CHARACTERIZATION OF SORPTION BEHAVIOR OF ORIENTED STRANDBOARD UNDER LONG-TERM CYCLIC HUMIDITY EXPOSURE CONDITION[1]

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(Received August 1999)

ABSTRACT

Sorption measurements for oriented strandboard (OSB) were carried out under cyclic relative humidity (RH) conditions at 25°C. The measurements were made by placing test materials in a climate-controlled conditioning chamber until the specimens reached their steady-state equilibrium moisture content (EMC) at each given RH. The EMC-RH data were fit to Nelson's sorption model through nonlinear regression analysis. The model was subsequently used to develop procedures for predicting EMC distribution in a board with a vertical density gradient and for predicting mean EMC change of OSB under cyclic RH exposure conditions.

It was shown that Nelson's model can be used to describe the sorption data of OSBs manufactured under various processing conditions. The parameters that define the sorption isotherm varied with sorption mode (adsorption or desorption) and processing variables. In a board with a vertical density gradient, the lower density range (core) reached higher EMCs than the higher density range (face) at a given RH level. Thus, it would be more appropriate to use an EMC distribution across panel thickness rather than a mean panel MC when modeling linear expansion and thickness swelling characteristics of OSB. Under long-term cyclic exposure condition, OSB's sorption isotherms are reproducible and can be predicted accurately with the model.

Keywords: Adsorption, desorption, EMC, moisture, OSB, sorption models, structural panels.

INTRODUCTION

Oriented strandboard (OSB) is often exposed to various environmental conditions during applications. One such application is exterior panels (e.g., OSB siding). A protective coating must then be used, but the variations of board moisture content (MC) are still quite high. In other applications, including wall and roof sheathing and single-layer flooring, moisture permeates into or out of the material due to seasonal variation in environmental conditions, which causes the product to expand and contract. Repeated moisture cycling often leads to warped and bowed boards, pushed out nails, and the separation of the panel from the structure (Burch and Thomas 1991). Prediction of OSB's performance characteristics (e.g., stability and strength) under all these circumstances requires a detailed knowledge of MC change and its relationship with environmental conditions (i.e., relative humidity (RH) and temperature).

The relationships between equilibrium

[1] This paper (No: 99-22-0343) is published with the approval of the Director of the Louisiana Agricultural Experiment Station.

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Wood and Fiber Science, 32(4), 2000, pp. 404–418

moisture content (EMC), RH, and temperature are known as sorption isotherms. Earlier work (Suchsland 1972; Richards et al. 1992; Wu and Suchsland 1996; Wu 1999b) in the field showed that wood composite materials have sorption isotherms that are different from those of solid wood. The difference was attributed largely to heat and pressure treatments that occur during wood composite manufacturing processes. Other studies (Halligan and Schniewind 1972; Geimer 1982) showed that panel density and resin content (RC) level affect the EMC at a given RH. However, little quantitative and systematic information is available for analyzing the effect of panel processing parameters on the sorption isotherms and for predicting long-term sorption behavior of OSB at varying exposure conditions. In this study, the EMCs of OSB manufactured under different processing conditions were measured under cyclic RH conditions at 25°C. The objectives of the study were: a) to determine sorption isotherms of OSB under cyclic RH exposure conditions; b) to fit the sorption data with an analytical model and to investigate effects of processing variables on model parameters; and c) to predict EMC distribution as a function of position in a panel with vertical density gradient and mean EMC changes under cyclic exposure conditions.

BACKGROUND

Relatively little literature is available in which the effect of wood composite processing on EMC for various RH levels has been studied. Jorgensen and Odell (1961) investigated dimensional stability of oak flakeboards and found that EMC increased with increases in resin spread while thickness changes were limited. Unassembled flakes that had resin treatment also equalized at a higher EMC in adsorption than either the dried or freshly cut flakes. Halligan and Schniewind (1972) presented sorption isotherms for two particleboards of different densities and different adhesive levels (urea-formaldehyde). They showed that board density was the most significant factor in reducing EMC; as density increased within each resin level, EMC decreased. Only at relative humidity above 90% was the EMC consistently reduced as the resin content increased. The reduced EMC at higher resin content levels was attributed to the blocking of sorption sites by the adhesive or to the adhesive itself. Similarly, Geimer (1982) showed that EMC decreased with increase in panel density for laboratory-made flakeboard and attributed the behavior to the lack of sorption sites for the high density boards.

Heat and pressure treatments are often attributed to the lower EMC values in wood-based panel products (Suchsland 1972; Geimer 1982). Suchsland (1972) measured sorption isotherms for ten commercial particleboards of both interior and exterior types. All boards exhibited large sorption hysteresis. Suchsland (1972) theorized that exposure to high temperatures commonly encountered in drying was responsible for the reduced hygroscopicity of particleboard as compared to solid wood. He also pointed out that press temperatures for the exterior particleboard are higher than those used for interior particleboard, possibly accounting for the lower hygroscopicity of the exterior boards. Repeated moisture cycling was shown to reduce the sorption hysteresis for both types of particleboard, leading to a gradual recovery of the lost sorption ability. Thus, sorption isotherms for particleboard were generally not reproducible under the cyclic exposure conditions. Very few experimental data are, however, available about the effect of cyclic moisture treatments on the sorption behavior of flake-type wood composites such as OSB.

Wood-based panels, including OSB, are manufactured with higher density faces and a lower density core to increase their bending properties (e.g., Harless et al. 1987). Because of the effect of panel density on its EMC, face and core layers of these products will arrive at different moisture levels when the panel is equilibrated at a given RH and temperature (Jorgensen and Odell 1961). This creates an

EMC distribution across panel thickness, which influences the swelling characteristics (e.g., linear expansion) of the panel. A theoretical analysis of the swelling and durability behavior thus requires a detailed knowledge of the EMC distribution across panel thickness for panels with vertical density gradient.

Various theories have been developed to describe sorption rates in solid wood. Anderson and McCarthy (1963) derived an equation for Type II adsorption on the basis of an exponential relationship between MC and differential heat of wetting. Combination of this exponential relationship with a form of the Gibbs-Helmholtz equation from thermodynamics results in a sigmoid relationship between MC and RH when temperature is constant. They showed that their isotherm accurately reproduces adsorption data for a number of fibrous materials over a range of relative humidities from 10 to 85%. Simpson (1971, 1973) developed nonlinear regression methods to fit sorption data for wood to several mathematical models of Type II adsorption. He found that the EMC of wood can be reproduced well with these techniques. Nelson (1983) developed a model based on Gibbs free energy to describe the Type II sorption behavior of cellulosic materials. The model is of the form

$$\frac{RH}{100} = \exp\left\{\left(-\frac{W_W}{R \cdot T}\right)\exp\left[A\left(1.0 - \frac{EMC}{M_V}\right)\right]\right\} \tag{1}$$

where:

- RH = relative humidity in percent
- $\exp$ = exponential function
- W_W = molecular weight of water (18 $mole^{-1}$)
- R = universal gas constant (1.9858 cal/mole/°K)
- T = absolute temperature (°K)
- A = natural logarithm (ln) of Gibbs free energy per gram of sorbed water as RH approaches zero (ΔG_0, cal/g), i.e., $A = \ln(\Delta G_0)$, and
- M_V = a material constant that approximates the fiber saturation point for desorption (%).

