THICKNESS SWELLING OF ORIENTED STRANDBOARD UNDER LONG-TERM CYCLIC HUMIDITY EXPOSURE CONDITION[1]

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(Received February 2001)

ABSTRACT

Thickness swelling (TS) measurements for oriented strandboard (OSB) were carried out under cyclic relative humidity (RH) conditions at 25°C. Measurements were made by placing test materials in a climate-controlled conditioning chamber until specimens reached their steady-state equilibrium moisture content (EMC) at each given RH.

Thickness swelling hysteresis or residual TS developed in all panels as a result of cyclic humidity exposure. The largest hysteresis occurred during the first adsorption cycle. Subsequent adsorption processes led to significantly smaller increases in the hysteresis. TS rate from the first adsorption cycle increased with increase in panel MC level and density, and decreased with increase in resin content. Flake alignment level and flake weight ratio for the three-layer boards played a less significant role in controlling the total TS and the swelling rate. The mean swelling rate was the largest from the first adsorption cycle. The rate decreased significantly during subsequent adsorption cycles.

A procedure was developed to predict TS and TS distribution for panels with a density gradient based on measured layer TS rate and density. The predicted total TS matched experimental data well. The predicted TS distribution across panel thickness followed the distribution of EMC change, rather than the vertical density profile. For a given RH exposure condition, TS was generally smaller in the high-density surface region compared to the low-density core because of smaller EMC changes in the face.

Keywords: Thickness swelling, moisture cycling, structural panel, processing variables, modeling.

INTRODUCTION

In-service environments that oriented strandboard (OSB) might be exposed to can be involved with various environmental factors and their combinations due to OSB's diverse applications. Especially, environmental conditions with repeated changes in relative humidity (RH) and temperature under exterior applications, such as OSB siding, often cause large variation in board moisture content (MC). This could lead to board deformations (e.g., bowing and warping), pushed-out nails, and even structural failure. In order to prevent OSB from having such deformations, fundamental information on MC change and its relationship with dimensional change of OSB is needed.

It is well known that wood-based composites swell significantly in the thickness direction under high RH. The total thickness swelling (TS) has two components: recoverable TS and nonrecoverable TS. Recoverable TS is the

[1] This paper is published with the approval of the Director of the Louisiana Agricultural Experiment Station.
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Wood and Fiber Science, 34(1), 2002, pp. 125–139

swelling of the wood due to MC change within the hygroscopic range. Nonrecoverable TS is a result of the combined effect of the compression stress release from the pressing operation and differential swelling potential due to inherent in-plane density variation. The latter results in normal swelling stresses between high- and low-density areas in the plane of a panel. These stresses are often large enough to break the adhesive bonds, leading to significant nonrecoverable TS (Liu and McNatt 1991; Suchsland and Xu 1991).

In order to reduce TS of wood composite panels, extensive studies on furnish treatments have been performed. These treatments include acetylating the fiber surface, studied by Arora et al. (1981), Youngquist et al. (1986), Rowell et al. (1986), and Chow et al. (1996); post-heat treatment, by Hsu (1987; 1989) and Suchsland and Woodson (1986); bulking cell walls by Haygreen and Gertjejansen (1972); and fiber plasticization, by Hawke et al. (1993). They all reported improvement on TS of treated panels. However, Carll (1997) commented in his review that some of these techniques require large equipment expense and high levels of chemical input.

Many investigations have been conducted to study the effect of process variables on TS of wood-based composites. In the manufacture of structural panels, vertical density gradient, resin content, and degree of flake-to-flake bonding are believed to be some of the main processing variables that control TS (Kelly 1977; Geimer 1982). Diverse approaches to optimizing processing parameters, i.e., density by Lehmann (1970) and Vital et al. (1974); horizontal density variation, by Xu and Steiner (1995); vertical density gradient across the board thickness, by Xu and Winistorfer (1995); resin content, by Hann et al. (1963); and flake configuration, by Gatchell et al. (1966), were studied to enhance thickness stability of wood composites. In particular, studies were performed to investigate the relationship between vertical density gradient and TS (Strickler 1959; Suchsland 1962; Davis 1989; Xu and Winistorfer 1995). In Xu and Winistorfer's work (1995), vertical density distributions before and after water soaking were used to determine the thickness swelling distribution of composite panels. It was shown that layer TS from water soaking was directly proportional to the layer density of boards. It was concluded that vertical density distribution was a major factor in controlling TS distribution under water soaking. In a more recent study, Xu and Winistorfer (1996) also showed that there was a direct relationship between water absorption and layer density of wood composites.

