

# PREDICTION OF MOISTURE CONTENT AND MOISTURE GRADIENT OF AN OVERLAID PARTICLEBOARD<sup>1</sup>

*Qinglin Wu*

Research Associate

and

*Otto Suchsland*

Professor

Department of Forestry  
Michigan State University  
East Lansing, MI 48824-1222

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## ABSTRACT

Equilibrium moisture contents (EMCs) and diffusion coefficients of a high pressure laminate (HPL) overlay, a wood particleboard (PB) substrate, and an HPL backer (BCK) were measured at different levels of relative humidity (RH). The EMCs as a function of RH were fitted to the Nelson's sorption isotherm. It was found that Nelson's model reproduced accurately the experimental data of these different materials. Over a given RH interval, the PB face layer had a smaller diffusion coefficient than the core layer. Diffusion coefficients for both PB face and core layers decreased with increase in moisture content (MC). For overlays, diffusion coefficients increased with MC for both HPL and HPL backer.

A model based on the diffusion theory was developed to predict MC and moisture distribution for a multi-ply wood composite panel. The model's prediction of the mean MC for a three-layer PB, a two-ply HPL + PB panel, and a three-ply HPL + PB + BCK panel compared favorably with experimental data. Developments of asymmetric moisture distributions within the HPL + PB and HPL + PB + BCK laminates were demonstrated, and their implication for the panel's warping potential was discussed.

*Keywords:* Diffusion, modeling, overlays, sorption isotherm, substrate, warping, wood composite.

## INTRODUCTION

Wood composite panels used in the furniture industry are generally combined with overlays to meet strength and appearance requirements. For economic reasons, a panel is often constructed with overlay on only one surface of the substrate (two-ply construction) or with a high quality overlay on the visible face of the substrate and a low quality overlay on the back (three-ply construction). This re-

sults in an unbalanced panel, which warps when it is subjected to a moisture content (MC) change and can lead to significant economic losses (Suchsland and Woodson 1986).

Some overlays are less pervious to moisture than wood composite substrate and interfere with the normal exchange of moisture between the substrate and environment. During service, moisture gradients may develop inside a panel due to different sorption behavior of the opposing face materials. These moisture gradients cause warp, which is known as transient warp (Suchsland and McNatt 1985). A recent study (Suchsland et al. 1993) showed that if overlays are rigid, the transient warp may not be recovered after eliminating the moisture

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gradient, and may contribute to permanent deformation of the panel. Therefore, analysis of the warping problem requires knowledge not only of the equilibrium moisture content (EMC) corresponding to a given relative humidity (RH), but also of the time-dependent moisture distribution within the laminate.

The EMCs of overlays and wood composite substrates have been studied by a number of investigators (Heebink and Haskell 1962; Suchsland 1972; McNatt et al. 1992). These studies, however, did not include their diffusion behaviors. As a result, information on diffusion coefficients, validity of Fick's law, and any anomalies in the diffusion coefficient caused by such variables as density and MC level for wood composite materials is still unknown. Various analytical models to predict warping of a wood composite panel have also been developed (Norris 1964; Tong and Suchsland 1993; Hong 1994). All those models require moisture distribution across a panel's thickness as input for the warping analysis. There is, however, no procedure available to predict such a moisture distribution for laminated wood composites under varying environmental conditions. The objectives of this study were: (a) to develop experimental data on sorption isotherms and diffusion coefficients of high-pressure laminate (HPL) overlays and a particleboard (PB) substrate; and (b) to develop a procedure for predicting MC and MC distribution in an overlaid particleboard.

## MATERIALS AND METHODS

### *Specimen preparation*

Materials used in the present study included an interior three-layer, mixed hardwood particleboard (19.1 mm thick), an HPL overlay (1.3 mm thick), and an HPL backer (BCK) (0.5 mm thick). All the materials were purchased from a local supplier. These three products were used to make two types of laminates (HPL+PB and HPL+PB+BCK) in a cold-press using polyvinyl acetate adhesive. Test specimens for EMC and diffusion coefficient were produced from the first three materials;

and MC samples were made from the PB and two laminates.

*Preparation of EMC specimens.*—Four types of EMC specimens were prepared for the study. These included PB face layer, PB core layer, HPL, and HPL backer. Figure 1 shows a schematic of the cutting procedure. In brief, six PB, three HPL, and three HPL backer strips (25.4 mm wide by 610 mm long by thickness) were first cut from the larger panels of the various materials using a table saw. Three parallel lines were drawn on the edge of each PB strip dividing it into four layers of equal thickness. The outer two layers were defined as the face layers and the inner two layers as the cores. The six PB strips were randomly divided into two groups (three strips in each group) for specimens of the PB face and PB core, respectively. One face layer from each of the three PB strips in one group was cut with one pass on the table saw, and the rest of the material was discarded. One core layer from each of the three PB strips of the second group was cut with two passes. In the first pass, a face layer (including the saw kerf) was removed from one surface of the strip, and in the second pass, the exposed core layer was cut. The final thickness of both face and core layers was 4.5 mm. All the strips obtained were cross-cut into 25.4-mm-long specimens, totaling 56 specimens for each material type. Four specimens from each of the four material types were randomly selected and numbered. They were combined to form one group, and a total of fourteen groups were prepared.

Before testing, seven groups of samples were randomly selected and conditioned in two desiccators over dry phosphorous pentoxide ( $P_2O_5$ ), which gives 0% relative humidity, to reach the dry state for the adsorption test. The seven other groups were conditioned over distilled water to reach the fiber saturation state for the desorption test.

