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Humidity Control Efficiency of Low-Density Particleboards for Interior Walls III.†

Moisture absorption rates and moisture conductivities*1

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低密度パーティクルボードの調湿性能（第3報）†

吸湿速度と湿気伝導率*1

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市販の低密度パーティクルボード（LDPB），木材羽目板（WLB），および実験室製ボードに対し，調湿性能の指標となる吸湿速度（V_a），湿気伝導率（λ'）を比較する目的で，吸湿試験と材内熱湿気移動のシミュレーションを行った。その結果，WLBと比較すると，LDPBは1.9倍のV_a，4.3倍のλ'を示し，また吸湿量の95%を占めるボード表面からの深さ（d_{95}）はWLBの1.6倍と計算された。これらの結果は，LDPB内の水蒸気拡散の経路がWLBに比べ大きくかつ連続性に富むことを示唆し，また，第1報に示したWLBよりも大きな調湿効果を説明するのに役立つ。一方，820 kg/m³から540 kg/m³への密度低下により，V_a，λ'，d_{95}はそれぞれ，1.7，4.7，2.1倍に増加した。低密度化は湿気容量の低下というマイナス要因を伴うが，粗空隙量の増大がもたらす著しいλ'の増加はそれを十分に補うことが示唆された。またシミュレーションにおいて，湿気容量を一定値ではなく湿度の関数として扱う方が熱湿気移動の推定に有利であることがわかった。

A moisture absorption test and a number of simulations predicting the heat and moisture transfer in a board were conducted for a low-density particleboard (LDPB), a wood lining board (WLB), and some laboratory particleboards. The moisture absorption rate (V_a), the moisture conductivity (λ'), and the moisture content profile of each board type were calculated and compared.

LDPB was more hygroscopic than WLB in that its V_a was calculated to be 1.9 times larger, its λ' 4.3 times greater, and its d_{95} (the depth from the board surface which accounts for 95% of the moisture absorbed) 1.6 times larger. These values help explain the superior performance of the LDPB over the WLB for humidity control as described in the first paper of this series. These differences suggest that the vapor diffusion paths are larger and more continuous in LDPB than those in WLB. A reduction in density from 820 kg/m³ to 540 kg/m³ increased V_a 1.7 times, λ' 4.7 times, and d_{95} 2.1 times. These results suggest that it is the void volumes which determine the penetration of moisture into a board, and that a greater permeability can more than compensate for a decrease of moisture capacity. Treating moisture capacities as a function of humidity for the simulation was found useful in predicting heat and moisture transfers.

Keywords: low-density particleboard, moisture conductivity, moisture absorption rate, heat-and-moisture transfer.

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1. INTRODUCTION

The first paper[1] in this series discussed the superior performance of low-density particleboards (LDPB) over wood lining board (WLB) for humidity control. The superiority of LDPB is considerd to be derived from its greater moisture permeability which allows rapid rates of adsorption and desorption. To confirm this, the moisture capacity and moisture conductivity of the two products was required. The moisture capacities of these two products were measured, then discussed in the previous paper.[2] In the work reported in this paper, the moisture conductivities of these two products, and some laboratory prepared particleboards, are determined by moisture absorption tests and various computer models.

2. EXPERIMENT

2.1 Materials

Table 1 summarizes the characteristics of the boards used. Refer to the previous paper[2] for details on the specifications of laboratory prepared particleboards.

2.2 Moisture absorption tests

Samples, 250 mm by 250 mm in size, were prepared for each board type; two for each laboratory board and three for the LDPB and the WLB.

Using the apparatus shown in Fig. 1, the moisture absorption responses to a specific increase in relative humidity (RH) were measured at a constant temperature for each board type. Each sample was allowed to absorb moisture only through its top surface.

The procedure for the test was as follows: The samples were equilibrated in the test chamber set at 20°C and 50% RH (7 days at most). The RH then was increased to 70%, this took about twenty minutes. The moisture absorption response was measured for 6 hours for the WLB and the LDPB, and 24 hours for the other materials. The experiment was repeated six times for the WLB and the LDPB, and twice for the other materials.

