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Estimation of the Chestnut Mass Transfer Coefficient through its Microscopic Structure*1

- Chestnut Mass Transfer Coefficient through its Microscopic Structure -

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ABSTRACT

Mass transfer behavior in wood was estimated through its microscopic structure. The diffusion coefficients which were decided by theoretical equations are influenced by different anatomical properties of wood. From the experiment, the moisture flux was linear to the square root of time. The diffusion coefficients had a regular tendency during the time elapse. During the modeling, it is necessary to understand the limitation of parameters and consider the particular situation to be simulated. In hardwood, because the apertures were not considered, tangential mass transfer simulation was totally different from experiment. As a result, a hardwood model design should consider the apertures which are even on the fiber walls.

Keywords : mass transfer coefficients, microscopic structure

1. INTRODUCTION

Mass transfer in wood is a topic which has been investigated by numerous researchers. It is well known that the mass transfer behavior in wood is difficult to decide especially in the whole hygroscopic range. It depends on wood properties which include anatomical shape, structural direction, pits and other impacts such as moisture content, temperature, time, etc. In this paper, mass transfer behavior in wood was estimated through its microscopic structure. The microscopic method of estimating diffusion coefficients has been conducted by many researchers (Stamm *et al.*, 1961; Choong, 1965; Kang *et al.*, 2008). It is a theoretical method in which the contributions to moisture movement of the various anatomical elements and other factors of wood are combined. This theoretical approach was initiated by Stamm (1960) on the assumption that the moisture movement was divided into bound water and water vapor, and that each diffusion coefficient could be estimated. Therefore, the combined bound water and water vapor diffusion depend on the ratio of the cell wall to cavity volume and the geometrical structure of the cavity. Stamm and Nelson's (1961)

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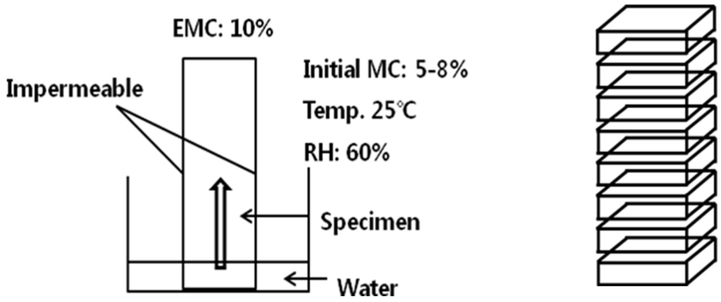

Fig. 1. Schematic diagram of the moisture sorption test and section.

theoretical research indicated that the diffusion coefficient can be analyzed by considering the diffusion through the separate wood components in a manner similar to electrical conduction. Stamm (1960), Choong (1965), Siau (1995) and Kang (2008) have different models in this electrical conduction method. However, this electrical conduction method can be applied only when moisture content of wood is under the fiber saturation point.

In this study, the amount of influence of each anatomical factor to mass transfer coefficient was quantitatively determined so that only by depending on the three directions' anatomical images can the mass transfer coefficient in wood be deduced.

2. MATERIALS and METHODS

2.1. Experimental Methods

To investigate the moisture diffusivity of wood in the three directions including bound water and free water movement, a liquid water absorption test was conducted at isothermal condition. Chestnut (*Castanea crenata*) samples were cut to a prismatic shape with approximate dimensions of 30 mm (width) × 30 mm (depth) × 50 mm (height). Also samples were cut by three different directions which are longitudinal, radial and tangential. All of the samples were dried to 3～6% moisture content. After drying, four vertical sides were coated by a varnish with heavy pigments. The top and bottom faces were left uncoated. The bottom surface was submerged only a few millimeters in order to avoid buildup of hydrostatic pressure. The top surface was exposed to ambient conditions. The environmental laboratory conditions were kept at a constant temperature of 25°C and 60% relative humidity during the experiments in order to keep equilibrium moisture content at the 10% level (Fig. 1).

Moisture uptake was recorded regularly at various time intervals. After the absorption test, the specimen was cut consecutively into 8 to 12 pieces for measuring moisture content.