*Preparation of diffusion coefficient specimens.*—Four types of diffusion coefficient specimens were prepared: PB face layer, PB core layer, HPL, and HPL backer. The cutting procedure was the same as described above for EMC specimen. The size and number of spec-

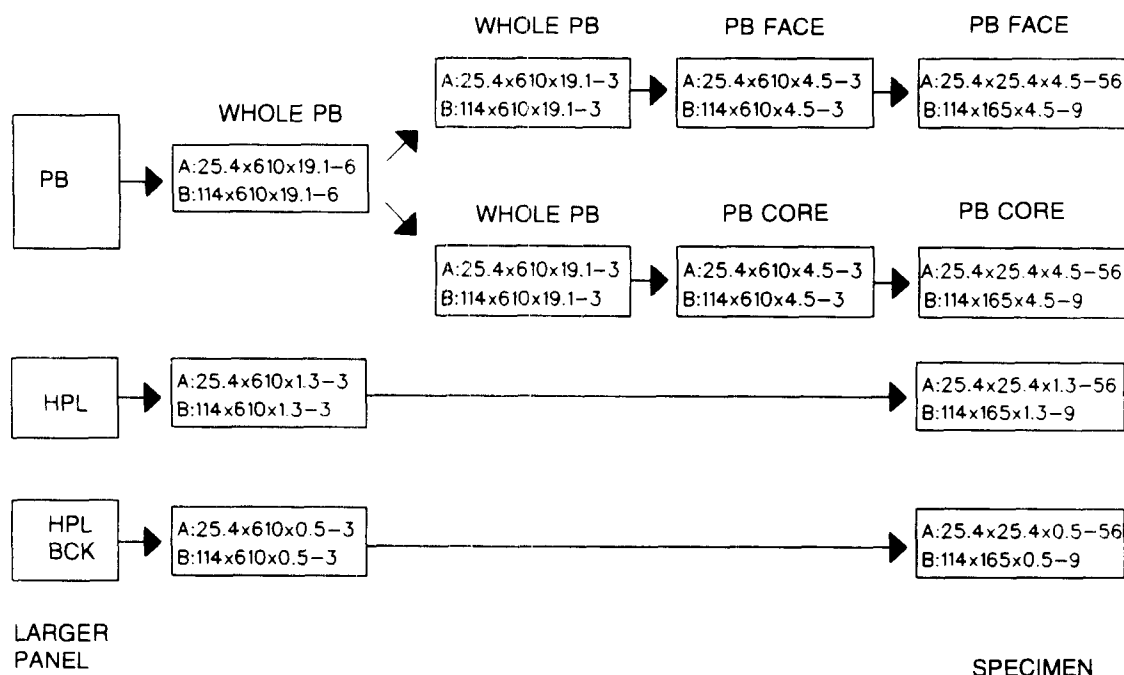


FIG. 1. A schematic of the procedure for preparing EMC and diffusion coefficient specimens. The notation 'A: 25.4 × 25.4 × 4.5-56' stands for EMC sample with a size of 25.4-mm wide by 25.4-mm long by 4.5-mm thick and a total of 56 samples in the group. The letter 'B' represents diffusion coefficient sample. All dimensions are in mm.

imens for each of the four materials are shown in Fig. 1. Three specimens from each of the four material types were randomly selected and numbered. They were combined to form one group, and a total of three groups were prepared.

The four edges of each sample were sealed with vapor-proof neoprene paint before testing. All samples were conditioned in three holding desiccators over saturated potassium acetate ( $KC_2H_3O_2$ ) to reach equilibrium at 20% relative humidity.

*Preparation of MC specimen.*—Three types of MC specimen were prepared: PB, HPL+PB laminate, and HPL+PB+BCK laminate. Three specimens (114 mm wide by 165 mm long by thickness) were cut on a table saw from each of the three material types (Fig. 2). They were numbered and combined into one group. The four edges of each specimen were sealed using neoprene paint. All specimens were conditioned in a climate-controlled room maintained at 45% RH and 25°C.

#### Testing equipment and procedure

*EMC test.*—EMC tests were made at relative humidities of 20, 35, 45, 66, 75, 81, and 93%. Seven desiccators charged with saturated salt solutions of different vapor pressures were used (Suchsland 1972). For adsorption, the seven groups of specimens preconditioned over dry phosphorous pentoxide ( $P_2O_5$ ) were randomly allocated to the seven atmospheric conditions. For desorption, the seven groups of specimens preconditioned over distilled water were used. After an eight-week conditioning for both adsorption and desorption, all specimens were weighed, oven-dried at 103°C for 24 hours, and reweighed. The MC of each specimen was calculated on the oven-dry basis.

*Diffusion coefficient test.*—The diffusion coefficients of PB face, PB core, HPL, and HPL backer were determined in three series of exposure conditions: (a). 20% → 66% → 83%; (b). 20% → 45% → 66% → 83%; and (c). 20% → 45% → 83%.

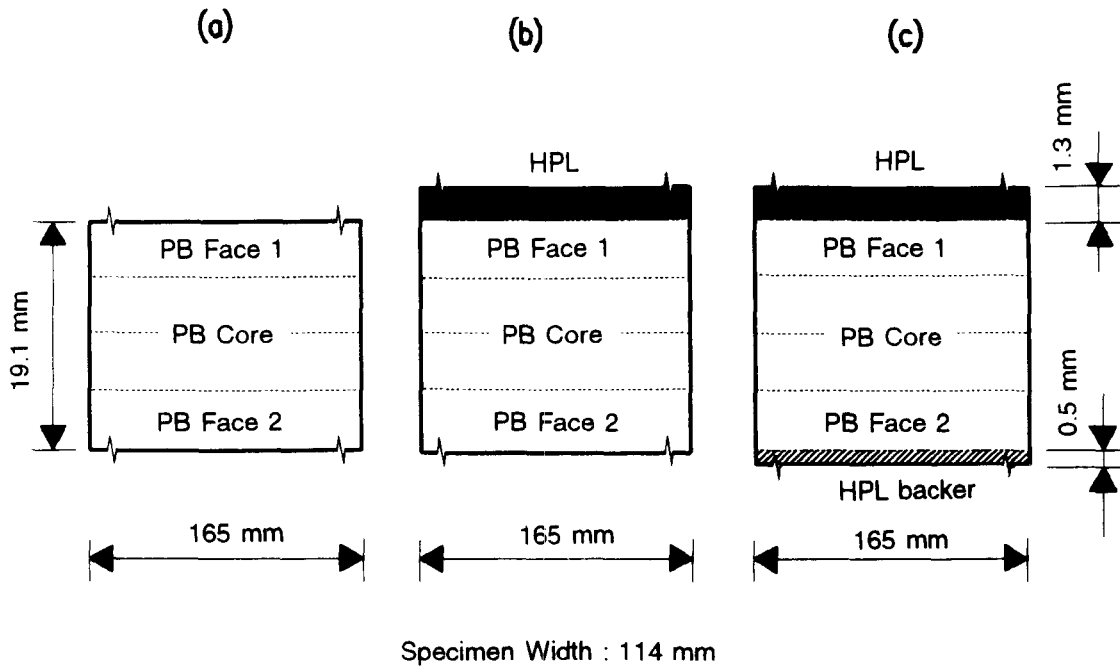


FIG. 2. Geometry of MC specimens. (a) particleboard (PB), (b) HPL+PB laminate, and (c) HPL+PB+BCK laminate.