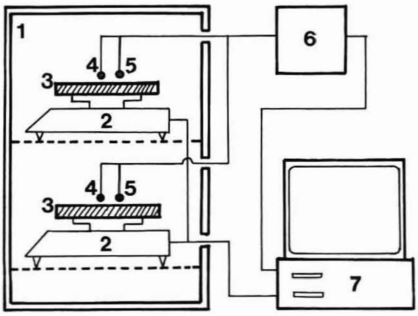

Fig. 1. An apparatus used for the moisture absorption test.

Legend: 1: Temperature and humidity test chamber (Isuzu Co., Ltd., Type μ-2001), 2: Balance (accurate to 10 mg), 3: Specimen, 4: Thermocouple (Type-T), 5: Humidity sensor (Vaisala Co., Ltd., HMW-20U), 6: AD converter and thermocouple signal amplifier, 7: Computer to record the temperature, relative humidity, and weight data.

Note: All specimen faces, except their top surfaces, were covered with aluminum foil and insulated with 10 mm thick styrofoam.

The surrounding air temperatures and RHs were monitored at 1 cm above each specimen and were used as boundary condition data. RHs before and after its change are shown in Table 3. The variation in temperature was 20±0.1°C throughout the tests. The wind velocity parallel to the top surface was measured at the same point with a hot-wire anemometer, and it was approximately 0.3 m/s. This value was

Table 1. Characteristics of the boards used.

Boards	Symbols	Thicknesses (mm)	Densities[a] ρ (kg/m^3)	Thermal conductivities[b] λ (kcal/mh°C)	Comments
Wood lining board	WLB	14	430	0.091	Japanese red pine (*Pinus densiflora* S. and Z.)
Low-density particleboard	LDPB	25	520	0.084	Bonded with isocyanate resin
Laboratory particleboards	PF5	10	535	0.085	Bonded with phenol-formaldehyde resin
	PF8	10	815	0.11	
	IC5	10	545	0.086	Bonded with isocyanate resin
	IC8	10	825	0.11	

[a] Values measured at 20°C, 60% RH. [b] Values measured at 20°C and about 10% moisture content.

used to determine coefficients of heat and moisture transfer at the boundary layer.

2.3 Simulation methods

2.3.1 Basic equations

The one-dimensional heat and moisture transfer model developed by Matsumoto[3] was used. This model is expressed by the following simultaneous equations for unsteady heat and moisture flow.

$$\frac{\partial X}{\partial t}=a\frac{\partial^2 X}{\partial x^2}+b\frac{\partial \theta}{\partial t} \quad (1)$$

$$\frac{\partial \theta}{\partial t}=c\frac{\partial^2 \theta}{\partial x^2}+d\frac{\partial X}{\partial t} \quad (2)$$

where $a=\lambda'/(C'\rho'+\kappa)$, $b=\nu/(C'\rho'+\kappa)$, $c=\lambda/(C_s\rho+r\nu)$, $d=r\kappa/(C_s\rho+r\nu)$, X is absolute humidity, θ is temperature, x is position coordinate, and t is time coordinate. Other symbols represent physical property constants and are listed in Tables 1 and 2 with their values as used in this experiment. The moisture conductivity, λ', used in Equaton 1, is defined by $J=-\lambda'\Delta X$, where J is moisture flux (kg/m^2) and ΔX is the absolute humidity gradient ((kg/kg of dry air)/m).

The boundary conditions of heat and moisture transfer at the top ($x=0$) and bottom ($x=l$) surface are expressed as below:

$$-\lambda d\theta/dx|_{x=0}=\alpha(\theta_a-\theta_s) \quad (3)$$

$$-\lambda' dX/dx|_{x=0}=\alpha'(X_a-X_s) \quad (4)$$

$$-\lambda d\theta/dx|_{x=l}=0 \quad (5)$$

$$-\lambda' dX/dx|_{x=l}=0 \quad (6)$$

where the subscripts a and s specify the air outside the boundary layer and on the surface of the sample, respectively. See Table 2 for definitions of α and α'.

2.3.2 Difference equations

The finite difference equations in an explicit solution for Equations 1 and 2 can be expressed as follows; respectively:

$$\theta_{m,n+1}-dX_{m,n+1}$$
$$=p\theta_{m+1,n}+(1-2p)\theta_{m,n}+p\theta_{m-1,n}-dX_{m,n} \quad (7)$$

$$X_{m,n+1}-b\theta_{m,n+1}$$
$$=p'X_{m+1,n}+(1-2p')X_{m,n}+p'X_{m-1,n}-b\theta_{m,n} \quad (8)$$

where $X_{m,n}$ and $\theta_{m,n}$ are absolute humidity and temperature at $x=m\Delta x$ (m=0, 1, 2, ⋯, M) and $t=n\Delta t$ (n=0, 1, 2, ⋯), respectively;

p is $c\Delta t/\Delta x^2$, p' is $a\Delta t/\Delta x^2$, Δx and Δt are distance and time increments, respectively.

