Mokchae Konghak 34(5) : 98~103, 2006

Evaluation of Diffusibility of Boron in Wood under Water Leaching Conditions[*1]

Jong-Bum Ra[*2†] and Gyu-Hyeok Kim[*3]

ABSTRACT

Radial and tangential diffusion coefficients of boron in wood under water leaching conditions were determined from the change of concentration profiles of boron. Egner's solution was used to obtain variable diffusion coefficients of boron because it has been known to be the only method to determine variable diffusion coefficients with no cumbersome assumption. The values of diffusion coefficients were between 0.18×10^{-6} cm^2/sec and 25.6×10^{-6} cm^2/sec. They increased with the increase of sample thicknesses, and decreased with the increase of leaching times. There was a region where Egner's method was not valid. However, Egner's solution illustrates a convenient way to evaluate diffusion characteristics of boron from wood under water leaching conditions. The diffusion coefficients at wood surface may be regarded as leaching coefficients.

Keywords : boron, diffusion coefficient, leaching coefficient, Egner's method

1. INTRODUCTION

Leaching of boron from wood is a very complex process. Factors such as moisture content (MC), temperature, specific gravity, diffusion direction, and the magnitude of concentration gradients which exist in wood affect the rate of boron movement during the leaching process. At an initial stage of a leaching process, water comes into wood and the boron molecules existing in wood start moving randomly from a region of higher concentration to a region of lower concentration through the free and bound water in wood. Since the moisture content of wood is changing continuously until wood is saturated with water, the boundary conditions of boron diffusion continuously vary.

The most convenient way to describe quantitatively the leaching characteristics is to determine boron diffusion coefficients under water leaching conditions. Most solutions to determine diffusion coefficients assume that diffusion coefficients are constant (Crank 1975). However, this assumption may not be applicable for boron leaching conditions because the profiles of MC and boron concentration vary until the leaching

*1 Received on February 15, 2006; accepted on May 3, 2006.
*2 Department of Interior Materials Engineering, Jinju National University, Jinju, Kyungnam 660-758, Korea
*3 Division of Environmental Science and Ecological Engineering, Korea University, Seoul 136-701, Korea
† Corresponding author : Jong-Bum Ra (jb@jinju.ac.kr)

process is over. The differential equation for unsteady-state diffusion with variable diffusion coefficients is shown in equation (1).

$$\frac{\partial C}{\partial t} = \frac{\partial (D\frac{\partial C}{\partial x})}{\partial x} \quad (1)$$

where: C = the concentration of diffusion substance (w/w %); t = diffusion time (sec); D = diffusion coefficients (cm^2/sec); and x = the thickness of sample in the direction of diffusion (cm).

Equation (1) can be reduced to Fick's second law when the values of diffusion coefficients are constant. But for the case where the diffusion coefficients are expressed by the function of concentration or distance, no general solution for equation (1) has been found (Skaar 1954, Crank 1975). The only mathematical solution to Fick's second law with variable diffusion coefficients is Egner's solution, which shown in equation (2).

$$D = \frac{\frac{\partial (\int_0^x C dx)}{\partial t}}{\frac{\partial C}{\partial x}} \quad (2)$$

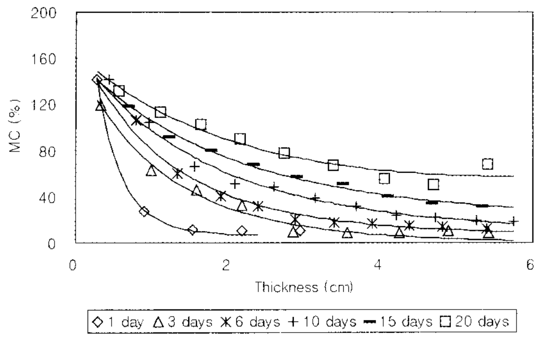
Egner's approach has been known to be more accurate than the other solutions of Fick's second law and can be applicable in any diffusible system (Ra and Barnes, 1999; Ra *et al.*, 2001). In this research, the radial and tangential diffusion coefficients of boron in wood under water leaching conditions were determined using Egner's solution.