Wu and Suchsland (1996) and Wu (1999b) applied the model to various wood composites and overlays. The model was shown to describe the isotherms accurately. However, effects of processing variables on the model parameters for different products were not investigated in the study. Determination of these effects will enable the prediction of EMC distribution across panel thickness and long-term sorption behavior of wood composites under cyclic exposure conditions.

MATERIAL AND METHODS

Board fabrication

Forty-four single-layer and thirty-two three-layer OSB panels were manufactured for the study. The details of flake preparation and the panel manufacturing process are given in Wu (1999a). The single-layer panels (609.6 × 711.2 × 12.7 mm) were pressed to thickness in a cold press and were then heated under pressure to cure the adhesive. The three-layer boards (609.6 × 609.6 × 12.7 mm) were pressed in a conventional manner for 8 min at a temperature of 190°C. All boards were made with 0.5% wax at the 4% and 6% resin content levels. After pressing, the boards were weighed and measured for thickness. The panels were then trimmed to reduce the edge effects on test specimens.

Flake orientation distribution

One hundred and twenty flakes were randomly selected from the top surface of each panel. The flakes were traced on to clear plastic film by drawing parallel lines along the long direction of the flakes. The orientation of each traced line was measured (Wu 1999a). The underlying flake orientation distribution was assumed to be the von Mises probability distribution (Harris and Johnson 1982). To obtain the concentration parameter, the alignment percent defined by Geimer (1982) and mean flake angle among the number of flakes measured were calculated for each panel. The look-up table published by Shaler (1991) with the alignment percent and mean angle as input was used to obtain the concentration parameter.

Density profile

Six 50.8 × 50.8 × 12.7 mm specimens were cut from each panel to determine the density profile across panel thickness. All specimens were conditioned to reach equilibrium at 60% RH and 25°C. Density profile in the specimen thickness direction was then determined on an X-ray based Quintek Density Profiler (Model QDP-01X). The specimens were positioned during measurements with the top surface as the starting position. The measured density values were given as a function of position at an increment of 0.0508 mm. The density values at the same position for the six specimens from each panel were averaged to obtain the average density profile for each panel. The density data (position and density) were read into the simulation program to study effects of density on the EMC distribution across panel thickness.

Sorption tests

Sorption tests were conducted in conjunction with thickness swelling and linear expansion measurements. Two samples, 25.4 × 304.8 × 12.7 mm, were cut along each of the two principal directions from each board, totaling 152 samples for each direction. This gave four replications for each combination of density, flake alignment level, and resin content. They were numbered according to board type, material direction (parallel or perpendicular), and replication number.

All specimens were initially dried in a convection oven at 60°C to reach a constant weight. Measurements, including specimen weight, length, width, and thickness of each specimen, were made at the dry state. The specimens were conditioned to reach equilibrium according to the following scheme:

$$
\begin{array}{ll}
1^{st}\text{ Cycle:} & \text{Dry} \rightarrow 35\% \rightarrow 55\% \rightarrow 75\% \\
 & \rightarrow 85\% \rightarrow 93\% \rightarrow 75\% \\
 & \rightarrow 35\% \\
2^{nd}\text{ Cycle:} & \rightarrow \ldots \rightarrow 75\% \rightarrow \ldots \\
 & \rightarrow 93\% \rightarrow \ldots \rightarrow 35\% \\
3^{rd}\text{ Cycle:} & \rightarrow \ldots \rightarrow 75\% \rightarrow \ldots \\
 & \rightarrow 93\% \rightarrow \ldots \rightarrow 35\% \\
 & \rightarrow \text{OD.}
\end{array}
$$

For both single-layer and three-layer boards, the exposure time was 12 months for the first cycle and 6 months each for the two subsequent cycles. The measurements (specimen weight, length, width, and thickness) were repeated at each RH condition. Finally, all specimens were oven-dried for 24 h at 103 ± 2°C to determine their oven-dry weight and dimension.

Fitting Nelson's model

Experimental data of EMCs at various RHs were fit to the inverse form of Eq. (1):

$$\text{EMC} = M_V\left\{1.0 - \frac{1}{A}\ln\left[\left(-\frac{R\cdot T}{W_W}\right)\ln\left(\frac{RH}{100}\right)\right]\right\} \tag{2}$$

to determine the material parameters A and M_V for the model (Wu 1999b). A regression analysis was performed with the measured EMC as the dependent variable and transformed relative humidity, RH^T, as the independent variable:

$$\text{EMC} = M_V + B\ RH^T \tag{3}$$

where, $B = -M_V/A$, and $RH^T = \ln[(-R\cdot T/W_W)\ln(RH/100)]$. Parameters M_V and A from the regression analysis were expressed as a function of processing variables using SAS (SAS Institute 1996) as:

$$P = aSG^b\kappa^cRC^dSR^e \tag{4}$$

where:

P = property: M_V or A
RC = resin content (%)

SG = panel specific gravity
κ = concentration parameter for the von Mises distribution
SR = shelling ratio, i.e., dry flake weight ratio between face and core layers in a three-layer board
a, b, c, d and e = regression constants.

In fitting Eq. (4), natural logarithm transformation of both dependent variables (MY and A) and independent variables (RC, κ, SG, and SR) was first performed. A multilinear regression analysis based on a backward selection procedure was then made with the transformed variables. The backward selection procedure removed insignificant terms at the 0.05 significance level from the model.

Predicting internal EMC distribution for three-layer boards

To predict internal EMC distribution for three layer boards with a vertical density gradient at a given RH level, panel thickness was divided into a number of N layers (Fig. 1). Average specific gravity of layer i, $SG_L(i)$, was calculated from the measured density profile within the layer:

$$SG_L(i) = \frac{\sum_{j=1}^{n} SG_{NP}(j)}{n} \quad (5)$$

where:

$SG_L(i)$ = average specific gravity of the layer i
$SG_{NP}(j)$ = measured specific gravity at nodal point j in the layer i
n = total number of nodal points within the layer i.