The Equations 3 and 5 on heat flow can be expressed as follows, respectively:

$$\theta_{1,n}-\theta_{-1,n}=-2\Delta xh(\theta_{a,n}-\theta_{0,n}) \quad (9)$$

$$\theta_{M+1,n}=\theta_{M-1,n} \quad (10)$$

where $h=\alpha/\lambda$ and $\theta_s=\theta_0$. Substituting Equation 9 into Equation 7, and Equation 10 into Equation 7, the difference equations for the boundary conditions are obtained as follows, respectively:

$$\theta_{0,n+1}-dX_{0,n+1}$$
$$=2p\theta_{1,n}+(1-2p-2p\Delta xh)\theta_{0,n}+2p\Delta xh\theta_{a,n}-dX_{0,n} \quad (11)$$

$$\theta_{M,n+1}-dX_{M,n+1}$$
$$=(1-2p)\theta_{M,n}+2p\theta_{M-1,n}-dX_{0,n} \quad (12)$$

Similarly, the difference equations for Equations 4 and 6 are obtained as follows, respectively:

$$X_{0,n+1}-b\theta_{0,n+1}$$
$$=2p'X_{1,n}+(1-2p'-2p'\Delta xh)X_{0,n}+2p'\Delta xh'X_{a,n}$$
$$-b\theta_{0,n} \quad (13)$$

Table 2. The symbols used in the models and their values.

Physical properties	Symbols	Units	Value
Moisture conductivity	λ'	kg/mh (kg/kg of dry air)	Parameter to be determined
Specific heat	C_s	kcal/kg°C	The WLB; 0.37, others; 0.36
Latent heat	r	kcal/kg	650
Air density	ρ'	kg/m^3	1.2[a]
Percentage of voids	C'	m^3/m^3	—[a]
Moisture capacities	$\kappa=\rho\frac{\partial u}{\partial X}$[b]	kg/m^3 (kg/kg of dry air)	See Table 4
	$\nu=\rho\frac{\partial u}{\partial \theta}$[b]	kg/m^3°C	See Table 4
Coefficient of heat transfer	α	kcal/m^{2}h°C	3.5[c]
Coefficient of moisture transfer	α'	kg/m^{2}h (kg/kg of dry air)	14.5[d]

[a] When calculating the coefficients in Eq. 1, the $C'\rho'$ value is ignored because it is quite small compared to κ values. [b] u is equilibrium moisture content on a volume basis (kg/m^3). [c] The value corresponding to the measured wind velocity. [d] The value calculated using Lewis's relation (Ref. 3).

$$X_{M,n+1} - b\theta_{M,n+1} = (1-2p')X_{M,n} + 2p'X_{M-1,n} - b\theta_{0,n} \quad (14)$$

where $h' = \alpha'/\lambda'$ and $X_s = X_0$.

2.3.3 Implementation of the simulation

Using Equations 7, 8, and 11-14, the tepmerature and humidity through the board thickness can be predicted for each time increment by iterative calculations. The sizes of Δt and Δx used were 1×10^{-4} hour and 5×10^{-4} m, respectively, which gave the model adequate stability.

A moisture conductivity was determined by the following procedure: 1) the temperature and humidity of the air measured in the test were enterd into the model as being equivalent to the initial conditions inside a board and the boundary conditions ($\theta_{a,n}$ and $X_{a,n}$); 2) temperature and humidity variations in a board from $t=0$ to 6 hours were predicted by iterative calculations with an approximate value of λ'; 3) the amount of moisture absorption, W_f, was calculated every half hour by the integration of the moisture flux at the boundary layer; 4) the mean squared deviation (MSD) between W_f and the observed data was calculated; 5) the simulation was repeated after changing the value of λ' by 1×10^{-4} or 0.5×10^{-4} (kg/mh (kg/kg of dry air)) until the minimun in the MSD was found.