A sorption device (Fig. 3) was built consisting of two separate chambers for conditioning and weighing, respectively. During testing, both chambers were maintained at the same humidity condition using saturated salt solution. The temperature and humidity inside the conditioning chamber were monitored by dry-bulb and wet-bulb thermometers. The air inside each chamber was circulated by electric fans. The weight change of the specimen was monitored by a digital balance (accuracy up to 0.001 g), placed outside the weighing chamber with an attached specimen hanger passing into the chamber. The whole test assembly was located in an air-conditioned room. The temperature inside the chambers was maintained at  $25 \pm 1^\circ\text{C}$ .

For each series of exposure conditions, a group of twelve specimens (three PB face, three PB core, three HPL, and three backer), preconditioned at 20% RH, were selected. The specimens were transferred to the weighing chamber in a plastic bag, and their initial weights were determined. They were then

transferred to the conditioning chamber maintained at the specified RH level using saturated salt solution. At measured time intervals, the specimens were removed from the shelves in the conditioning chamber, weighed in the weighing chamber, and placed back in the conditioning chamber. The process was repeated until the specimens reached equilibrium, and the whole process was repeated for the next level of RH.

At the end of each exposure condition, the edge coating of each specimen was carefully removed using a razor blade. All specimens were oven-dried, and their weight and dimensions were measured for the determination of MC and density.

*MC test.*—Tests to determine the MC change of the PB, HPL+PB laminate, and HPL+PB+BCK laminate were conducted over RH change from 45% to 83%. A group of nine preconditioned specimens (three from each laminate type) were used. The equipment and test procedure were the same as those used for the diffusion coefficient test. At the end of the

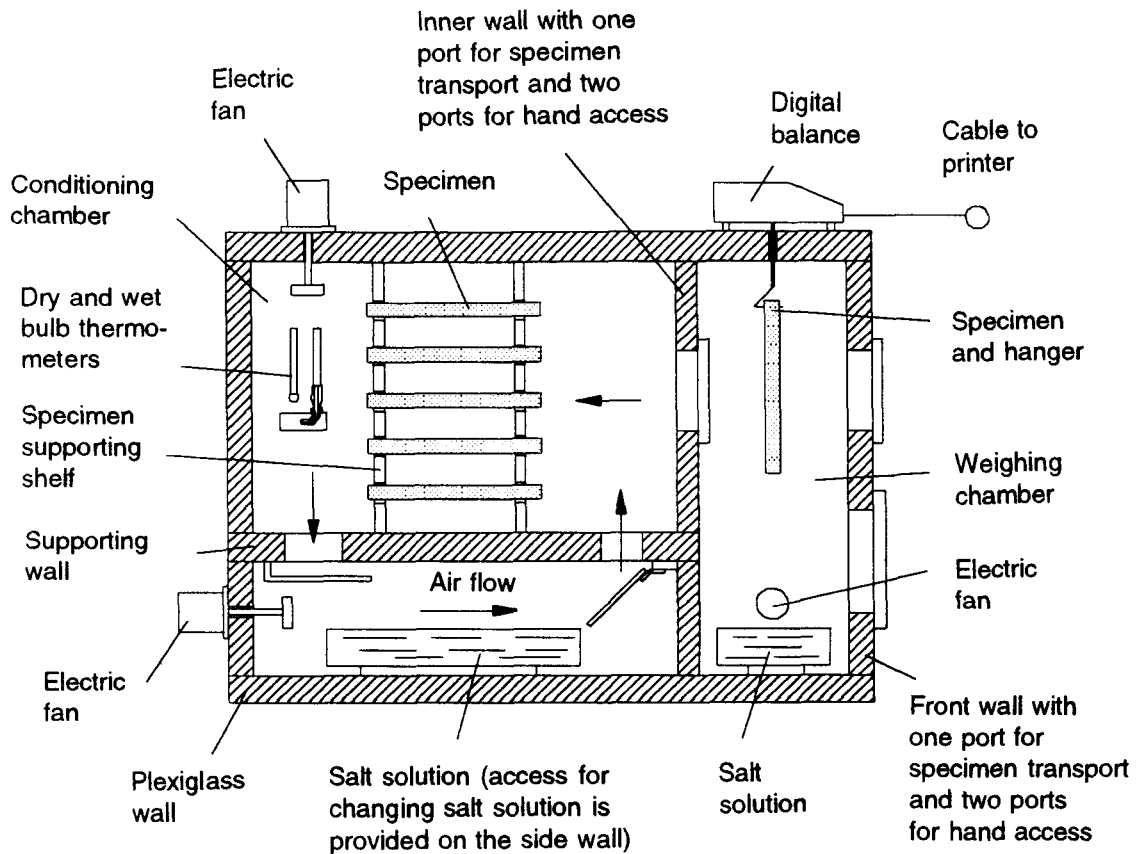


FIG. 3. A schematic of the testing apparatus.

test, the edge coating was removed, and all specimens were oven-dried for MC determination.

*Data analysis*

*Sorption isotherm.*—EMC test data were fit to the sorption isotherm proposed by Nelson (1983). The sorption isotherm is of the form:

$$RH = \text{EXP} \left\{ \left( -\frac{W_w}{RT} \right) \text{EXP} \left[ A \left( 1.0 - \frac{EMC}{M_v} \right) \right] \right\} \quad (1a)$$

or

$$EMC = M_v \left\{ 1.0 - \frac{1}{A} \text{LN} \left[ \left( -\frac{RT}{W_w} \right) \text{LN}(RH) \right] \right\} \quad (1b)$$

where

- EXP = exponential function;
- $W_w$  = molecular weight of water (18 l/mole);
- $R$  = universal gas constant (1.9858 cal/mole/°K);
- $T$  = absolute temperature (°K);
- $A$  = natural logarithm of the Gibbs free energy per gram of sorbed water as RH approaches zero ( $\Delta G_0$ , cal/g), i.e.  $A = \text{LN}(\Delta G_0)$ ;
- $M_v$  = material constant which approximates the fiber saturation point

for desorption (%).