$A_L(i)$ and $M_{VL}(i)$ of the layer were calculated from Eq. (4) using calculated $SG_L(i)$ and panel manufacturing variables (e.g., RC, AL, etc.). $EMC_L(i)$ of the layer was calculated from Eq. (2) with known $A_L(i)$ and $M_{VL}(i)$. Finally, panel EMC at the given RH level was calculated as:

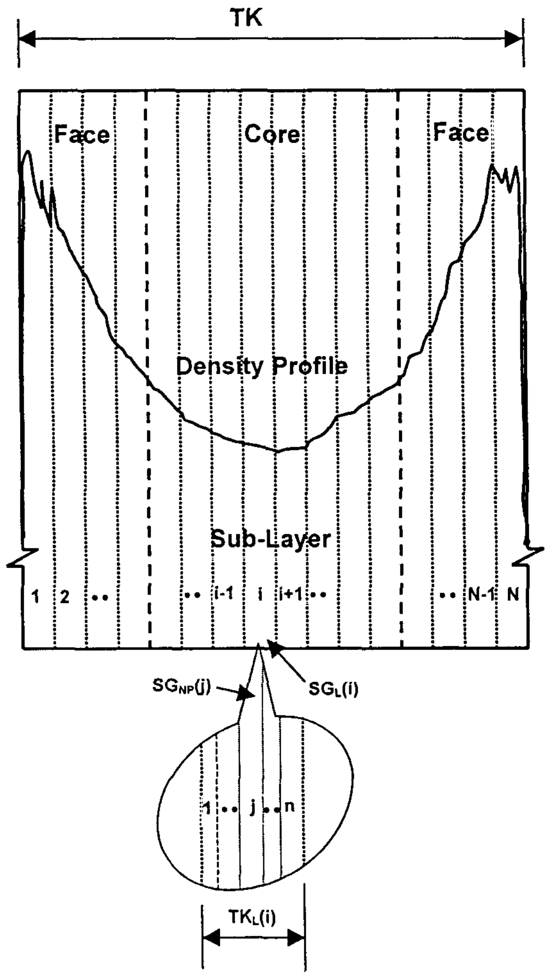

FIG. 1. Division of panel thickness into a number of N layers for predicting EMC distribution across panel thickness and panel sorption isotherm.

$$EMC(RH) = \frac{\sum_{i=1}^{N} EMC_L(i)}{N} \quad (6)$$

where N is the number of layers divided across board thickness. A computer program was written to perform the calculation outlined above. The calculation was repeated for various RH levels to generate sorption isotherms for different panels. The simulated sorption isotherm for a given panel type was compared with measured EMC data from the first exposure cycle.

Predicting EMC under cyclic exposure conditions

For each panel type, the model parameters, A and M_V, from the first adsorption and desorption cycle were used to predict EMC change of the subsequent adsorption and desorption cycles respectively using Eq. (2). This was done to see whether the isotherms are reproducible under cyclic exposure conditions and whether the characterized model Eq. (2) from the first exposure cycle can be used to predict EMC change of subsequent exposure cycles. The predicted EMCs were compared to the measured values for various panels.

RESULTS AND DISCUSSION

Flake orientation distribution and density profile

Initial measurements of board properties included flake orientation distribution, density, and vertical density gradient across panel thickness. A comparison of measured flake orientation and density distributions for the single- and three-layer boards is shown in Fig. 2. The concentration parameter averaged 9.23, 2.34, and 0.13 for the single-layer boards with high, low, and random alignment levels, respectively (Fig. 2a). The corresponding alignment percentages were 82%, 61%, and 5%. Random boards were not completely random (i.e., κ was not equal to zero) according to the measured flake orientation distribution. For three-layer boards (Fig. 2c), the concentration parameter averaged 6.23 for high alignment boards and 1.87 for low alignment boards. The corresponding alignment levels were 78% and 50%. For both single- and three-layer boards, as the value of κ decreased, a greater percentage of flakes was aligned towards the direction perpendicular to the major alignment direction. Vertical density gradient for the single-layer boards at various panel density levels was effectively eliminated by using a cold press at closing (Fig. 2b). All three-layer boards had a regular vertical density profile across panel thickness as a result of hot pressing (Fig. 2d).

Figure 2 demonstrates the primary difference between single- and three-layer boards manufactured for the study. Test data generated from the single-layer uniform density boards enable the simulation of layer properties for predicting panel behavior of a three-layer board with density gradient.

Sorption isotherms from the first exposure cycle

Isotherms.—Typical sorption isotherms from the first exposure cycle are shown in Fig. 3 (a: single-layer board and b: three-layer board). The adsorption curve being lower than the desorption curve indicates a lower EMC value at a fixed RH level as approached from adsorption (i.e., sorption hysteresis). For single-layer boards, boards at higher density levels reached lower EMCs at a given RH level, especially at higher RH levels. For three-layer boards, the EMC difference between adsorption and desorption at a given RH level was larger, compared to that of the single-layer boards. However, board density, resin content, flake alignment level, and board construction variable (i.e., shelling ratio) had little effect on the shape of the sorption curve. Thus, the general shape of all sorption curves is essentially the same.

Density was a primary variable that affected EMC values of the single-layer boards at a given RH level. Also, the effect of density varied with RH levels. Statistical comparison using SAS PROC REG showed that panel density had no significant effect on EMC at the 0.05 significance level under the 32% RH exposure condition (P-value = 0.084). However, density effect was significant at the 72%, 85%, and 94% RH levels (P-value < 0.0001). At the higher RH levels, a higher panel density led to lower EMC values of the board. This result agrees with that reached by Halligan and Schniewind (1972) for particleboard and Geimer (1982) for flakeboard. This was attributed to the fact that more sorption sites are avail-

