor pressure gradient of the water vapor, which is usually restricted to sorption below the fiber saturation point (FSP). Diffusion coefficient is dependent on temperature and moisture content. If they are assumed to be constant, it is difficult to predict moisture change of wood in the entire range of moisture content. However, the concept that the diffusion coefficient is constant with moisture content change might be acceptable at least in the moisture change below FSP after drying. To describe the diffusion phenomenon, two diffusion coefficients must be classified : the true diffusion coefficient due to the internal resistance of wood, and the apparent diffusion coefficient which includes both internal and external resistances. The external resistance decreases with temperature and increases with moisture content (Siau and Avramidis 1996). In this study, however, the apparent diffusion coefficient was only obtained and it was assumed to be constant with moisture change because it mainly focused on the variations within a cross section.

It was shown that the longitudinal diffusion coefficient was higher than the transverse one among which the radial diffusion coefficient was higher than the tangential one. This result is consistent with the results of Koumoutsakos and Avramidis (2002). This could be theoretically explained with the fact that the relative ease of moisture movement in the radial direction is more dependent on vapor movement because the ray cells have thin walls and the cross walls are less numerous (Choong and Fogg 1968).

In structural direction, the degree of anisotropy on desorption was smaller than that on adsorption. The ratio of desorption (D) to adsorption diffusion coefficient (A), D/A, varies with the structural direction. D/A in the longitudinal, radial and tangential directions was inversely proportional to the order of diffusion coefficient and it was 1.33, 1.67 and 2.17, respectively.

Choong and Skaar (1972) attributed the difference in D/A to lower moisture contents and more resistance due to compressive stresses in the cell wall than would be expected in desorption. Siau and Avramidis (1996) reported that

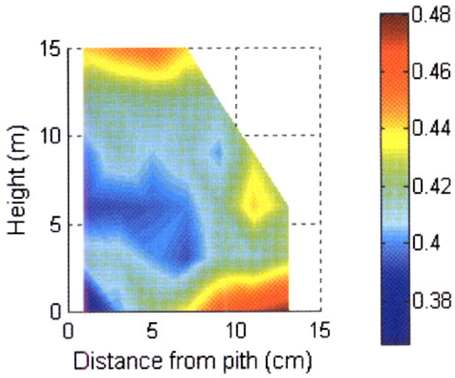


Fig. 2. The radial and axial variation in dry density of aspen (Kärki, 2001).

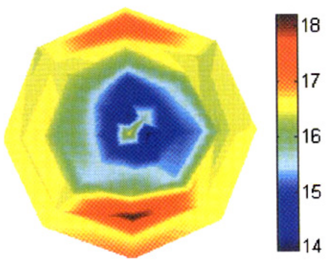
the external resistance during adsorption are higher than that of desorption.

The difference of D/A in the structural direction might be mainly due to the effect of stress because the moisture change was the same and the stress due to moisture gradient increases with a decrease in the diffusion coefficient.

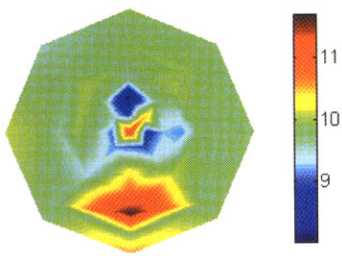
3.2. Variation of EMC

Fig. 3 shows the variations in EMC at RH 90% and 60%. And these results were obtained from the specimen of longitudinal diffusion coefficient. However, similar results were obtained from the specimen of radial and tangential diffusion coefficients. EMC differed in the same annual rings as well as between in the radial direction. The average EMC in the direction of N-S was slightly higher than that in the direction of E-W. The former was 16.2% and the latter 15.7% at RH 90%. At RH 60%, the former was 10.1% and the latter 9.5%.

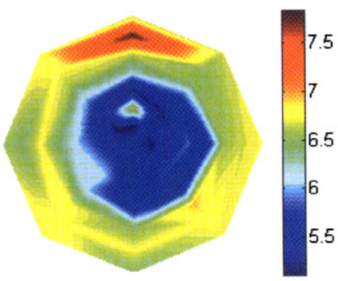
The change of EMC between RH 90% and 60%, △EMC, was also not constant in the radi-



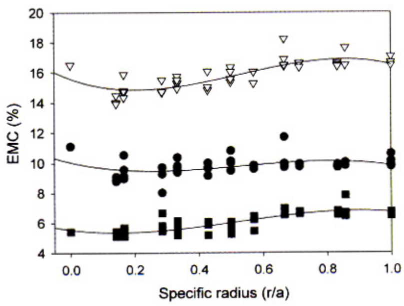
(a) EMC at RH 90%



(b) EMC at RH 60%



(c) △EMC



(d) Radial variation

Fig. 3. The radial and circumferential variation and change of EMC at RH 90% and 60% within a disk (▽ RH 90%, • RH 60%, ■ *ΔEMC*). r : the distance from pith, a : radius of tree disk.