For a given temperature, the term  $(-RT/W_w)$  becomes a constant, and parameters  $A$  and  $M_v$  define the sorption isotherm. To determine the values of  $A$  and  $M_v$ , a linear re-

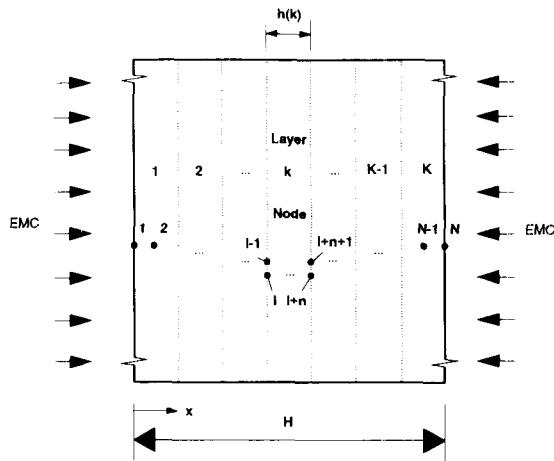


FIG. 4. A schematic of a multi-ply wood composite laminate in sorption. Variables shown are:  $K$ —total number of plies (or layers) in the panel,  $N$ —total number of nodes in the panel,  $n$ —number of nodes in a ply,  $H$ —panel thickness,  $h$ —ply thickness,  $l$ —index for node, and  $k$ —index for ply.

gression analysis was performed using Eq. 1b with the measured EMC as the dependent variable and transformed RH, i.e.  $\text{LN}[(-RT/W_w) \text{LN}(\text{RH})]$  as the independent variable.

*Diffusion coefficient.*—The fractional change in specimen weight for each humidity step was calculated and plotted against the square root of sorption time. The average diffusivity  $D$ ,  $\text{mm}^2/\text{hr}$ , was calculated from the slope of the linear portion of the sorption curve (Crank 1965; Siau 1984):

$$D = \left( \frac{\pi L^2}{4} \right) \left[ \frac{E_2 - E_1}{\sqrt{t_2} - \sqrt{t_1}} \right]^2 \quad (2)$$

where

- $E = (W - W_1)/(W_E - W_1)$ ;
- $W$  = specimen weight (g);
- $W_1$  = initial specimen weight (g);
- $W_E$  = specimen weight at equilibrium (g);
- $t$  = time (hr);
- $L$  = half specimen thickness (mm);

and subscripts 1 and 2 represent two points on the linear part of the sorption curve. In calculating the diffusivity, the values of  $t_1$  and  $t_2$  were taken to correspond to  $E = 0$  and  $E =$

0.5, respectively (Crank 1965). Moisture content at the two-third saturation point for each RH step was calculated and assigned to the diffusion coefficient (Stamm 1959). The data were fit to an exponential function (Simpson 1993) through regression analysis:

$$D = B \text{EXP}[C M_{2/3}] \quad (3)$$

where

- $B$  = regression constant ( $\text{mm}^2/\text{hr}$ );
- $C$  = regression constant ( $1/\%$ );
- $M_{2/3}$  = moisture content at the two-third saturation point of a given RH interval (%).

#### Prediction of MC and moisture distribution

Fick's second law was used to describe the MC distribution inside a multi-ply laminate (Fig. 4). The laminate consists of the materials that have different sorption and diffusion characteristics. The one-dimensional form of the equation with MC as the driving force states:

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left[ D(x, M) \frac{\partial M}{\partial x} \right] \quad (4)$$

where

- $M$  = moisture content (%);
- $t$  = time (hour);
- $x$  = spatial coordinate starting from one surface of the laminate (mm)

(Fig. 4), and the diffusion coefficient  $D$ ,  $\text{mm}^2/\text{hr}$ , may vary with MC and  $x$ .

The initial and boundary conditions for Eq. 4 are:

$$\begin{aligned} M(x, t) &= \text{EMC}_0(x, t < 0) \\ 0 &\leq x \leq H \quad t < 0 \\ M(x, t) &= \text{EMC}(x, t) \\ x &= 0 \quad t \geq 0 \\ M(x, t) &= \text{EMC}(x, t) \\ x &= H \quad t \geq 0 \end{aligned} \quad (5)$$

where  $H$  is the panel thickness (mm), and  $\text{EMC}_0(x, t < 0)$  represents the initial equilibrium MCs across panel's thickness.

At each interface between two adjacent layers of different materials, two additional conditions must be specified. The first is that the rates of moisture crossing the surfaces of two materials per unit area are equal

$$\left[ -D_{1-1}\rho_{1-1} \frac{\partial M}{\partial x} \right]_{1-1} = \left[ -D_1\rho_1 \frac{\partial M}{\partial x} \right]_1 \quad (6)$$

where  $\rho$  is the density at the oven-dry condition ( $\text{g}/\text{mm}^3$ ), and subscripts 1-1 and 1 refer to the adjoining regions at the interface (Fig. 4). The second condition is that MCs at the surfaces of two interfacing materials correspond to the same relative humidity:

$$F_{1-1}(M|_{1-1}) = \text{RH} = F_1(M|_1) \quad (7)$$

where  $F$  represents the function defined by the right-hand side of Eq. (1a). It is noted that at the interface RH is continuous, but MC is discontinuous. For an isotherm condition, Eq. 7 after substituting Eq. 1a and replacing EMC with  $M$  becomes:

$$M|_{1-1} = M_v|_{1-1} \left[ 1.0 - \left( \frac{A|_1}{A|_{1-1}} \right) \right] + \left[ \left( \frac{A}{M_v} \right)_1 \left( \frac{M_v}{A} \right)_{1-1} \right] M|_1 \quad (8)$$

which provides an additional equation for the MCs of two materials at each interface.

Equations 4 to 8 define the entire problem. The Crank-Nicholson's finite difference method (Crank 1965) was used to transform the differential equations into a set of algebraic equations that were solved through matrix operation. The presence of the interface discontinuity in MC makes the coefficient matrix asymmetric. A matrix solver based on the LU decomposition procedure (Press et al. 1989) was used to perform the matrix inversion and multiplication. The algorithm was implemented in a Fortran program, which was used together with measured sorption isotherm and diffusion coefficients to simulate the experimental data in this study.