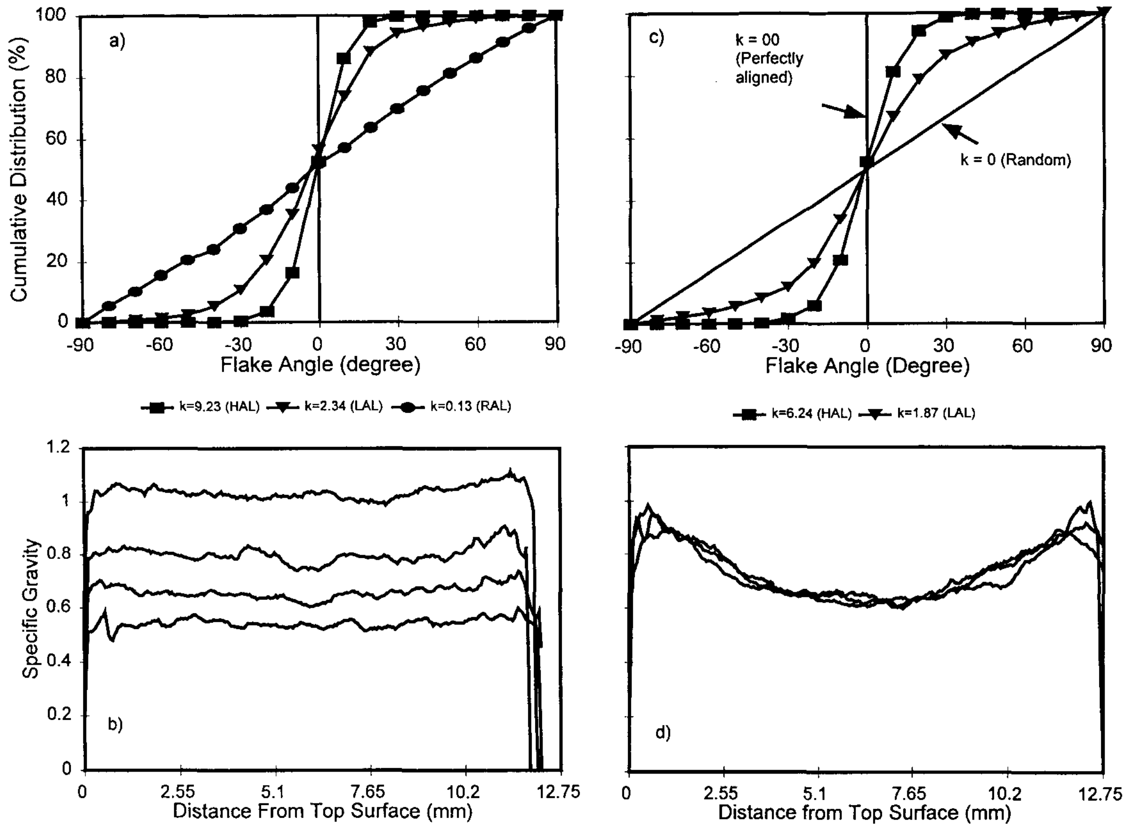

FIG. 2. Measured flake orientation distribution (a: single-layer boards and c: three-layer boards) and density profile (b: single-layer boards and d: three-layer boards). RAL = random alignment level, LAL = low alignment level, and HAL = high alignment level.

able for water sorption in low density boards than in high density boards. The larger amounts of wood material in the high density boards should not reduce the EMC as the hygroscopicity of the wood is the same. However, additional heating and pressing time required for the high density boards may have reduced the hygroscopicity of the wood (Kelly 1977).

The average EMC for panels at 6% resin content levels was about 0.5% higher than the value from the boards at 4% resin content level at all exposure levels. Thus, even though resin content had a significant effect on EMC, the EMC difference at the two resin content levels was practically small. Halligan and Schniewind (1972) reported that the EMC was reduced as the resin content increased only at RHs above 90%. They contributed the behavior to increased bonding efficiency at higher resin levels and to the increased amount of adhesive itself.

Flake alignment level did not affect the EMC values significantly (P-value > 0.05). The reason for this is because different levels of flake alignment did not change the sorption sites in a panel under the same resin and density level.

Effect of panel processing parameters on EMC values reached was less obvious for the three layer boards. The EMC differences from boards at various levels of alignment, resin content, and shelling ratio (i.e., dry flake weight ratio between face and core layers) were within 0.5% at a given RH level, which is practically insignificant. This behavior was

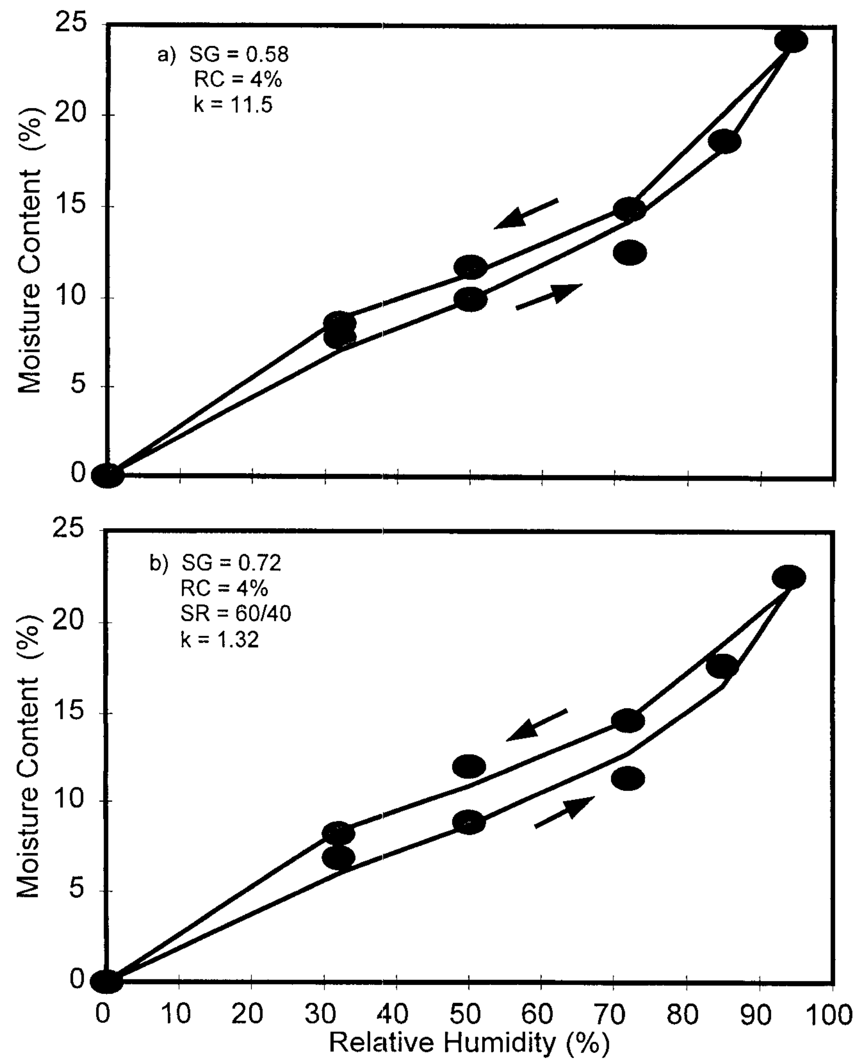

FIG. 3. Typical sorption isotherms of OSB (a: single-layer boards and b: three-layer boards). Dot line—measured data and solid line—predicted value by Nelson's model.

primarily due to the fact that panel density had a dominant effect on EMC reached and there was only one density level used in the manufacture of the three-layer panels.

Fitting the sorption model.—Nelson's model fits the experimental EMC-RH data well with the estimated coefficient of determination varying from 0.92 to 0.99 (Fig. 3—lines). The model parameters (A and M_V) are summarized in Table 1 for single-layer boards and Table 2 for three-layer boards. Typical plots of the parameters from the single-layer boards as a function of panel density are shown in Fig. 4.