The moisture capacity values, κ and ν, were chosen carefully because they have a marked affect on the output of the simulation. In the previous paper,[2] the values of κ and ν were found to change with relative humidity changes. Thus, the simulation was conducted for two fixed sets of (κ, ν); one at the initial humidity, the other at the middle of the humidity change.

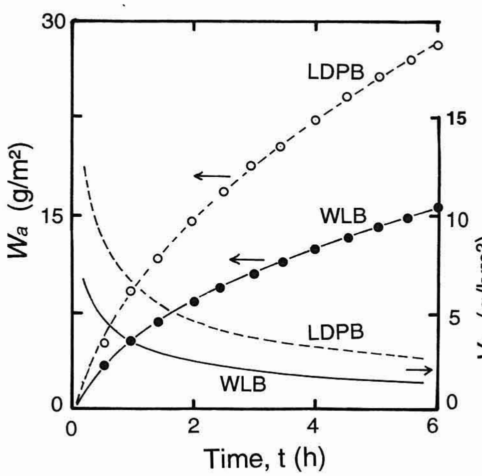

Fig. 2. Variations in moisture absorptions (W_a) and absorption rates (V_a) for LDPB and WLB.
Notes: V_a was obtained by calculating the slope of the W_a-t curves fitted to the data. The data points shown are the average of six replicates.

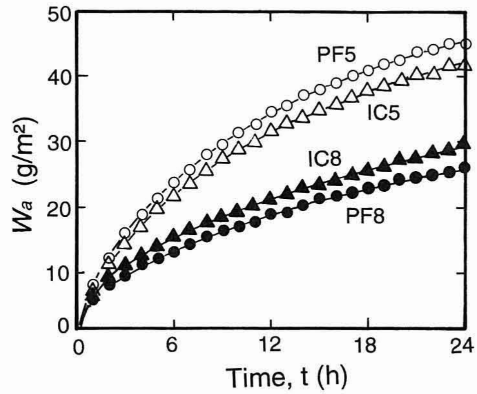

Fig. 3. Variations in moisture absorptions (W_a) of the laboratory prepared particleboards.
Notes: The data points shown are the averages of two replicates. See Table 1 for symbols.

Table 3. The results of the moisture absorption tests.

Boards	Relative humidities (%)		Constants of the regression equations[a]		ΔEMC[b] (%)	W_e[c] (g/m²)	$W_a(t)/W_e\times100$ (%)[d] Times (h)				
	Before	After	A	B			1	3	6	12	24
WLB	53.6	74.5	7.02	−1.68	2.7	145	4	7	11	—	—
LDPB	54.9	76.2	13.20	−4.13	2.2	255	4	7	10	—	—
PF5	49.4	68.9	9.98	−1.89	1.7	83	10	19	27	39	57
PF8	47.5	68.1	5.38	−0.92	1.8	135	3	6	9	13	19
IC5	49.2	68.8	9.21	−2.02	1.6	79	9	18	26	38	55
IC8	47.5	67.9	5.94	−0.26	1.6	119	5	8	12	17	24

[a] Regression coefficients were from 0.994 to 0.999. [b] Differences in equilibrium moisture content (EMC) between before and after the humidity changes. [c] Maximum moisture absorption over test conditions calculated from ΔEMC. [d] A percentage of moisture absorption at t (h) to W_e.

3. RESULTS AND DISCUSSION

3.1 Moisture absorption rates

Moisture absorption, W_a, is expressed as weight per unit of exposed board surface. The regression lines drawn between the data points in Figs. 2 and 3 were calculated using an equation of the formula:

$$W_a = A\sqrt{t} + B \quad (15)$$

Using regression analysis, the equation was found to fit the data, gathered over the time range of this experiment, although this equation makes W_a infinite if we let t approach infinity. The constants calculated are shown in Table 3.

By differentiating Equation 15, the rate of moisture absorption at time t, $V_a(t)$ can be calculated and is equivalent to $A/(2t^{1/2})$. This indicates that the absorption rates of the different specimens can be compared by checking the values of A. This analysis also suggests that V_a decreases with time as shown in Fig. 2.

Obviously, W_a for the LDPB was much greater than that for the WLB as shown in Fig. 2; the LDPB absorbed moisture 1.9 times faster than the WLB. Since, however, these two types of material absorb almost the same amount of moisture per unit volume for the humidity change of this test, as described in the previous paper,[2] then this suggests that moisture penetration into the LDPB is deeper than that of the WLB.