## RESULTS AND DISCUSSION

### Sorption isotherm

Figure 5 shows measured EMCs (symbols) as a function of relative humidity for the various materials. The particleboard face layer (Fig. 5a) had a slightly lower EMC at a given RH than the core layer (Fig. 5b). This was thought to be due to the fact that the face layer had experienced more severe heat treatment than the core layer during manufacturing. The face and core layer densities were 0.75 and 0.53  $\text{g}/\text{cm}^3$ , respectively. A reduction of available hygroscopic bonding sites at higher density for the face layer may also contribute to its lower EMCs. For overlays, HPL (Fig. 5c) had lower EMC than backer (Fig. 5d). The higher density of HPL (1.32  $\text{g}/\text{cm}^3$ ) compared with backer (1.2  $\text{g}/\text{cm}^3$ ) may cause its lower EMC. Both particleboard and overlay showed a sorption hysteresis, i.e. the adsorption curve being lower than the desorption curve.

Nelson's model fitted experimental data well (lines in Fig. 5) with the correlation coefficient varying from 0.94 to 0.99. Table 1 lists the results of the regression analysis of the material parameters defining the sorption isotherm. Also shown in Table 1 are Nelson's data for solid wood at 25°C temperature. As shown, the magnitudes of the parameters  $A$  and  $M_v$  are different for particleboard and overlay. There seemed to be no systematic variation for parameter  $A$  among different materials. For parameter  $M_v$ , both PB face and core had lower values for both adsorption and desorption compared with Nelson's data for wood. Since  $M_v$  approximates the MC at saturation in desorption (Nelson 1983), a lower value of  $M_v$  for PB means a lower saturation MC, which was probably caused by heat treatment during manufacturing. The hysteresis ratio,  $r = (M_v)_{\text{Ads.}} / (M_v)_{\text{Des.}}$  for PB was lower than the value for solid wood. This indicates that wood composites exhibit a larger sorption hysteresis effect than solid wood. This behavior was similar to that reported in an earlier study (Suchsland 1972). HPL had a lower value of  $M_v$  and a lower hysteresis ratio compared with HPL

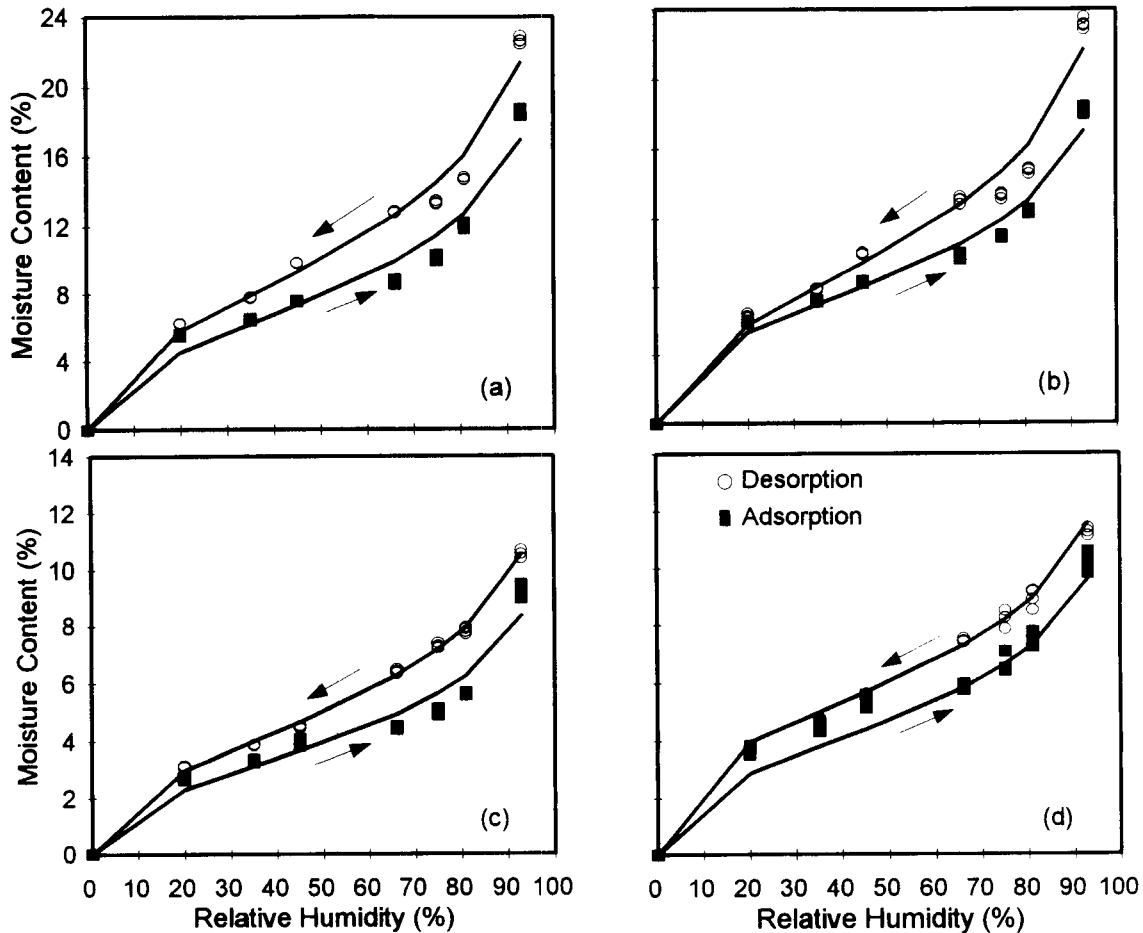


FIG. 5. Sorption isotherms for PB face (a), PB core (b), HPL (c), HPL backer (d). Lines showing the fit with Nelson's model.

backer, indicating a lower saturation MC and a larger hysteresis effect of HPL.

#### Diffusion coefficient

Typical sorption curves under various RH steps are shown in Fig. 6 for each of the four

types of materials. The rate of moisture sorption (initial slope of a sorption curve in Fig. 6) for both PB face and core layers decreased with increase in RH level (Fig. 6a and 6b). The rate increased, however, for the overlays (Fig. 6c and 6d) as RH level increased.