The mean values of M_V were 24.5 for adsorption and 26.3 for desorption for all single-layer boards (Table 1). M_V decreased significantly with increase in panel density in adsorption, while only a slight decrease occurred in desorption (Figs. 4a and 4c). Parameter M_V, as defined in the Nelson's model, approximates the fiber saturation point in desorption occurring in a reproducible sorption cycle. The

TABLE 1. *Results of regression analysis on sorption isotherms for single-layer boards with uniform density profile. Values in parentheses are standard deviations.*

Board type	Specific gravity	k	Adsorption M_V (%)	Adsorption A (cal/g)	Desorption M_V (%)	Desorption A (cal/g)
4% Resin Content						
High alignment level	0.58 (0.06)	11.5	27.94 (0.20)	4.86 (0.04)	26.96 (0.25)	5.41 (0.04)
	0.84 (0.06)	9.47	24.52 (0.49)	5.30 (0.04)	26.26 (0.24)	5.42 (0.02)
	1.05 (0.03)	9.05	22.41 (0.32)	5.36 (0.09)	25.53 (0.38)	5.44 (0.04)
	1.23 (0.04)	8.67	22.13 (2.22)	5.20 (0.11)	24.86 (1.08)	5.40 (0.04)
Low alignment level	0.62 (0.01)	2.35	26.72 (0.25)	4.84 (0.02)	27.29 (0.39)	5.30 (0.05)
	0.81 (0.03)	2.50	23.64 (0.45)	5.11 (0.09)	26.14 (0.50)	5.38 (0.05)
	1.01 (0.03)	2.29	21.93 (0.40)	5.54 (0.06)	25.97 (0.33)	5.38 (0.03)
	1.20 (0.01)	2.42	21.31 (0.30)	5.36 (0.05)	25.27 (0.46)	5.35 (0.03)
Random alignment level	0.59 (0.05)	0.15	26.01 (0.15)	4.89 (0.06)	27.84 (0.12)	5.25 (0.02)
	0.80 (0.04)	0.21	25.49 (0.61)	5.06 (0.04)	26.80 (0.41)	5.42 (0.03)
	0.95 (0.04)	0.15	23.97 (0.29)	5.15 (0.20)	25.45 (0.26)	5.45 (0.06)
6% Resin Content						
High alignment level	0.59 (0.02)	9.69	27.78 (0.36)	4.80 (0.09)	27.46 (0.52)	5.36 (0.09)
	0.84 (0.02)	9.73	24.83 (0.66)	5.31 (0.09)	26.56 (0.10)	5.47 (0.03)
	1.03 (0.07)	8.49	23.18 (0.63)	5.48 (0.11)	25.86 (0.46)	5.45 (0.03)
	1.23 (0.04)	7.06	22.83 (2.13)	5.17 (0.15)	25.20 (1.07)	5.37 (0.07)
Low alignment level	0.62 (0.02)	2.18	27.36 (0.24)	4.93 (0.02)	27.08 (0.14)	5.35 (0.02)
	0.83 (0.04)	2.36	23.82 (0.45)	5.36 (0.13)	26.41 (0.22)	5.44 (0.03)
	1.01 (0.02)	2.29	23.86 (1.03)	5.53 (0.20)	26.91 (0.33)	5.38 (0.03)
	1.15 (0.05)	2.33	23.57 (0.24)	5.41 (0.05)	26.71 (0.38)	5.38 (0.06)
Random alignment level	0.56 (0.04)	0.10	26.99 (0.35)	5.00 (0.05)	27.02 (0.31)	5.44 (0.04)
	0.74 (0.03)	0.13	24.78 (0.44)	5.18 (0.14)	25.93 (0.24)	5.47 (0.03)
	0.97 (0.04)	0.04	23.03 (0.43)	5.72 (0.06)	25.41 (0.21)	5.52 (0.02)

TABLE 2. *Results of the regression analysis on sorption isotherms for three-layer boards with density gradient. Values in parentheses are standard deviations.*

Board type	Specific gravity	k	Adsorption M_V (%)	Adsorption A (cal/g)	Desorption M_V (%)	Desorption A (cal/g)
4% Resin Content						
High alignment level	0.75 (0.03)	6.35	24.62 (0.37)	4.67 (0.09)	26.27 (0.24)	5.24 (0.02)
	0.76 (0.03)	5.02	24.75 (0.33)	4.62 (0.02)	26.23 (0.35)	5.24 (0.04)
	0.76 (0.02)	6.57	25.19 (0.29)	4.74 (0.04)	26.00 (0.26)	5.29 (0.02)
	0.75 (0.03)	6.62	25.73 (0.37)	4.72 (0.02)	26.73 (0.56)	5.28 (0.03)
Low alignment level	0.74 (0.03)	1.54	24.89 (0.22)	4.77 (0.06)	26.61 (0.22)	5.30 (0.02)
	0.74 (0.03)	1.51	24.81 (0.31)	4.81 (0.04)	26.79 (0.23)	5.30 (0.03)
	0.74 (0.03)	1.84	25.25 (0.42)	4.80 (0.02)	26.94 (0.27)	5.30 (0.04)
	0.72 (0.02)	1.32	26.32 (0.17)	4.73 (0.05)	26.99 (0.35)	5.36 (0.19)
6% Resin Content						
High alignment level	0.73 (0.03)	5.78	26.09 (0.51)	4.91 (0.04)	26.83 (0.24)	5.41 (0.04)
	0.75 (0.02)	6.09	25.81 (0.43)	4.87 (0.07)	27.53 (0.16)	5.33 (0.04)
	0.76 (0.04)	6.44	24.65 (0.38)	4.82 (0.09)	26.75 (0.16)	5.31 (0.03)
	0.75 (0.03)	7.00	25.43 (0.52)	4.89 (0.02)	26.08 (0.35)	5.40 (0.06)
Low alignment level	0.71 (0.02)	1.47	26.40 (0.42)	4.70 (0.09)	25.90 (0.25)	5.42 (0.03)
	0.75 (0.02)	1.67	25.70 (0.54)	4.82 (0.05)	26.12 (0.56)	5.45 (0.06)
	0.71 (0.02)	1.79	26.60 (0.28)	4.89 (0.06)	26.67 (0.39)	5.46 (0.04)
	0.73 (0.02)	1.61	26.11 (0.17)	4.88 (0.06)	26.64 (0.76)	5.37 (0.12)