2.2. Theoretical Mass Transfer Coefficients

The mass transfer model in wood can be described as Equation 1. Here, D_w is the liquid water diffusivity (m^2/s), D_v is the water vapor diffusivity (m^2/s), and D_b is the bound water diffusivity (m^2/s).

$$\frac{\partial m}{\partial t} = \nabla \cdot \left[\left(D_w + D_v + D_b \right) \nabla m \right] \tag{1}$$

From the above equation, we cansee the simulation of mass transfer in the entire moisture range requires some material properties.

2.2.1. Above Fiber Saturation Point

The liquid water diffusivity can be expressed by Darcy's Law (2).

$$D_w = -\frac{\rho_w}{\rho_0}\frac{K_r K_a}{\mu_w}\frac{\partial P_c}{\partial S}\frac{\partial S}{\partial m} \qquad m > m_{FSP} \tag{2}$$

where ρ_w : water density (kg/m^3);
ρ_0 : basic density (kg/m^3)
K_r : relative permeability;
K_a : absolute permeability (m^2)
μ_w : water dynamic viscosity (Ns/m^2)
P_c : capillary pressure (Pa)
S : saturation

Free water saturation is showed in Equation 3. In this paper, fiber saturation point is assumed to be 0.3.

$$S = \frac{m - m_{FSP}}{m_{\max} - m_{FSP}} \qquad m > m_{FSP} \tag{3}$$

Maximum moisture content $M_{\max}$ (Wood Handbook, 1999) for any specific gravity can be calculated from Equation 4.

$$m_{\max} = 100(1.54 - G_0)/1.54G_0 \tag{4}$$

G_0 is basic specific gravity based on oven dry weight and green volume. 1.54 is specific gravity of wood cell walls (Skaar, 1988).

From the Equation 2, the coefficient of liquid water diffusivity in wood, we can see three parameters, such as absolute and relative permeability and capillary pressure-saturation relation, need to be known. The absolute permeability of Chestnut is based on the Carman-Ergun equation which is used widely for the permeabilityof uniformly sized spheres (Lago *et al*., 2001).

$$K_a = \frac{1}{180}\frac{\phi^3}{(1-\phi)^2}d^2 \tag{5}$$

where ϕ : porosity; d : diameter (m)

Relative permeability of a material is equal to unity when the fluid saturates the material completely. In this study, we adapt the Mualem model (*p = 0.5, q = 1.0, r = 2*) (Mualem, 1986). From Equation 6, we can see the relative permeability can be estimated if the capillary pressure-saturation relation (CSR) is known.

$$K_r = S^p\left(\frac{\int_0^S P_c(S)^{-q}\,dS}{\int_0^1 P_c(S)^{-q}\,dS}\right)^r \tag{6}$$

Wood is an anisotropic material, but the relative permeability may not depend on the structuraldirection because the CSR is not dependent on the structural direction of test samples. The relation of capillary pressure and saturation in here is based on an empirical equation 7 (Perre *et al*., 1991).

$$P_c = J(S)\times\sigma\times\sqrt{\frac{\phi}{K_a}} \tag{7}$$

$$J(S) = \frac{a_1}{S-a_2} + \frac{a_3}{S+a_4} - a_5\times S + a_6 \tag{8}$$

The function *J(s)* depends on the mathematical formulation which was used to fit the experimental data. The surface tension of water (σ) at 25° Celsius is 71.97 × 10^{-3} N/m. a_1 to

a_6 are parameters. The specific value is a_1 = 0.009547 a_2 = 1.028 a_3 = 0.020023 a_4 = 0; a_5 = 0. 12; a_6 = 0.4415.

2.2.2. Below Fiber Saturation Point

2.2.2.1. Water Vapor Diffusion Coefficient

D_{va} is bulk binary diffusivity of water vapor in air which can be described by Equation 9 (Dushman *et al.*, 1962).

$$D_{va} = 2.2\times10^{-5}\left(\frac{1.013\times10^{5}}{P}\right)\cdot\left(\frac{T}{273}\right)^{1.75} \quad (9)$$

where P : total pressure of air and water vapor (Pa); T : temperature (K)

The water vapor diffusivity coefficient of air-in the lumens based on the concentration of bound water in the cell wall is calculated from Equation 10 (Siau, 1995).

$$D_v = \frac{D_{va}}{\rho_W}\frac{M_v p_{vs}}{RT}\frac{\partial h}{\partial m} \quad (10)$$

where M_v : molecular weight of water vapor (kg/mol); ρ_W : wood density (kg/m^3); P_{vs} : saturation vapor pressure (Pa); h : relative humidity