This conclusion also is supported by the fact that these boards showed a similar degree of saturation in moisture absorption, which is expressed by the W_a/W_e ratio in Table 3. If the depth of moisture penetration for the LDPB was equivalent to that for the WLB, then the LDPB would have much smaller W_a/W_e values compared with the WLB.

The effect of board density on moisture absorption rates was remarkable; lower density laboratory prepared boards (540 kg/m³) absorbed moisture 1.55 to 1.85 times (1.7 times on average) faster than the greater density boards. Note that the value of W_a/W_e increased by two to three times. It is likely that the

Table 4. Moisture conductivities (λ') determined by the simulation for various sets of moisture capacities (κ, ν).

Boards	Cases[a]	κ (kg/m³ (kg/kg'))	ν (kg/m³°C)	$\lambda' \times 10^3$ (kg/mh (kg/kg'))	MSD[b] between W_f[c] and W_a[d]	MSD[b] between W_n[e] and W_a[d]	W_n/W_f at t=6 hours
WLB	A	3264	1.58	1.2	0.02	8.87	0.71
	B	2217	1.39	1.8	0.09	1.30	1.14
	C	—	—	1.5	0.04	0.07	0.99
LDPB	A	3171	1.60	5.3	0.03	33.60	0.65
	B	2213	1.28	8.5	0.03	2.09	1.09
	C	—	—	6.5	0.05	1.86	0.91
	D	—	—	6.0	0.03	1.60	0.91
PF5	A	2745	1.44	4.4	0.10	4.42	0.81
	B	2157	1.22	5.6	0.08	0.75	1.03
	C	—	—	5.0	0.09	0.53	0.95
PF8	A	4567	2.44	0.65	0.05	1.78	0.79
	B	3625	1.97	0.80	0.05	0.08	1.04
	C	—	—	0.70	0.03	0.28	0.93
IC5	A	2878	1.71	3.3	0.11	4.04	0.82
	B	2314	1.29	4.2	0.11	0.05	0.99
	C	—	—	3.7	0.10	1.25	0.90
IC8	A	4141	2.24	1.1	0.08	2.35	0.80
	B	3167	1.97	1.5	0.10	1.24	1.11
	C	—	—	1.3	0.09	0.03	0.96

[a] The simulation was conducted for the following four cases: A, fixed values of κ and ν at the middle of the humidity change; B, values fixed at the initial humidity; C, variable values with a within void relative humidity; D, variable values with a density variation in addition to a within void relative humidity. [b] Mean squared deviation. [c] Moisture absorption calculated from the boundary layer moisture flux. [d] Observed moisture absorption. [e] Moisture absorption recalculated *via* moisture content change.

moisture can penetrate the low-density boards more readily because of the greater void volume present.

3.2 Moisture conductivity

Moisture conductivities determined by simulation are listed in Table 4. It is recognized that the value of λ' for each board varies with each set of $(\varkappa, \nu)$ used; smaller $\varkappa$ and ν values gave larger λ' values.

The question is, which of the two sets most closely approximates real heat and moisture transfer rates and the resultant moisture content profiles? To answer this question, moisture absorption responses, under the same set of $\varkappa$, ν, and λ' values, were recalculated by another method. This involved calculating the relative humidity and temperature of each layer within a board, and using these values to predict the moisture content of the layers from the equilibrium moisture content curves shown in the previous paper.[2] These predicted moisture contents were then summed to give an overall change in moisture content for the board (W_n). As shown in Fig. 4 and Table 4, this recalculated value, W_n, did not agree with W_f; it was less than W_f by about 20-30% when the $\varkappa$ and ν values for the intermediate humidity were used, and it was greater than W_f by 14% when the initial humidity values were used (see the ratio of W_n to W_f in Table 4).