TABLE 1. Material constants defining the sorption isotherm. Data for wood at 25°C is from Nelson (1983).

Material	Adsorption		Desorption		Ratio (Ads./Des.)	
	A (cal/g)	$M_v$ (%)	A (cal/g)	$M_v$ (%)	$r_A$	$r_{Mv}$
PB face	5.10	20.48	5.11	25.78	0.998	0.794
PB core	5.37	20.31	5.09	26.17	1.055	0.776
HPL	5.15	10.05	5.19	12.68	0.992	0.793
HPL backer	5.77	11.52	5.55	13.68	1.039	0.845
Wood	4.92	24.60	5.11	29.60	0.963	0.831



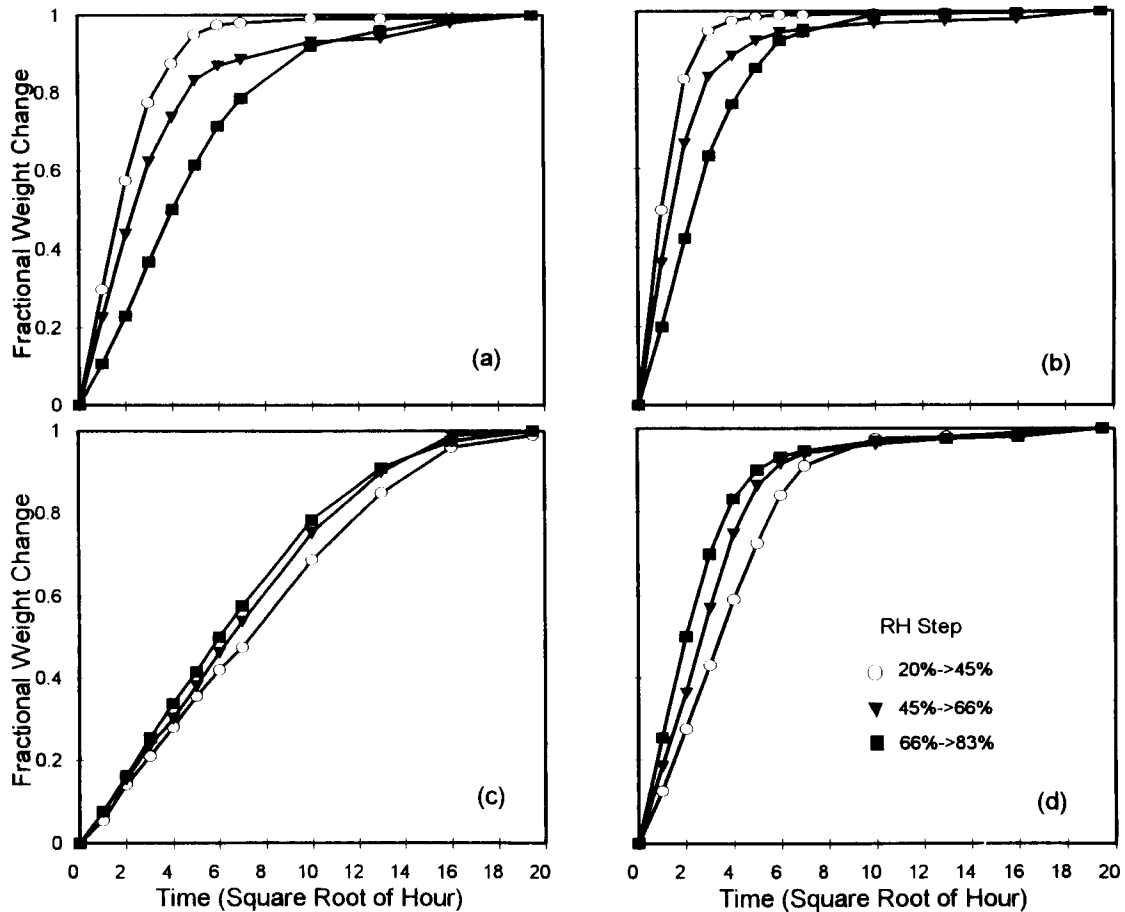


FIG. 6. Sorption curves for various RH intervals. (a): PB face, (b) PB core, (c). HPL, and (d). HPL backer.

The PB core layer had a larger diffusion coefficient than the face (Fig. 7a). This was due to lower density and larger internal void volume of the core. The coefficients for both face and core decreased as MC increased. The difference between the diffusion coefficients of core and face became less pronounced as the MC increased. Decrease in diffusion coefficient for PB with increase in MC differs from the behavior of solid wood. The coefficient for solid wood normally increases as the MC increases at a given temperature (Stamm 1959; Siau 1984). Burch et al. (1992) measured diffusion coefficient of a 12-mm-thick fiber board with a steady-state cup method. They also observed

a decrease in diffusion coefficient with increase in MC and attributed the difference to the dominant moisture transfer mechanism in the material. In fiber-board or particleboard as in the present case, the dominant moisture transfer mechanism may be water-vapor diffusion through air-filled pore spaces, while in solid wood bound water diffusion may play a more important role. In case of overlays, HPL backer had a higher diffusion coefficient than HPL (Fig. 7b). This may be due to the lower density of the backer. The diffusion coefficients for both HPL and backer increased with increase in MC. The difference between the diffusion coefficients of HPL backer and HPL became more

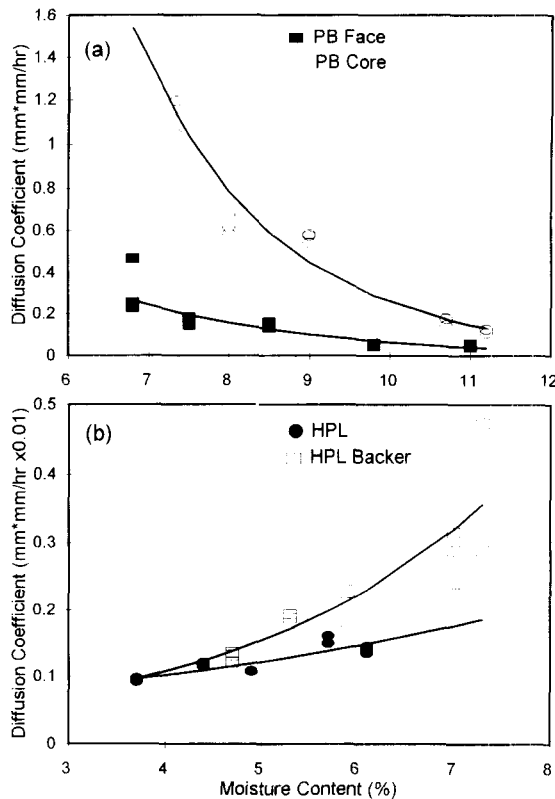


FIG. 7. Diffusion coefficient as a function of MC. (a): PB face and PB core, (b): HPL and HPL backer. Lines showing the exponential fit.

pronounced as the MC increased. The exponential function (Eq. 3) fitted data well for both PB and overlays (Table 2 and Fig. 7).