From Equation 10, we should decide the sorption isotherm of wood. There are lots of sorption models in wood. In general, they are grouped into four categories, based on the physical models assumed in their derivations. These are: localized monolayer sorption models, multilayer sorption models, sorption models used in polymer science, and empirical models (Skaar, 1988). That model, which was simplified by Simpson (1973), is used in this study.

$$m = \frac{1800}{W}\left(\frac{kh}{1-kh}+\frac{k_1kh+2k_1k_2k^2h^2}{1+k_1kh+k_1k_2k^2h^2}\right) \quad (11)$$

$$W = 349 + 1.29T + 0.0135T^2 \quad (12)$$

$$k = 0.805 + 0.000736T - 0.00000273T^2 \quad (13)$$

$$k_1 = 6.27 - 0.00938T - 0.000303T^2 \quad (14)$$

$$k_2 = 1.91 + 0.0407T - 0.000293T^2 \quad (15)$$

2.2.2.2. Bound Water Diffusion Coefficient

The bound water diffusion coefficient in the transverse direction can be estimated by Equation 16. Bound water diffusion coefficient was first measured by Stamm (1959) in the longitudinal direction after sealing off the lumens with molten bismuth. Siau (1984) converted it to the diffusion coefficient of the cell wall in the transverse direction, and obtained the Arrhenius-type equation with the least-square method.

$$D_{bT} = 7\times10^{-6}\exp\left[-\left(38500-29000m\right)/RT\right] \quad (16)$$

Stamm (1960) reportedthat the longitudinal bound water diffusion coefficient of the cell wall is two or three times that in the transverse directions with the radial value being 17% to 25% greater than the tangential. Assuming an average ratio of 2.5, the following relationship can be assumed.

$$D_{bL} = 2.5D_{bT} \quad (17)$$

2.3. Mass Transfer Model

Material properties determined by wood structure models can be applied over a wide

Table 1. Resistance of each element

Resistance	Expression	Direction	Specific Length
r1: side wall	$r_1 = \frac{1}{D_{bT/bL}} \cdot \frac{L_1}{A_1}$ (19)	Longitudinal, Radial, Tangential	A1 = (1-porosity) × 20 × 20 mm^2; L1 = 20 mm
r2: lumen	$r_2 = \frac{1}{D_{v/w}} \cdot \frac{L_2}{A_2}$ (20)	Longitudinal, Radial, Tangential	A2 = porosity × 20 × 20 mm^2; L2 = 20 mm
r3: ray	$r_3 = \frac{1}{D_{v/w}} \cdot \frac{L_3}{A_3}$ (21)	Longitudaial, Radial	A3 = 20 × ray width mm^2; L3 = 20 mm
		Tangential	A3 = 20 × 20 mm^2; L3 = ray width mm

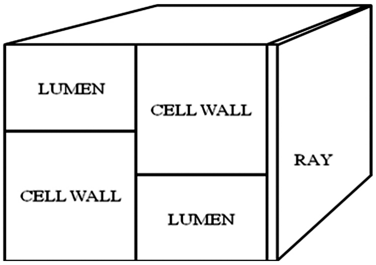

Fig. 2. Longitudinal mass transfer model of chestnut.

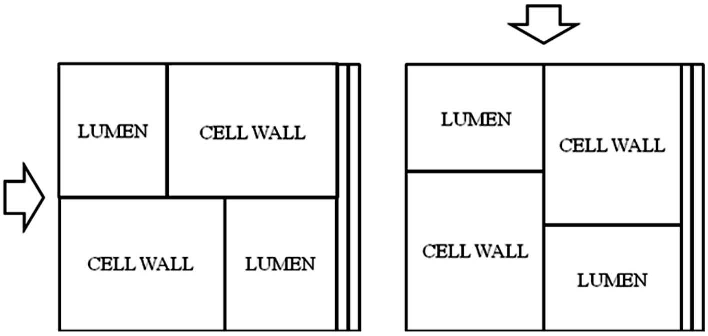

Fig. 3. Tangential and radial mass transfer model of chestnut.

range. Modeling physical phenomena based on the micro scale structure observation makes that possible. The geometric models for the mass transfer in wood proposed in this study are based on the consideration of earlywood, intermediate wood, and latewood percentage and arrangement in an annual ring. One annual ring in chestnut is divided into three zones depending on the porosity. Porosity of the three zones is 31, 40 and 51% respectively. Each ratio of zone in one annual is equal to 1/3. The width of ray cells also was measured by image processing. The mean value of width is 7.7 μm.