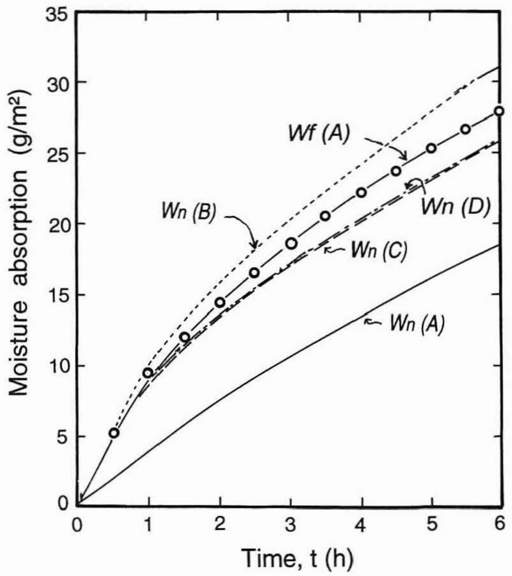

Fig. 4. Variations in moisture absorption with time as predicted by the simulation with various moisture capacities for the LDPB.

Notes: Plots: Measured values. W_f: Values calculated by moisture flux at the boundary layer. W_n: Values calculated by predicted moisture content changes through the board thickness. (A), (B), (C), and (D) shown with W_n classify the moisture capacities used. See Table 4.

The disagreement between the W_f and W_n values probably is caused by the following assumptions in the calculations:

1. The humidity dependence of $\varkappa$ and ν were disregarded.

2. Board density was considered uniform through the board thickness, which, if true, would ensure consistent permeability and moisture capacities through the board.

Futhermore, prediction errors in the equilibrium moisture content used for the calculations of W_n, can cause the disagreement. Essentially, W_n should agree with W_f. However, at the moment, it is appropriate to think that the closer they are, the more reliable is a moisture content profile being discussed.

To reduce the disparity, the simulation treating the moisture capacities as functions of within-void relative humidity was conducted. In this simulation, the values of $\varkappa$ and ν were renewed for each time increment at each differential member, using the moisture capacity curves shown in the previous paper.[2] The results are shown in Table 4 and Fig. 4. The obtained value of λ' was found to be intermediate between the values for the fixed $\varkappa$ and ν set of values. Judging from the W_n/W_f ratio and the MSD between W_n and W_a, the disagreement was reduced remarkably for the WLB, and to some extent for the other boards, excluding IC5 and PF8.

For a further improvement, density variation through the board thickness was taken into account in the simulation for the LDPB. However, as shown in Fig. 4 and Table 4, the improvement obtained was only a little. Some correction might be required not only to $\varkappa$ and ν but also to λ' before a satisfactory agreement between W_f and W_n is reached. However, calculating a variable λ' value through the board thickness would involve a great deal of computing time. This is an area that requires further experimental work.

There are some reports which show moisture conductivities measured by a "cup" method for some products similar to those used in this paper. Suzuki[4] reported a value of 2.4×10^{-3} kg/mh (kg/kg of dry air) for akamatsu (*Pinus densiflora S. and Z*) heartwood of 530 kg/m^3 density at 19°C, 56-76% RH; Miyano and Inaba[5] gave a value of 1.9×10^{-3} kg/mh (kg/kg of dry air) for a particleboard of 682 kg/m^3 density at 65% RH. Compared with these, the values of λ' listed in Table 4 are considered to be reasonable.

If the λ' with the minimun MSD between W_n and W_a in each board is considered as being representative, then the λ' for the LDPB is 4.3 times greater than that of the WLB. A similar difference in moisture conductivity is apparent when the low-density laboratory prepared boards are compared to the higher-density boards.

Nakao and Ohshima[6] described a theoretical relationship linking moisture absorption rate, moisture conductivity, and moisture capacity, by solving the first term of Equation 1 analytically as a simplified model; the relationship they presented was $\lambda'\kappa \propto A^2$. The results shown in Tables 3 and 4 were found to agree approximately with this relationship; the ratio of A squared for the LDPB to that for the WLB, calculated from Table 3, was 3.5, which is close to the λ' ratio of 4.3 between the two products; the ratio of A squared for PF5 to that for PF8 was 3.4, while the ratio of $\lambda'\kappa$ was 3.9 when κ of 2500 and 4000 kg/m^3 (kg/kg of dry air) were used for PF5 and PF8, respectively; similary 2.4 between IC5 and IC8, while 2.1 when κ of 2300 and 3500 kg/m^3 (kg/kg of dry air) were used for IC5 and IC8, respectively.

3.3 Moisture content profiles

Moisture content profiles through the board thicknesses, as calculated with the set of κ, ν, and λ' values with the minimum MSD between W_n and W_a, are discussed below.