#### Comparison between predicted and measured MC

Figure 8 shows a comparison of the predicted and measured mean MC of PB,

TABLE 2. Material constants defining relationship between diffusion coefficient and MC ( $D = B \text{EXP}[C M]$ ) for the various materials used in the study.

Material	Constant B (mm <sup>2</sup> /h)	Constant C (1/%)	Correlation coefficient*, r <sup>2</sup>
PB face	5.13	-0.437	0.86
PB core	69.44	-0.561	0.95
HPL	$4.91 \times 10^{-4}$	0.183	0.77
HPL backer	$2.51 \times 10^{-4}$	0.364	0.81

\* Correlation between diffusion coefficient and moisture content (MC).

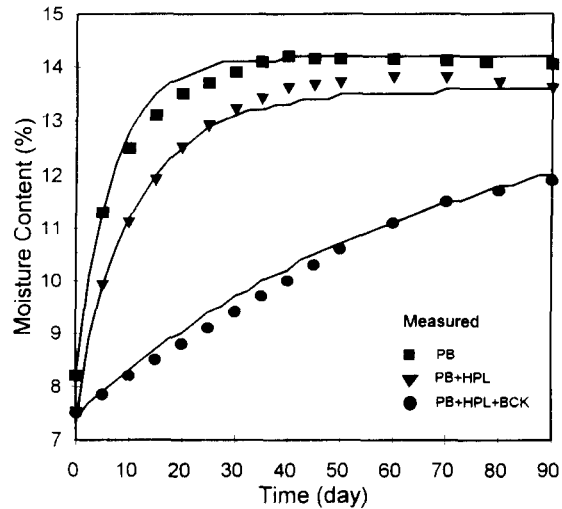


FIG. 8. A comparison of predicted and measured mean MC for PB, HPL+PB laminate, and HPL+PB+BCK laminate for RH change from 45% to 83%. Lines showing the predicted value.

HPL+PB laminate, and HPL+PB+BCK laminate for RH change from 45% to 83%. The mean MC for PB reached a maximum at about 40 days, and there was a slight decrease in MC after the maximum point. The mean MC for HPL+PB laminate reached the maximum at about 70 days. For HPL+PB+BCK laminate, the mean MC was still increasing after a 90-day test. Thus, during service, an overlaid wood composite panel probably never reaches a steady-state condition because of the continuous change in the environmental conditions. It would, therefore, be misleading to assess the warping potential of overlaid wood composites based on the EMC data, as this condition is very unlikely to develop. There was good agreement between predicted and measured MC for the three different panels.

#### Predicted moisture distribution

Warping develops in a wood composite laminate due to: (a) unbalanced panel construction, or (b) uneven change in MC across the panel's thickness, or (c) a combination of both. It is a primary objective of this study to examine how the moisture distributes inside different panels during a given RH change.

Figure 9a shows the predicted MC distribution in a three-layer particleboard for RH change from 45% to 83%. The curves labeled 'Face 1' and 'Face 2' represent the average MC within the two PB face layers (Fig. 2a). They coincide because of the identical exposure condition for both faces of the panel. The curve labeled 'Core' represents the average MC within the PB core (Fig. 2a). Also shown is a time-dependent differential MC between the face and core layer. A maximum 2.2% MC differential developed at the early stages of the sorption process. This differential MC gradually levelled off over a period of 40 days. The MC differential, however, did not cause any warping of the panel. The MC distribution was symmetric about the center line, and stresses generated by the moisture gradient were balanced within the panel.

The MC distribution for HPL+PB laminate is shown in Fig. 9b. Again, various curves as labeled in the graph represent average MCs within different layers of the panel (Fig. 2b). The differential MC is the MC difference between Face 1 and Face 2 within the PB. As shown, HPL had a lower EMC compared with PB. Due to a slower rate of moisture transmission through HPL, an asymmetric MC distribution developed inside the PB substrate. During the early stages of sorption, the face layer adjacent to HPL (Face 1) had lower MC than the face layer that was open to air (Face 2). The maximum differential MC exceeded 4.7%. This uneven change in MC at different positions in the PB substrate would cause an imbalance of the swelling stresses in the PB and would contribute to the warping of the panel. An additional element of imbalance is introduced in this case by unopposed overlay. Suchsland et al. (1993) demonstrated experimentally the effect of the moisture gradient on warping of overlaid particleboards. They showed that a significant amount of warping developed in both two-ply HPL- and vinyl-particleboard laminates early in sorption. For HPL-overlaid particleboards, warping was shown to be unrecoverable after eliminating the moisture gradient. They attributed this to

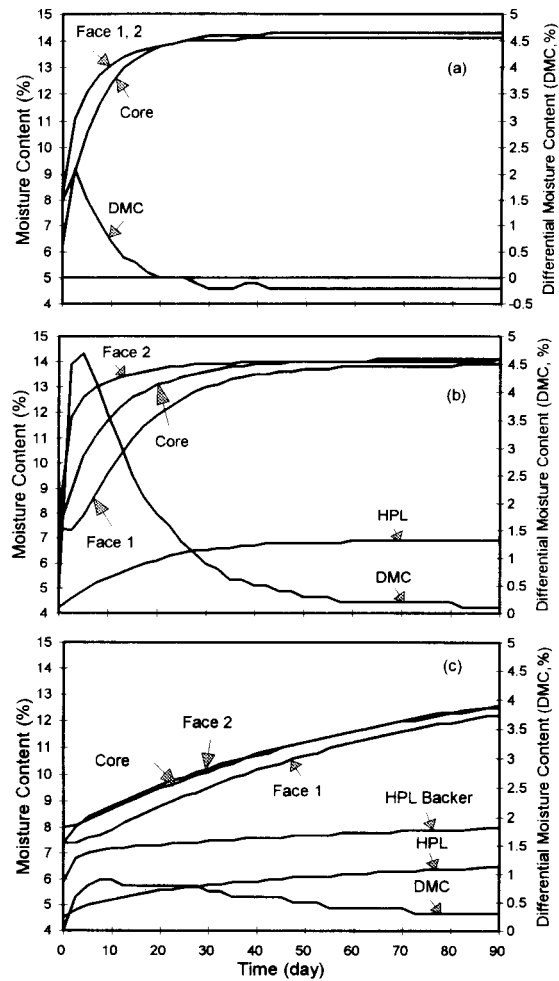


FIG. 9. Moisture distribution within PB (a), HPL+PB laminate (b), and HPL+PB+BCK laminate (c) for RH change from 45% to 83%.