That wood cell components offer several re-

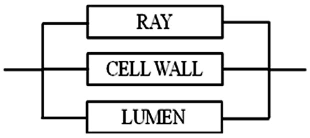

Fig. 4. Electrical analog model of longitudinal direction.

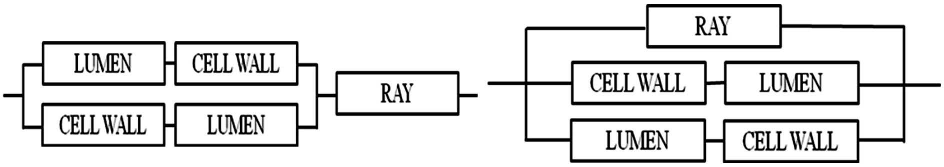

Fig. 5. Electrical analog model of tangential and radial direction.

sistances to moisture movement is analogous to an electrical circuit. This kind of theoretical diffusion coefficient determination is not a new concept. Determine diffusion coefficients from theoretical means by combining the contributions to moisture movement of the various structural components of wood.

The conductivity which is equal to diffusion coefficient in this paper is defined by Equation 18.

$$K = \frac{1}{r} \cdot \frac{L}{A} \tag{18}$$

Here, K is the conductivity (m^2/s), r is the resistance, L is the length in the flux direction, and A is the cross sectional area perpendicular to the flux direction. The size of the model which was calculated in this paper was 20 × 20 × 20 mm. So the L is 20 mm and A is 400 mm^2. r contains three different anatomical elements (Table 1). Thediffusion coefficients are based on theoretical results discussed in 2.2.

In chestnut, we only consider the cell wall, lumen, and ray elements. The mass transfer models for the chestnut longitudinal, tangential and radial structure are shown in Figs. 2 and 3. From the Figs, we can see the models are designed by cell wall percentage in each of the directions. Thegeometric model was set up by moving all the cell walls together on one side, and all the lumens together on the other side. Fig. 4 shows an electrical analog model of longitudinal direction. The total resistance of this direction can be calculated by Equation 22.

$$r_L = \frac{1}{\frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3}} \tag{22}$$

When the moisture transfers in tangential and radial directions, it passes the cell wall, lumen and ray. In the tangential direction, ray cells are a series, in the radial direction, ray cells are a parallel (Fig. 5).

The resistance of each direction is can be calculated by Equation 23 and 24.

$$r_T = \frac{1}{\frac{1}{r_1 + r_2} + \frac{1}{r_1 + r_2}} + r_3 \tag{23}$$

$$r_R = \frac{1}{\frac{1}{r_1 + r_2} + \frac{1}{r_1 + r_2} + \frac{1}{r_3}} \tag{24}$$

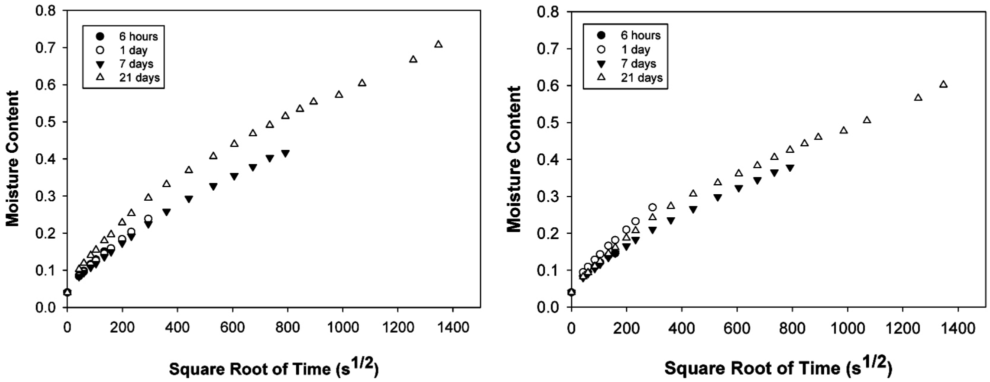

Fig. 6. Changes of moisture content with square root of time (Longitudinal direction of sapwood and heartwood).