2. MATERIALS and METHODS

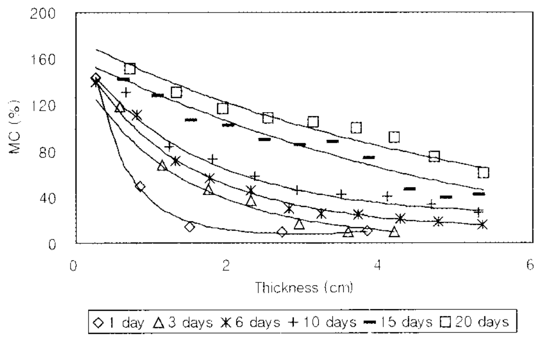
Radiata pine (*Pinus radiata* D. Don) lumber was cut into defect-free sapwood samples (nominal 5-cm by 5-cm by 6-cm long). The end-matched samples were prepared to minimize sample variation, and they were treated with water under full vacuum for 24 hours and then stored under distilled water until they reached 140% moisture content (MC). The samples were dip-treated for five minutes with 25% boric acid equivalent (BAE) Timbor® solution [disodium octaborate tetrahydrate (DOT, $Na_2B_8O_{13} \cdot 4H_2O$)] at 50°C. The ratio of solution to specimen volumes was large enough that these dip treatments did not materially affect the solution concentration.

The treated samples were stored at room temperature under non-drying conditions for six months. After six months, three samples were analyzed to investigate whether or not the samples reached concentration equilibrium. Since the concentration was in the range of 0.9 ± 0.02% BAE, all samples were regarded to reach concentration equilibrium. The samples were dried very carefully to minimize the occurrence of checking or any drying defects. Samples with any drying defect were not used for this research. The final MCs of samples were approximately 10%. The dried samples were coated using silicone sealant except only one of the surfaces of samples to restrict the boron leaching direction. A tangential surface was not coated for boron leaching only in the radial direction, and an outer radial surface for the tangential direction.

The samples were immersed under distilled water at 20°C for 1, 3, 6, 10, 15, and 20 days. The distilled water in the container was changed every 6 hours for 3 days and then changed everyday. As leaching times passed, the samples were trimmed with a band saw to remove silicone coating on the wood surface, and then they were sliced into approximately 5-mm-thick wafers. Slicing was perpendicular to the flow direction of boron. From the obtained slices, MC and concentration profiles

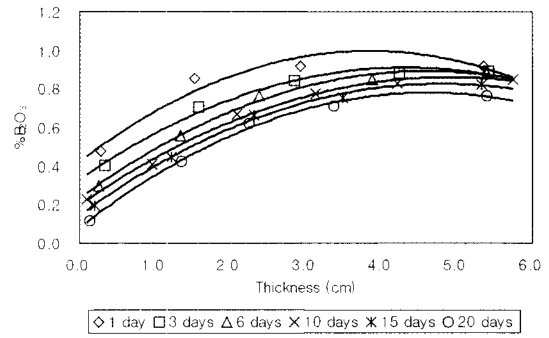


(A) Tangential direction

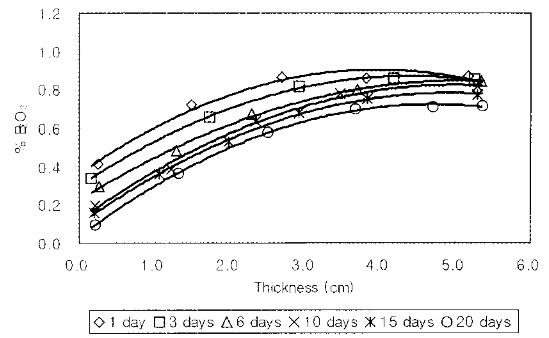


(B) Radial direction

Fig. 1. Moisture content profiles of wood under water leaching conditions in the tangential (A), and radial (B) directions.



(A) Tangential direction



(B) Radial direction

Fig. 2. Concentration profiles of boron in wood under water leaching conditions in the tangential (A), and radial (B) directions.

were measured. The slices were weighed to 0.01g on an analytical balance and oven-dried in their respective bottles at 103±2°C. The oven-dried slices were ground to 20 mesh and the boron content was determined using an azomethine-H method according to the American Wood-Preservers' Association standard A2-94 (AWPA, 1997). Then the variable diffusion coefficients were determined using Egner's solution. More detailed explanation about Egner's solution can be found in the literature (Skaar, 1954; Ra and Barnes, 1999; Ra *et al.*, 2001).