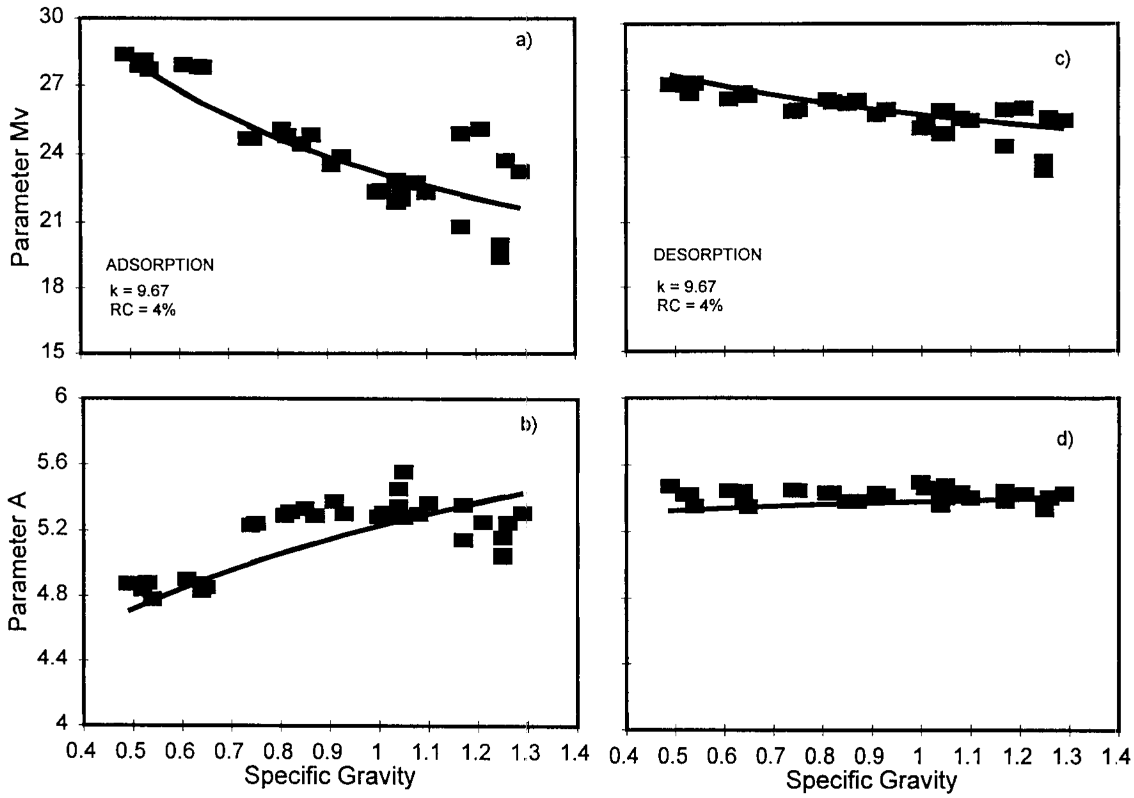

FIG. 4. Model parameters as a function of specific gravity for the single-layer boards. Adsorption (a: M_V and b: A) and Desorption (a: M_V and b: A). Dot line—measured and solid line—predicted by Nelson's model.

larger M_V values for cellulosic materials reflect more sorption sites available so that there are higher saturation MCs associated with sorption in these materials. Nelson (1983) reported that the solid wood at 25°C had M_V values of 24.8 for adsorption and 29.6 for desorption. The mean value of M_V for OSB in adsorption was, thus, similar to that of solid wood. However, the desorption value was about 3% smaller, indicating a reduced saturation point for the material. As shown in Table 1, parameter A ranges from 4.80 to 5.72 with an average of 5.21 for adsorption and from 5.25 to 5.52 with an average of 5.40 for desorption for the single-layer boards. Parameter A increased with increase in panel density in adsorption, while it varied little in desorption (Figs. 4b and 4d).

A multilinear regression analysis was carried out to establish correlations between model parameters (A and M_V) and panel processing variables (Eq. (4)). The regression equations for adsorption are:

$$M_V = 21.5SG^{-0.2780}K^{0.0044}RC^{0.051}$$

$$R^2 = 0.74$$

$$A = 4.93SG^{0.1464}K^{-0.005}RC^{0.0499}$$

$$R^2 = 0.56 \qquad (7)$$

and for desorption,

$$M_V = 25.14SG^{-0.0948}K^{0.0019*}RC^{0.0178*}$$

$$R^2 = 0.48$$

$$A = 5.28SG^{0.0143}K^{-0.0015*}RC^{0.0169*}$$

$$R^2 = 0.17 \qquad (8)$$

where variables marked with a "*" sign are not significant at the $\alpha = 0.05$ level. Equations (7) and (8) indicate that effects of all processing variables (i.e., SG, RC, and k) on parameters A and M_V for adsorption were significant at the 5% significance level. For desorption, however, panel SG was the only variable that had an effect on M_V. Also, the overall correlations between the parameters and processing variables were weak for the desorption cycle. Equations (8) and (9) provide sorption parameters as a function of processing variables for the individual strand layers with a uniform density. These functions enable the prediction of sorption behavior of OSB panels with density gradient across panel thickness.

Similar to the single-layer boards, Nelson's model provides an excellent fit to the EMC-RH data from the three-layer boards with density gradient (Fig. 3b). Among all three-layer boards, the model parameter A ranges from 4.62 to 4.91 (mean = 4.79) for adsorption and from 5.24 to 5.46 (mean = 5.34) for desorption. The mean values of M_V were 25.5 for adsorption and 26.6 for desorption for three-layer boards. The desorption M_V was also smaller than that of solid wood. A nonlinear regression analysis between model parameters and processing variables for all three-layer boards led to weak correlations between various variables. The regression equations for adsorption are:

$$M_V = 19.97 SG^{-0.2802} \kappa^{0.0092} RC^{0.0561} SR^{0.0216}$$
$$R^2 = 0.49$$
$$A = 4.16 SG^{0.023*} \kappa^{-0.003*} RC^{0.0599} SR^{0.0148}$$
$$R^2 = 0.36 \tag{9}$$

and for desorption:

$$M_V = 24.98 SG^{-0.0973} \kappa^{0.0012} RC^{-0.0036} SR^{0.0096}$$
$$R^2 = 0.05$$
$$A = 4.88 SG^{-0.023*} \kappa^{-0.0069} RC^{0.0479} SR^{0.004*}$$
$$R^2 = 0.41 \tag{10}$$

where variables marked with a "*" sign are not significant at the 0.05 level. In the analysis, specimen density was also included in the model, even though there was only one target panel density. Equations (9) and (10) indicate that panel processing variables had little effect on the model parameters for the boards considered. This implies that the sorption behavior was similar for those three-layer boards.

Hysteresis ratio.—The hysteresis ratio, a ratio of the boundary adsorption MC to the boundary desorption MC (A/D ratio) at a given RH, was calculated as a function of relative humidity for both single- and three-layer boards. The ratios ranged from 0.81 to 0.95 for single-layer boards and from 0.76 to 0.86 for three-layer boards. The A/D ratios for three-layer boards were lower than those for single-layer boards, indicating a larger sorption hysteresis for these boards. For both of single- and three-layer boards, the A/D ratios were higher at lower RH conditions. Stamm (1964) reported that the hysteresis (A/D) ratio varies from about 0.75 to 0.90. This variability primarily depends upon the RH level and the nature of the sorbing material. Among the processing variables (density, resin content, flake alignment level, and shelling ratio) for both single- and three-layer boards, resin content was the only variable that affected the A/D ratio significantly. Boards made with 6% resin content had higher A/D ratios compared to those at the 4% RC level.

Internal EMC distribution for boards with density gradient

There were 250 measured density points ($SG_{NP}(j)$ in Fig. 1) with a uniform spacing of 0.0508 mm for a 12.7-mm-thick panel. The panel was divided into twenty layers with the first five layers from each face containing 13 density points and the rest 12 points. The individual data points within each layer were averaged to get the mean density for the layer ($SG_L(i)$ in Fig. 1). Internal EMC distribution at a given RH level was predicted using the mean density and fitted model parameters (Eqs. (7) and (8)).