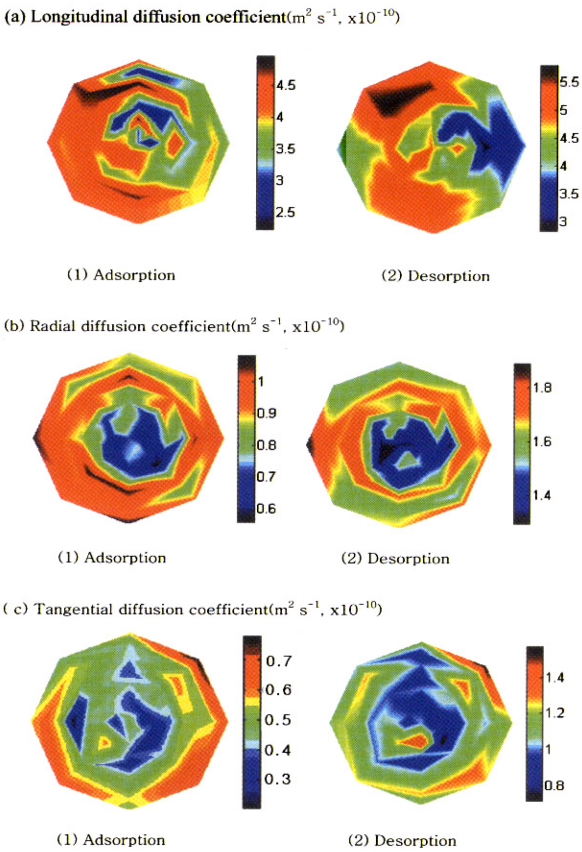


Fig. 5. The radial and circumferential variation of diffusion coefficients on adsorption and desorption within a tree disk.

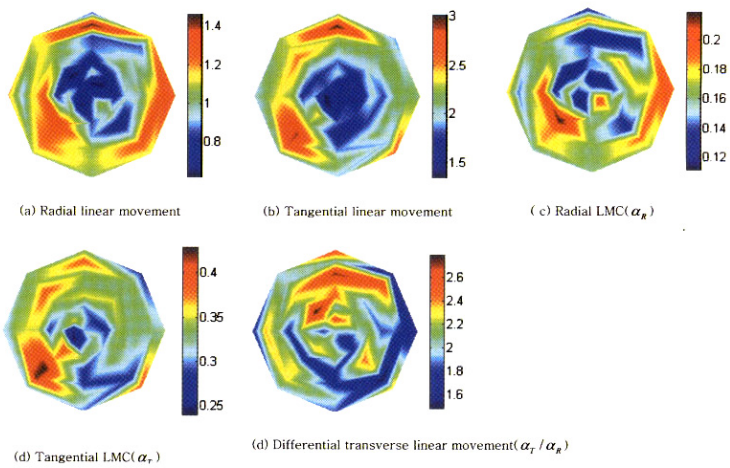


Fig. 7. The radial and circumferential variation of linear movement (%) and LMC (m m^{-1} $MC\%^{-1}$) within a tree disk.

al direction and increased gradually from pith. The EMC variation at RH 90% was higher than that at RH60% and the hygroscopicity increased from pith to bark.

The variations in EMC can be explained in regard to their chemical compositions. Hemicellulose are the most hygroscopic, and lignin the least hygroscopic (Rowell 1984). The hygroscopicity depends on the cellulose content, the crystallinity of microfibiril and porosity of cell wall. The hygroscopicity increases with increasing the celluose content while it decreases with increasing the crystalline portion of cellulose microfibril and the porosity (Kolin and Janezic 1996).