3. RESULTS and DISCUSSION

The changes of moisture content profiles with the increase of leaching times are shown in Fig. 1. As expected, MC increased as leaching times passed. Increase of MC in the radial direction appeared to be a little faster than in the tangential direction and the flow rates of water into the wood appeared to be proportionally increased with time. The change of boron concentration profiles were shown in Fig. 2. The radial direction showed a little faster leaching of boron than the tangential direction did, but the differences were slight. A little faster leaching of boron in the radial direction is related with a little faster increase of MC in the radial direction than in the tangential direction. Diffusion direction is one of the factors to affect the rate of boron diffusion because of the different anatomical characteristics of each direction. In the radial direction, the ray cells

Table 1. Variable diffusion coefficients determined using Egner's solution

Leaching direction	Thickness	Leaching periods (day)					
		1	3	6	10	15	20
	(cm)	----------------($\times 10^{-6}$ cm^2/sec)----------------					
Tangential	0.5	0.57[*1]	0.51	0.42	0.34	0.26	0.19
	1.0	1.18	1.08	0.95	0.79	0.63	0.51
	1.5	1.99	1.85	1.66	1.42	1.18	0.98
	2.0	3.19	2.99	2.71	2.38	2.02	1.71
	2.5	5.37	5.06	4.63	4.12	3.55	3.07
	3.0	9.46	8.98	9.30	7.48	6.57	5.77
	3.5	25.70	24.50	22.80	20.72	18.40	16.40
Radial	0.5	0.71	0.61	0.50	0.37	0.26	0.18
	1.0	1.38	1.24	1.06	0.85	0.65	0.50
	1.5	2.23	2.04	1.79	1.59	1.22	0.98
	2.0	3.43	3.19	2.86	2.47	2.06	1.71
	2.5	5.37	5.04	4.59	4.04	3.45	2.94
	3.0	9.23	8.76	8.03	7.17	6.23	5.41
	3.5	21.40	20.30	18.81	17.00	14.97	13.18

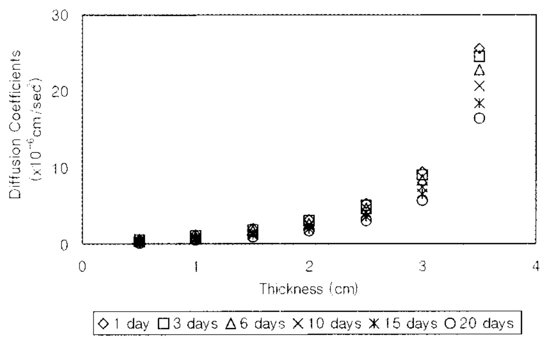
[*1] Each value is the average of three replicates.

offer more feasible pathways of water that is the medium for boron diffusion. Previous studies of boron diffusion have reported that under high MC conditions (above 70% MC), the radial diffusion coefficients of boron in wood were 2 to 4 times larger than the tangential diffusion coefficients (Ra *et al.*, 2001).

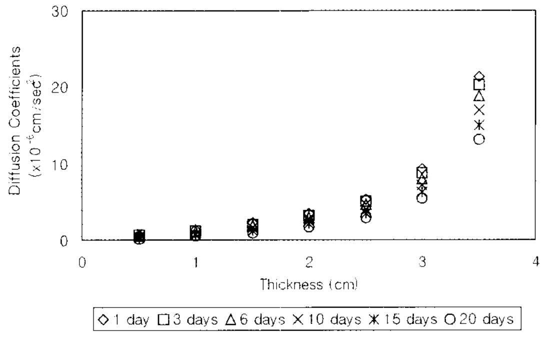
From the obtained concentration profiles of boron, variable diffusion coefficients were determined using Egner's solution (Table 1). The concentration profiles of boron were fitted using polynomial functions and the values of R-square of each equation were above 0.9, suggesting that this equation properly fit the data.