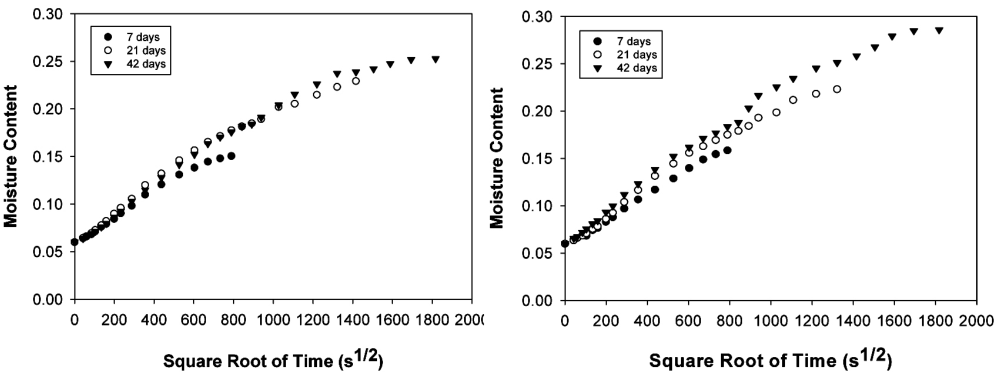

Fig. 7. Changes of moisture content with square root of time (Tangential and radial direction of sapwood)

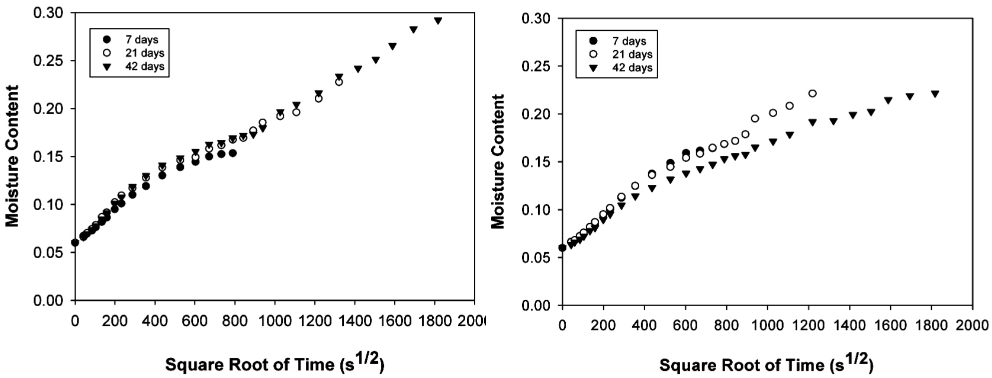

Figure 8. Changes of moisture content with square root of time (Tangential and radial direction of heartwood).

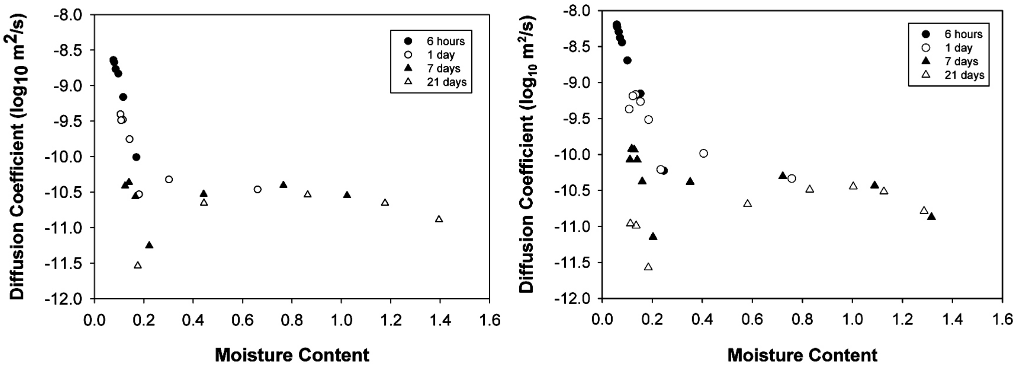

Fig. 9. Longitudinal diffusion coefficient of sapwood and heartwood.