Typical measured density profile and predicted EMC distribution (at 90% RH exposure

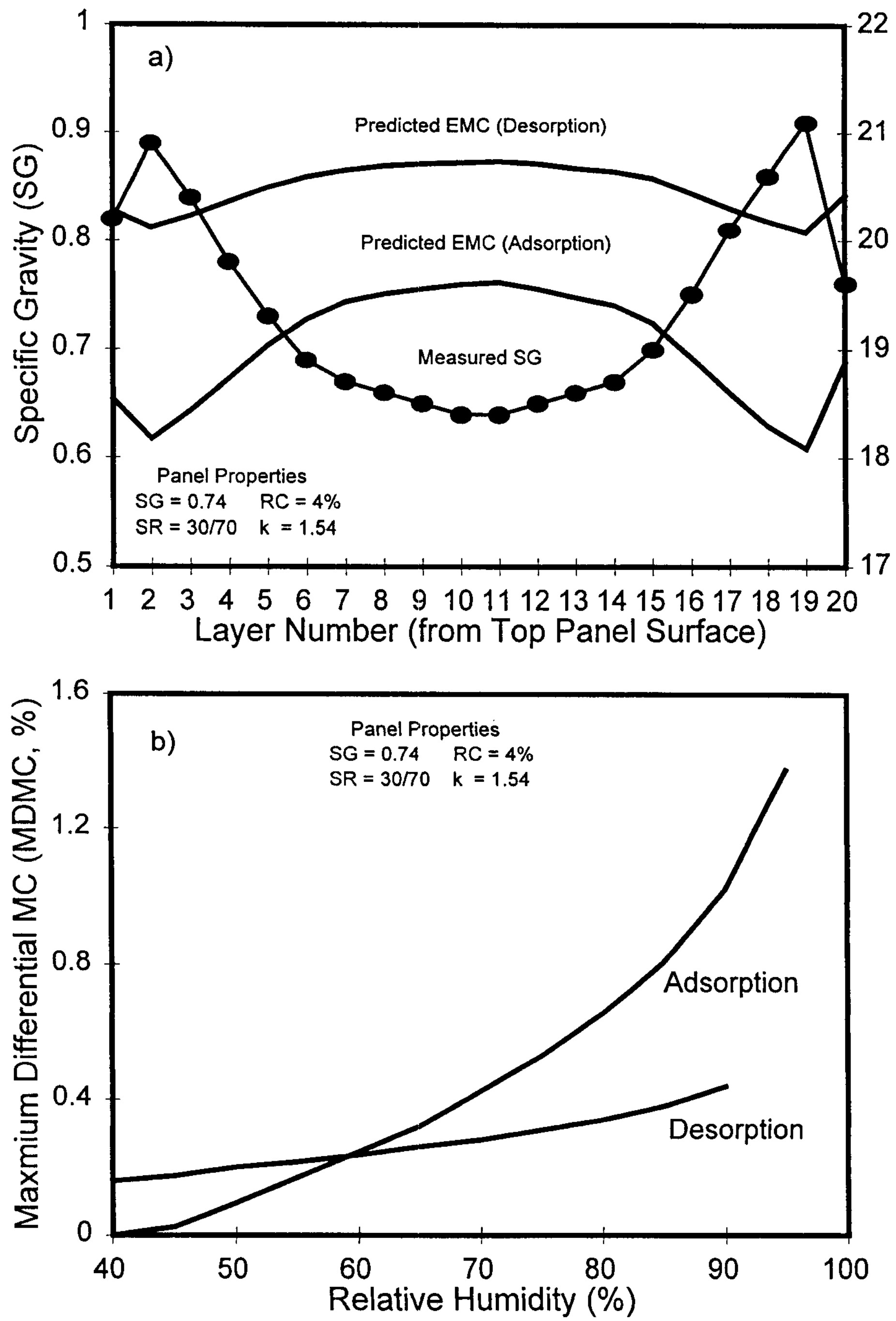

FIG. 5. Typical internal EMC distribution for a three-layer board with density gradient. (a) Predicted EMC at 90% RH level (board thickness = 12.7 mm) and (b) maximum differential MC as a function of RH.

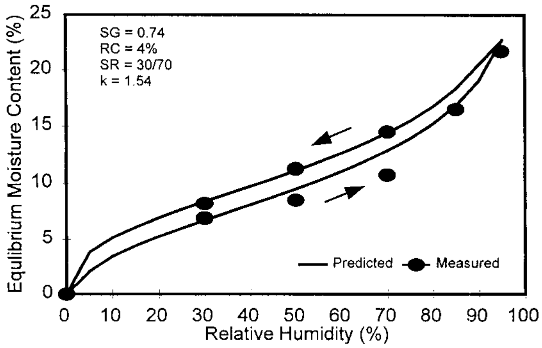

FIG. 6. Predicted sorption isotherms for three-layer boards with density gradient in comparison with measured values.

condition) across board thickness are shown in Fig. 5a. As shown, the maximum density occurred at the face region (about 1 mm from the surface), while the minimum density value in the center of the panel. A reverse pattern of EMC occurred in both adsorption and desorption. The face region had the minimum EMC value and the core had the maximum EMC value, reflecting the effect of density on panel EMC as shown earlier. Desorption cycle led to higher EMC values compared to the adsorption cycle (i.e., sorption hysteresis). Panel processing variables (i.e., RC, AL, and SR) had little effect on the shape of the EMC curve.

The maximum differential MC (MDMC = Maximum face MC − Minimum core MC) within the panel was calculated as a function of RH. A typical plot of MDMC versus RH is shown in Fig. 5b. In adsorption, density gradient across board thickness had little effect on internal EMC distribution at low RH levels (i.e., below 50%). At the higher RH levels, however, lower core density led to a higher EMC value in the core, while higher face density led to a lower EMC value. As a result, MDMC increased with an increase in the RH level. At the 95% RH level, MDMC reached about 1.5%. Thus, for accurate prediction of swelling behavior of OSB, an EMC distribution, rather than a mean panel EMC, needs to be considered. In desorption, MDMC was less than 0.5% over the entire RH range due to a

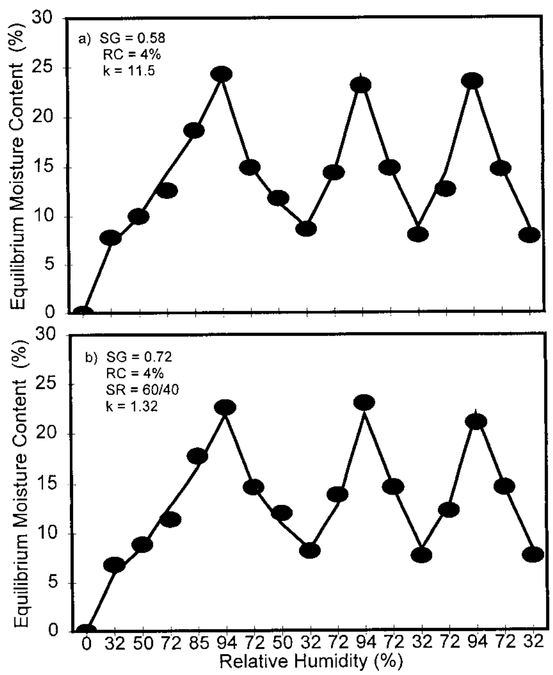

FIG. 7. A comparison of measured and predicted sorption isotherms under cyclic exposure conditions. a) single-layer boards and b) three-layer boards. Dot line—measured data and solid line—predicted value by Nelson's model.

lesser effect of density on EMC under the sorption mode as discussed earlier.