As shown in Fig. 5(a), it was recognized that the moisture content increased both at the surface and inside the board with time. Fig. 5(a) also shows that the moisture content deep in the board changed slightly even in the early stages. This behavior may be caused by the rise in the top surface temperature as a result of the heat generated by moisture adsorption; the heat is transferred relatively early to the bottom surface; the temperature rise in the board causes moisture desorption; the generated moisture is tran-

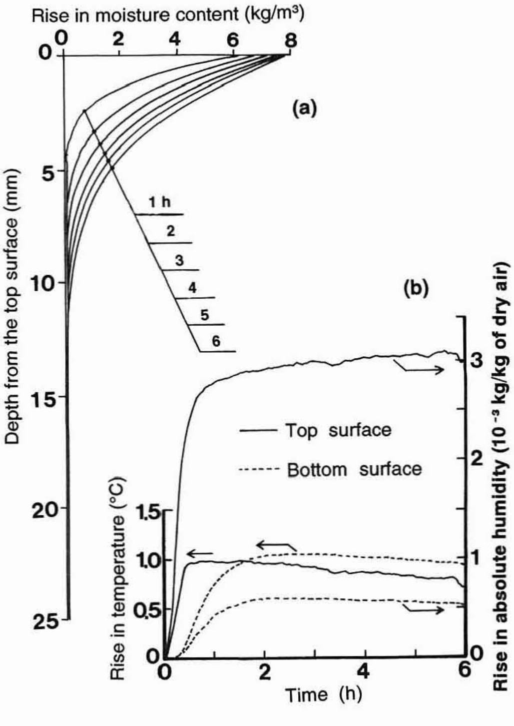

Fig. 5. Moisture content profiles through the board thicknesses (**a**), and variations in temperatures and absolute humidities with time (**b**) for the LDPB.

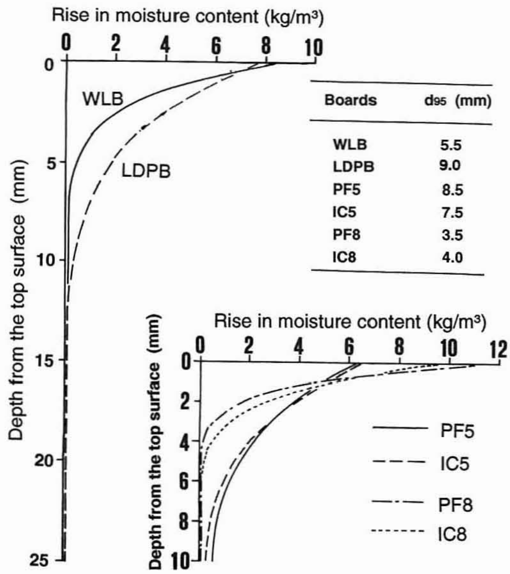

Fig. 6. Comparison of moisture content profiles at t=6 hours among specimens.

Note: d_{95} shows a depth from the top surface which accounts for 95% of all the moisture absorbed.

ferred towards the bottom due to the difference in vapor pressures caused by the temperature gradient.

Moisture content profiles at $t=6$ hours for the boards are shown in Fig. 6. The d_{95} values indicate the depth from the top surface required to account for 95% of the moisture absorbed. The d_{95} for the LDPB was found to be 1.6 times greater than that of the WLB. The d_{95} values of the low-density laboratory prepared boards were more than twice those of the high-density boards.

4. CONCLUSION

The main results obtained in this study are as follows:

1. LDPB is more hygroscopic than WLB in that its V_a is 1.9 times larger, its λ' is 4.3 times greater, and its d_{95} 1.6 times larger. These values help explain the superior performance of the LDPB over the WLB for humidity control as described in the first paper[1)] of this series. These differences suggest that the vapor diffusion paths are larger and more continuous in LDPB than those in WLB.

2. A reduction in density from 820 kg/m^3 to 540 kg/m^3 increases V_a 1.7 times, λ' 4.7 times, and d_{95} 2.1 times. These results suggest that it is the void volume which determines the penetration of moisture into a board, and that a greater permeability can more than compensate for a decrease of moisture capacity.

3. Treating moisture capacities as a function of humidity for the simulation was found useful in predicting heat and moisture transfers.

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