plastic deformation in the PB caused by swelling stresses due to a large moisture gradient as shown in Fig. 9b and by resistance to stress (strain) from the rigid and unopposed HPL during the initial stage of moisture sorption.

Figure 9c shows the MC distribution for the HPL+PB+BCK laminate. The various curves represent average MCs for the different layers shown in Fig. 2c. Compared with HPL, HPL backer had a higher EMC and a faster rate of MC change due to its smaller thickness and higher diffusion coefficient. Moisture content for both HPL and backer was smaller than that

of PB. The PB face layer adjacent to the HPL (Face 1) had a slower rate of MC change compared with the face layer adjacent to the backer (Face 2). As a result, a differential MC between the two PB face layers developed. However, the magnitude of the differential MC was relatively small, the maximum being less than 1% compared with 4.7% in the two-ply laminate shown in Fig. 9b. Iwashita and Stashevski (1963) measured the warping of HPL-overlaid particleboards. They showed that the use of backing sheets greatly reduced the warping tendencies of the panel. The decrease in MC differential within the PB as shown in this study no doubt played an important role in stabilizing their panels during sorption. An important function of the backer is thus to reduce the extent of the moisture differential and swelling stress imbalance within the PB substrate.

#### SUMMARY AND CONCLUSIONS

Warping of overlaid particleboards is due to the imbalance of swelling stresses over the cross section of the panel. Among many variables, asymmetric moisture distribution across the panel thickness plays an important role in causing such a stress imbalance. The study described in this paper investigates the sorption behavior of particleboard substrate and HPL overlays and examines moisture distribution inside various panels of different construction.

It is found that Nelson's sorption isotherm can be used to describe the EMC data of a particleboard and HPL overlays. The material parameters that define the sorption isotherm varied with types of material and sorption mode. Diffusion coefficient of the PB face layer was smaller than that of the core layer and decreased at higher MCs for both face and core. Diffusion coefficients of HPL and backer increased with increase in MC.

The analytical procedure demonstrated that a highly skewed moisture distribution developed inside a particleboard substrate due to the addition of an HPL overlay to one of its surfaces. It was also shown that by adding one

HPL backer to the other surface of the substrate, the extent of moisture imbalance was largely reduced. This method, coupled with internal stress analysis, could be used to assess more accurately the warping potential of a multi-ply wood composite panel.

#### REFERENCES

- BURCH, D. M., W. C. THOMAS, AND A. H. FANNEY. 1992. Water vapor permeability measurements of common building materials. *ASHRAE Transactions*. 98:486-494.
- CRANK, J. 1965. *Mathematics of diffusion*. Oxford University Press. London. UK. 346 pp.
- HEEBINK, D. M., AND H. H. HASKELL. 1962. Effect of heat and humidity on the properties of high-pressure laminates. *Forest Prod. J.* 12(11):542-548.
- HONG, X. 1994. Application of a linear visco-elastic plate theory to hygroscopic warping of laminates. Unpublished Ph.D dissertation. Michigan State University, East Lansing, MI. 205 pp.
- IWASHITA, M., AND A. M. STASHEVSKI. 1963. The influence of physical properties of some Japanese particleboards and high pressure decorative laminates on stability of overlaid boards. *Bull. Japanese Govt. Forest Exp. Sta. Meguro*. No. 215:1-37.
- MCNATT, J. D., J. YOUNGQUIST, AND T. XIN. 1992. Physical and mechanical properties of laminating materials. USDA Forest Service. U.S. Forest Products Laboratory, Madison, WI. Unpublished report.
- NELSON, R. M. 1983. A model for sorption of water vapor by cellulosic materials. *Wood Fiber Sci.* 15(1):8-22.
- NORRIS, C. B. 1964. Warpage of laminated materials due to change in moisture content. Appendix in: HEEBINK, B. G., E. W., KUENZI, and A. C. MAKI. Linear movement of plywood and flakeboards as related to the longitudinal movement of wood. USDA Forest Service Research Note FPL-073. U.S. Forest Products Laboratory, Madison, WI.
- PRESS, W. R., B. P. FLANNERY, S. A. TEUKOLSKY, AND W. T. VETTERLING. 1989. *Numerical recipes*. Cambridge University Press. New York, NY. 818 pp.
- SIAU, J. F. 1984. *Transport processes in wood*. Springer-Verlag. New York, NY. 245 pp.
- SIMPSON, W. T. 1993. Determination and use of moisture diffusion coefficient to characterize drying of northern red oak (*Quercus rubra*). *Wood Sci. Technol.* 27:409-420.
- STAMM, A. J. 1959. Bound-water diffusion into wood in the fiber direction. *Forest Prod. J.* 9(1):27-32.
- SUCHSLAND, O. 1972. Linear hygroscopic expansion of selected commercial particleboards. *Forest Prod. J.* 22(11):28-32.

- , AND J. D. McNATT. 1985. On the warping of laminated wood panels. Michigan State University. East Lansing, MI. 120 pp.
- , AND G. E. WOODSON. 1986. Fiberboard manufacturing practices in the United States. USDA Forest Service. Agri. Handbook No. 640. 263 pp.
- , Y. FENG, AND D. XU. 1993. The warping of laminated particleboard. Michigan State University. East Lansing, MI. 27 pp.
- TONG, Y, AND O. SUCHSLAND. 1993. Application of finite element analysis to panel warping. Holz Roh- Werkst. 51:55–57.