The values of tangential diffusion coefficients calculated by Egner's solution were between 0.19×10^{-6} cm^2/sec and 25.6×10^{-6} cm^2/sec. The radial diffusion coefficients were between 0.18×10^{-6} cm^2/sec and 21.4×10^{-6} cm^2/sec. The diffusion coefficients steadily increased with the increase of diffusion distances. But rapidly increasing values were observed in the area where the slope of boron concentration profiles was small. This indicates that Egner's solution is not valid in areas where the slope of the concentration-distance curves approaches zero.

Fig. 3 shows the effect of diffusion distances on the diffusion coefficients of boron in the tangential and radial directions. Near the surface contacting with water, boron diffusion coefficients tended to be stable. This may be explained by the wood surface saturated with water, resulting in little change in the boundary conditions affected by water, the medium for boron diffusion. Figure 4 shows the effect of diffusion times on the boron diffusion coefficients at the wood surface. Because the diffusion coefficients could not be determined at wood surface in this research, the diffusion

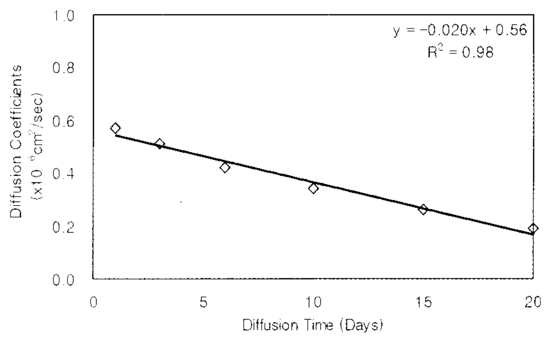


(A) Tangential direction

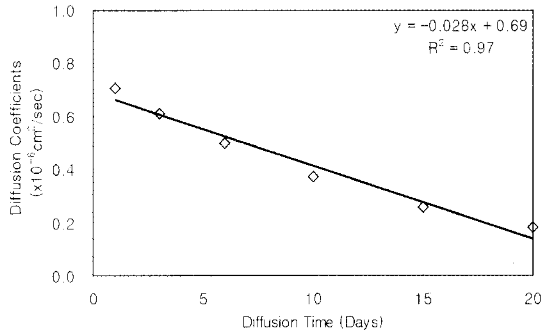


(B) Radial direction

Fig. 3. Effect of diffusion distance on boron diffusion coefficients in the tangential (A), and radial (B) directions.



(A) Tangential direction



(B) Radial direction

Fig. 4. Effect of diffusion time on boron diffusion coefficients at wood surface in the tangential (A), and radial (B) directions.

coefficients determined at 0.5-cm distance from the wood surface were regarded as the diffusion coefficients at wood surface. The values of diffusion coefficients were between 0.18×10^{-6} cm^2/sec and 0.71×10^{-6} cm^2/sec. Although MC conditions were continuously changing with the influx of water into wood, linear relationships between diffusion time and diffusion coefficients were observed in both directions. The diffusion coefficients at the wood surface with maximum MC conditions may be called leaching coefficients.

4. CONCLUSIONS

The tangential and radial diffusion coefficients for boron were determined using Egner's solution. Although the leaching of boron was tended to be a little faster in the radial directions than the tangential directions, the differences were slight. In both directions, the diffusion coefficients increased with the increase of thicknesses and decreased with the increase of diffusion times. Linear relationships between diffusion times and diffusion coefficients were observed at the wood surface. The diffusion coefficients of boron at the wood surface may regarded as leaching coefficients.

REFERENCES

1. American Wood-Preservers' Association (AWPA). 1997. Book of standards. Standard A2-94. standard methods for determining penetration of

preservatives and fire-retardant. AWPA, Granbury, TX.
2. Crank, J. 1975. The mathematics of diffusion. Oxford Univ. Press, New York, p. 414.
3. Ra, J. B. and H. M. Barnes. 1999. A method for determining boron diffusion coefficients in wood IRG/WP 99-30200. The Inter. Research Group on Wood Preservation, Stockholm, Sweden.
4. Ra, J. B., H. M. Barnes, and T. E. Conners. 2001. Determination of boron diffusion coefficients in wood. Wood and Fiber Sci. 33(1): 90～103.
5. Skaar, C. 1954. Analysis of methods for determining the coefficients of moisture diffusion in wood. Foest Prod. J. 4(12): 403～410.