Bertaud and Holmbom (2004) studied the distribution of chemical components along a cross section of a spruce stem. They showed that heartwood contained significantly more lignin and less cellulose than sapwood. Andersson *et al.* (2004) showed that the crystallinity of cellulose did not change from pith, but the mass fraction of cellulose increased as a function of annual ring in Norway spruce and Scots pine. In this study, however, it should be noted that EMC gradually increased in heartwood from pith. Therefore, the chemical components might differ even in heartwood and the EMC radial variation might have a close relationship with the cellulose content within a cross section. In addition, the specific gravity increases gradually from pith and the porosity can not explain the variation of EMC within a tree disk.

4. VARIATION of DIFFUSION

All the diffusion coefficients in the longitudinal, radial and tangential direction were gradually increased from pith as shown in Fig. 4. The pattern of variation was somewhat different. However, the contours of diffusion coefficients between adsorption and desorption was very similar (Fig. 5).

Diffusion coefficient in the longitudinal direction exhibited irregular variability compared to those in radial and tangential directions.

The longitudinal diffusion coefficient did slightly increase from pith, which is consistent with the results of Koumoutsakos and Avramidis (2002) that sapwood has a higher longitudinal diffusion coefficient by 30～100% for hemlock and by 25～80% for cedar compared to heartwood. They explained the difference in diffusion coefficient between sapwood and heartwood by the fact that the permeabilty of sapwood was 10 times larger than that of heartwood in both hemlock and cedar. For the permeability of hemlock, the sapwood-heartwood ratio of 2 : 1 remained for both the radial and tangential directions.

In comparing the radial and tangential diffusion coefficients of sapwood with heartwood no significant difference was found, even though the permeability values had a great difference (Koumoutsakos and Avramidis 2002; Choong and Fogg 1968). They explained that it was due to other dominant factors, such as moisture content that has a higher effect on the diffusion than do structural differences of heartwood and sapwood. In addition, it was reported that juvenile wood in heartwood zone usually had a higher radial diffusion coefficient than that of the mature wood in the heartwood zone (Bao *et al.* 2001). In this study, however, both the radial and tangential diffusion coefficients exhibited clear trend of increase from pith. This phenomenon can be explained by the greater permeability of sapwood with larger intercellular pitting and lesser pit aspiration. Therefore, vapor movement might be a dominant factor at least in this study because there are more passageways for water vapor in sapwood.

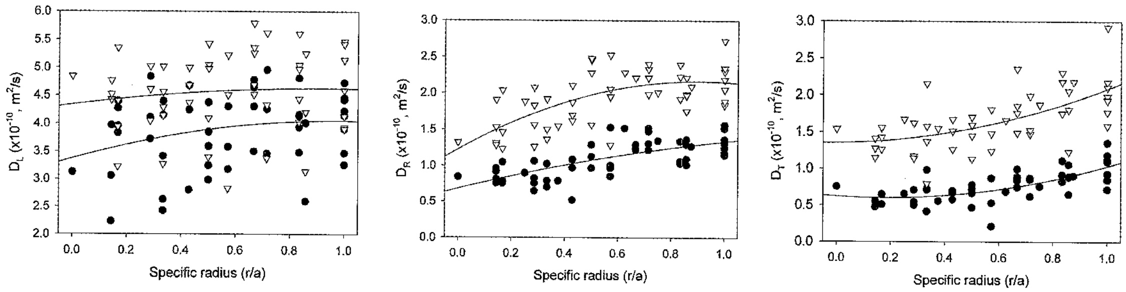


Fig. 4. The radial variation of diffusion coefficients on adsorption and desorption (• adsorption, ▽ desorption). *ΔEMC*). r : the distance from pith, a : radius of tree disk.

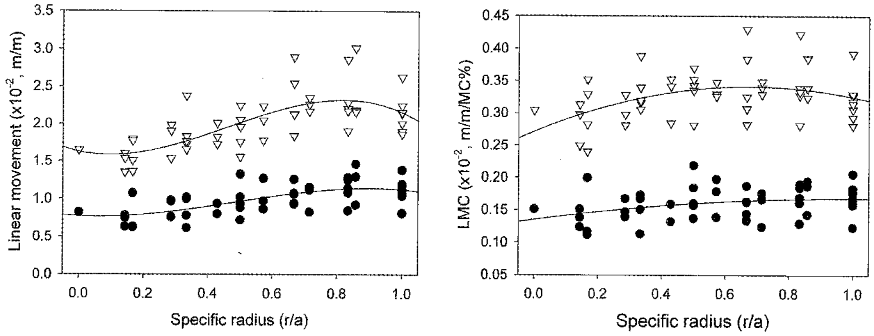


Fig. 6. The radial variation of linear movement and LMC (• radial, ▽ tangential). r : the distance from pith, a : radius of tree disk.