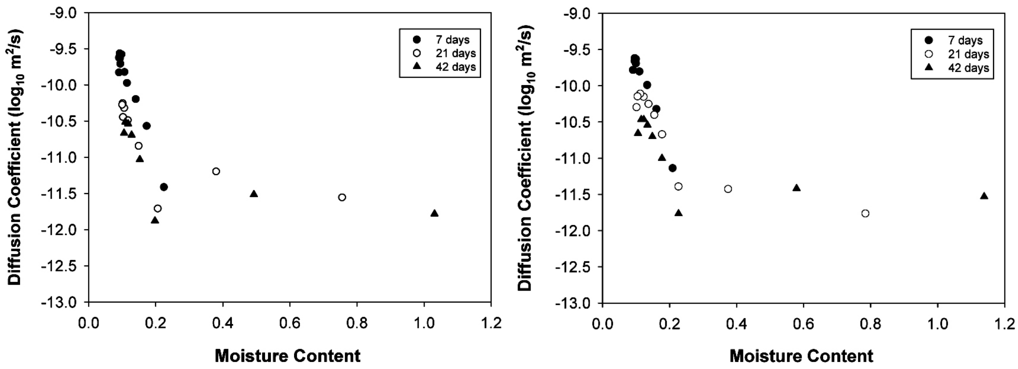

Fig. 10. Tangential and radial diffusion coefficient of sapwood.

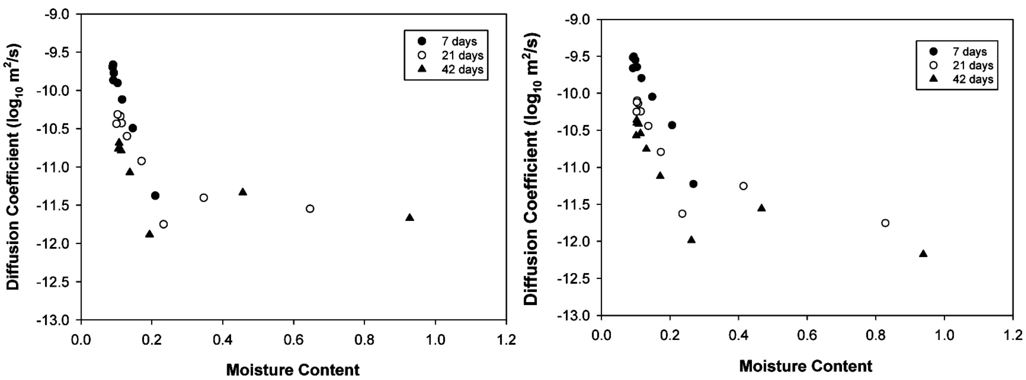

Fig. 11. Tangential and radial diffusion coefficient of heartwood.

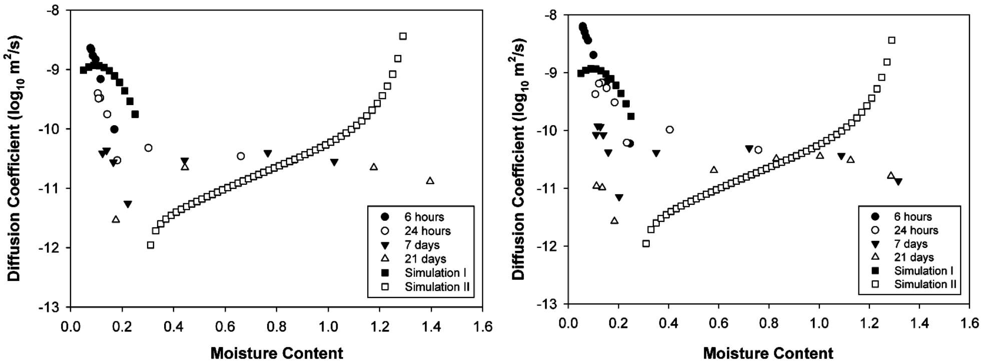

Fig. 12. Comparison between experiment and simulation results (Longitudinal diffusion coefficient of sapwood and heartwood.