The predicted EMCs of individual layers within a given board at each RH condition were averaged to get the mean EMC for the board at the specified RH level. The obtained values were plotted against RH for both adsorption and desorption cycles in comparison with measured EMC data (Fig. 6). As shown, the sorption isotherm for a three-layer board can be predicted reasonably well based on measured density profile and fitted model parameters of individual layers.

Sorption isotherms under cyclic exposure conditions

Typical sorption isotherms of OSB under long-term cyclic RH exposure conditions are shown in Fig. 7 (a: single-layer boards and b: three-layer boards). The exposure time was 12 months for the first cycle and 6 months each for the two subsequent cycles. The predicted isotherms (lines) for both single- and three-layer boards were based on the model parameters fitted from the first exposure cycle for each board type.

For both single- and three-layer boards, the EMC values reached in the subsequent exposure cycles were practically the same as those reached during the first exposure cycle at the same RH level. This indicates that the isotherms for OSB are practically reproducible. Suchsland (1972) showed that repeated cycling in RH condition led to a reduction of the sorption hysteresis for particleboard, indicating that the lost sorption ability for particleboard gradually recovered under cyclic exposure condition. As a result, the sorption isotherms for particleboard were generally not reproducible. The difference was thought to be due to differences in particle size and treatments (e.g., heat and pressure) applied for manufacturing different products (Wu 1999b).

The predicted isotherms based on the parameters from the first exposure cycle show an excellent agreement with measured EMC values. In practice, OSB is often subjected to long-term cyclic RH exposure conditions which lead to repeated shrinkage and swelling of the product. Thus, the ability to predict EMC change under long-term cyclic exposure conditions may help develop control measures for improving long-term durability properties of OSB. The results from this study showed that long-term sorption behavior of OSB can be predicted based on the sorption data from the initial exposure cycle.

SUMMARY AND CONCLUSIONS

Sorption behavior of OSB under long-term cyclic RH exposure conditions was investigated in this study. Experimental data were analyzed with Nelson's sorption model. From the study, the following conclusions were reached:

1. Nelson's sorption model can be used to accurately describe the sorption data of OSB. The parameters that define the sorption isotherm varied with sorption mode (adsorption versus desorption) and panel processing variables.
2. Panel density is the primary variable that influences the magnitude of EMCs in OSB reached at a given RH level and its effect varies with the RH levels.
3. For a panel with vertical density profile, face layers with a higher density generally reach a lower EMC value compared to that of the core layer at a given RH level.
4. Under cyclic exposure conditions, sorption isotherms in OSB are reproducible and can be predicted by Nelson's model and parameters from the initial exposure cycle.

This study provides a more fundamental understanding of the long-term sorption behavior of OSB. The layer sorption properties and analytical approach developed to predict EMC distribution across panel thickness could provide accurate predictions of linear expansion of a three-layer, cross-laminated panel with density gradient in future studies.

ACKNOWLEDGMENTS

The authors wish to thank Dr. Otto Suchsland and Mr. Bob Geimer for their assistance at the early stages of this project. This work is currently being supported, in part, by the USDA NRI Competitive Grant Program (97-35103-5055) and by the Louisiana Educational Quality Support Fund [LEQSF(1997-99)-RD-A-03]. Their financial contribution to the project is gratefully acknowledged.

REFERENCES

ANDERSON, N. T., AND J. L. MCCARTHY. 1963. Two-parameter isotherm equation for fiber-water systems. Ind. Eng. Chem. Process Des. Develop. 2:103–105.

BURCH, D. M., AND W. C. THOMAS. 1991. An analysis of moisture accumulation in a wood frame wall subjected to winter climate. NISTIR 4674. National Institute of Standards and Technology, United States Department of Commerce, Gaithersburg, MD. 30 pp.

———, ———, AND A. H. FANNEY. 1992. Water vapor permeability measurements of common building materials. ASHRAE Trans. 98:486–494.

GEIMER, R. L. 1982. Dimensional stability of flakeboards as affected by board specific gravity and flake alignment. Forest Prod. J. 32(8):44–52.

HALLIGAN, A. F., AND A. P. SCHNIEWIND. 1972. Effect of moisture on physical and creep properties of particleboard. Forest Prod. J. 22(4):41–48.

HARLESS, T. E. G., F. G. WAGNER, P. H. SHORT, R. D. SEALE, P. H. MITCHELL, AND D. S. LADD. 1987. A model to predict the density profile of particleboard. Wood Fiber Sci. 19(1):81–92.

HARRIS, R. A., AND J. A. JOHNSON. 1982. Characterization of flake orientation in flakeboard by the Von Mises probability distribution. Wood Fiber 14(4):254–266.

JORGENSEN, R. N., AND R. L. ODELL. 1961. Dimensional stability of oak flake board as affected by particle geometry and resin spread. Forest Prod. J. 11(10):463–466.

KELLY, M. W. 1977. Critical literatures review of relationship between processing parameters and physical properties of particleboard. Gen. Tech. Rep. FPL-20. USDA Forest Serv., Forest Prod. Lab. Madison, WI. 65 pp.

NELSON, R. M. 1983. A model for sorption of water vapor by cellulosic materials. Wood Fiber Sci. 15(1):8–22.

RICHARDS, R. F., D. M. BURCH, AND W. C. THOMAS. 1992. Water vapor sorption measurements of common building materials. ASHRAE Trans. 98:475–485.

SAS INSTITUTE INC. 1996. SAS/STAT user's guide. Version 6. SAS Institute Inc. Cary, NC. 1688 pp.

SHALER, S. M. 1991. Comparing two measures of flake alignment. Wood Sci. Technol. 26:53–61.

SIMPSON, W. T. 1971. Equilibrium moisture content prediction for wood. Forest Prod. J. 21(5):48–49.

———. 1973. Predicting equilibrium moisture content of wood by mathematical models. Wood Fiber 5(1):41–49.

STAMM, A. J. 1964. Wood and cellulose science. Ronald Press, New York, NY. 549 pp.

SUCHSLAND, O. 1972. Linear hygroscopic expansion of selected commercial particleboard. Forest Prod. J. 22(11): 28–32.

WU, Q. 1999a. In-plane dimensional stability of oriented strand panel: effect of processing variables. Wood Fiber Sci. 31(1):28–40.

———. 1999b. Application of Nelson's sorption isotherm to wood composites and overlays. Wood Fiber Sci. 31(2)187–191.

———, AND O. SUCHSLAND. 1996. Prediction of moisture content and moisture gradient of an overlaid particleboard. Wood Fiber Sci. 28(2):227–239.