4.1. Variation of Linear Movement

As shown in Fig. 6, the transverse linear movement increased from pith. This could be attributed to the fact that microfibirl angle decreases from pith (Zobel and Sprague 1998). However, their patterns vary with structural directions. The radial increase of LMC in tangential direction was greater than those in radial direction. For radial direction, the variation in linear movement was rather axisymmetrical as shown in Fig. 7. For tangential direction, it did not show a particular pattern and the linear movement was higher at N-W-S direction. Because the variation in EMC difference between RH 60% and 90% (*ΔEMC*) is close to be axisymmetrical (Fig. 3), the variation pattern of LMC was similar to that of the linear movement.

The variation of the differential transverse linear movement (α_T/α_R) was somewhat different form that of linear movement and higher at N direction. This result suggests that it is likely to crack at N direction because the drying stress is proportional to α_T/α_R during drying (Kang and Lee 2004). At present, there are several theories to explain the α_T/α_R (Gu *el al.* 2001) but it varies degrees in different woods or circumstances, or both (Stamm 1964). From these results, it is extremely difficult to make definitive conclusion about the reason of the variation of α_T/α_R within a tree disk.

4.2. Relationship Among Diffusion, EMC and Linear Movement

As shown above, diffusion coefficient, EMC and linear movement increased from pith to

Table 3. Coefficients of diffusion equation

Direction		a ($\times 10^{11}$)	b	c	R^2
Tangential	D_a[1)]	0.544	0.506	0.445	0.64
	D_d[2)]	2.38	0.596	0.299	0.59
Radial	D_a	1.34	0.960	0.242	0.65
	D_d	3.00	0.969	0.202	0.80
Longitudinal	D_a	10.6	1.32	0.0692	0.38
	D_d	15.8	1.35	0.0275	0.39

[1)]adsorption, [2)] desorption

bark. This result indicates that there could be any possible the relationship among them.

It is well known that the diffusion coefficient decreases with an activation energy and specific gravity (G). If we assume that the activation energy has a close relationship with , the relationship may be written as Eq. (2) :

$$D = \frac{a}{G^b}\exp(c \times \Delta EMC) \qquad (2)$$

The multiple regression analysis of the Eq. (2) gave the results as shown in Table 3. The result showed that the correlation in the longitudinal direction was the poorest, indicating a poor reliability in prediction. The effect of specific gravity and on the diffusion varied according to the structural direction of wood. This may be due to the effect of the external resistance by environmental condition in the humidity chamber that was not taken into consideration in this study. The amount of external resistance may vary depending on the structural direction. However, it showed that the activation energy decreased with increasing ΔEMC because the sign of c in. Eq. (2) was positive and diffusion increased with ΔEMC. Hygroscopicity of wood might be inversely proportional to the activation energy. The apparent activation energy as well as ΔEMC may depends on the chemical constituents of cellulose, hemicellulose and lignin. As the number of sorption sites and sorption capacity of wood increase, therefore, it might be assumed that the hygroscopicity of wood increases while activation energy decreases.

Basically, linear movement is a function of ΔEMC and density. In this study, however, it was independent of them because the variation of linear movement was greater as shown in Fig. 6. This may be mainly due to the difference in the ratio of earlywood to latewood among specimen.

5. CONCLUSION

The variations of EMC, linear movement, and diffusion coefficient in structural direction within a tree disc of Korean red pine were investigated. In spite of difficulty in drawing definitive conclusion on the variation in physical properties within a tree disk, it was possible to detect certain trends depending on each physical property within a tree disk. All the properties that were investigated in this study increased from pith to bark. ΔEMC and tangential diffusion coefficient were close to be axisymmetrical but others were deviated from axisymmetry. The diffusion coefficient increased with and hygroscopicity of wood was inversely proportional to the activation energy. It appears that the variations in a wooden member depend on sawing method and position with which structural directions of wood member change. If a wooden member were assumed to be homogeneous, the results to be predicted would be more erroneous as the size of member increases. Modeling physico-mechanical behavior of wood, the variations should be considered to improve the accuracy. Further researches related to the variations of chemical compositions could help better understanding the variations in physical properties.

ACKNOWLEDGMENT

This work was supported by Regional Research Centers Program (Bio-housing Research Institute), granted by the Korean Ministry of Education & Human Resources Development.

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