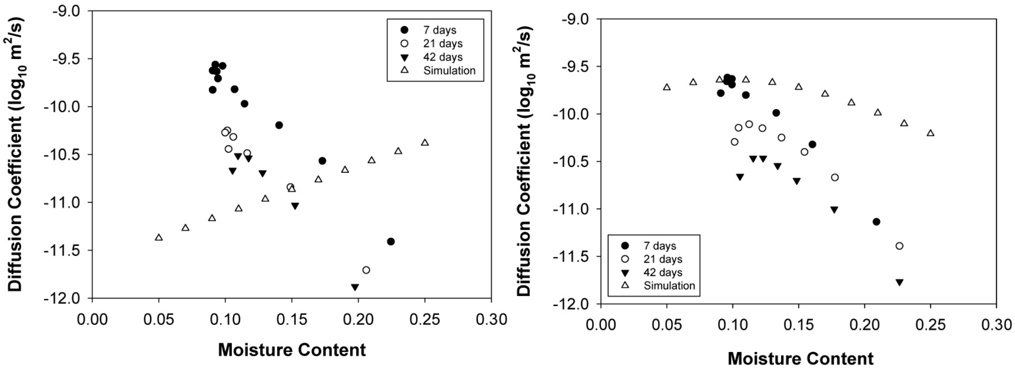

Fig. 13. Comparison between experiment and simulation results (Diffusion coefficient of tangential and radial direction of sapwood)

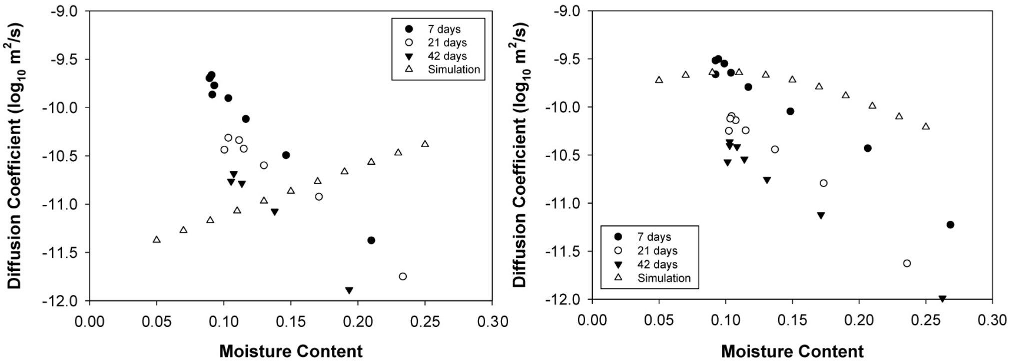

Fig. 14. Comparison between experiment and simulation results (Diffusion coefficient of tangential and radial direction of heartwood)

3. RESULTS and DISCUSSION

3.1. Experimental Results

Figs. 6 to 8 show the correlation between moisture flux and square root of time. Only the longitudinal direction exceeds the fiber saturation point. All the results show the linear correlation between moisture flux and the square root of time. Mass transfer in the tangential and radial direction was so slow that the moisture content was still less than the fiber saturation point even after 42 days.

Figs. 9 to 11 show chestnut diffusion coefficients based on experiment. There are similar results between tangential and radial direction. Also, there is not an obvious difference between sapwood and heartwood.

3.2. Comparison between Experimental and Theoretical Results

Figs. 12 to 14 show comparison results of experiment and simulation. Chestnut simulation is not considered any of the apertures. However, from the experimental results, the apertures in hardwood were not supposed to be ignored, especially in the tangential direction. Because of the neglect of the apertures, tangential diffusion contains only bound water diffusion. Chestnut is not as impacted by the heartwood and sapwood difference. From the experimental results, the diffusion coefficients had a regular tendency during the time elapse. So the impact of time should be considered in the modeling process.

4. CONCLUSIONS

Theoretical mass transfer coefficients and the moisture movement model based on microscopic structure were used to calculate mass transfer coefficients theoretically. The theoretical mass transfer coefficients were compared to experimental results. The theoretical mass transfer coefficients are not easy to determine. Even though the mathematical expressions are based on physical laws, the parameters which were used in these expressions were decided by empirical study. Therefore, there are limitations to using these parameters directly. It is necessary to understand the limitations of parameters and consider the particular situation to be simulated. In hardwood, because the apertures were not considered, tangential mass transfer simulation was totally different from experiment. As a result, a hardwood model design should consider the apertures which are even on the fiber walls.

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