Roffael and Rauch (1972) investigated the TS rate of particleboards with various densities under water soaking. Low-density boards showed a constant TS rate (i.e., TS/water absorption) for a 10-day water soaking period. A TS rate increase was observed for the specimens with density above 0.7 g/cm^3 with increased soaking time. This was explained by an initial slow TS rate for the high-density boards because reduced porosity in these high-density boards tended to have low moisture diffusion rate. Wu and Piao (1999) presented TS curves as a function of moisture content change (MCC) for commercial OSB. They showed that nonrecoverable TS increased in an increasing rate up to 25% MC level.

A major negative consequence of TS is the reduction of strength properties of wood composites (Lehmann 1978; Winistorfer and DiCarlo 1988; Wu and Piao 1999). These studies demonstrated that high humidity exposure and/or direct water soaking treatments led to significant loss of internal bond (IB) strength of the panels due to large TS involved. Wu and Piao (1999) showed a linear relationship between nonrecoverable TS and IB loss of commercial OSB. Thus, improving long-term durability properties of OSB relies largely on the fundamental understanding of the TS behavior of OSB. However, very little systematic experimental data are available about effects of panel processing variables on the swelling behavior of OSB under long-term cyclic humidity exposure conditions. In this study, equilibrium moisture content (EMC) and TS of OSB manufactured under different processing conditions were measured under cyclic RH conditions at 25°C in a two-year period. The objectives of the study were: (a) to investigate TS and TS rates of OSB as influenced by panel processing variables under long-term cyclic RH exposure conditions, and (b) to develop a modeling approach for predicting TS and TS distributions of panels with vertical density gradient based on measured layer properties.

MATERIALS AND METHODS

Test materials and sample preparation

The details of the manufacturing procedure for the experimental panels used are given in two early papers (Wu 1999; Wu and Ren 2000) and are reviewed briefly as follows. Forty-four single-layer and thirty-two three-layer OSB panels were manufactured using aspen flakes under various flake alignment levels. Single-layer boards were pressed to a thickness of 12.7-mm in a cold press, and the mats were then heated under pressure to cure the resin. This process produced panels with uniform density profile across panel thickness. Three-layer boards were made with four flake weight ratios (FWR—a ratio of face layer flake weight to the total flake weight in the manufacture of three-layer boards). They were pressed in a conventional manner to produce vertical density profile across panel thickness (Wu 1999). Flake orientation distribution for each panel was characterized by fitting measured flake orientation data to the von Mises distribution. Actual density profile across panel thickness was measured using an X-ray density profiler with samples taken from each panel.

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 for the TS tests in this study. 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.

Thickness swelling tests

All specimens for TS tests were initially dried in a convection oven at 70°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:

1st Cycle:	Dry →	32 % →	55% →	75% →	85% →	93% →	75% →	32%	
2nd Cycle:			→	75%	→	93%	→	32%	
3rd Cycle:			→	75%	→	93%	→	32%	→ OD.

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 105°C to determine their oven-dry weight and dimension.

Thickness swelling data analysis

Measured sample thickness at various levels of RH condition was used to calculate TS according to the following equation:

$$\mathrm{TS}\ (\%) = \frac{\mathrm{TK(RH)} - \mathrm{TK(DRY)}}{\mathrm{TK(DRY)}} \times 100\% \tag{1}$$

where

TK(RH) = sample thickness (mm) at a given RH; and
TK(DRY) = sample thickness (mm) at the initial dry condition.

TS data were plotted against moisture content change, MCC, from the initial dry condition. For a given change of relative humidity (ΔRH), TS rate (TSR) was evaluated as:

$$\text{TSR }(\%\text{TSI}/\%\text{MC}) = \frac{\text{TSC}(\Delta\text{RH})}{\text{MCC}(\Delta\text{RH})} \quad (2)$$

where

TSC = thickness swelling change (%) over ΔRH; and
MCC = moisture content change (%) over ΔRH.

Statistical comparison was performed to investigate effects of panel processing variables on measured TS and TSR. The measured thickness swelling rate, TSR, was expressed as a function of panel processing variables and MC level for both single- and three-layer boards using:

$$\text{TSR }(\%\text{TS}/\%\text{MC}) = a\text{MC}^{b}\text{SG}^{c}k^{d}\text{RC}^{e} \quad (3)$$

where MC is moisture content in percent, RC is resin content (%), SG is specific gravity, k is concentration parameter used to describe flake orientation distribution (Wu 1999), and a, b, c, d, and e are regression constants.

Predicting TS of three-layer boards with density gradient

Measured TSR from single-layer uniform density boards and density distribution from the three-layer boards were used to predict TS and TS distribution of three-layer boards with a vertical density gradient according to the following procedure.

1. Panel thickness (TK) was divided into a number of N layers (e.g., 12) across panel thickness (Fig. 1). This was done without considering boundaries between face and core layers. Each layer (i = 1 . . . N) contains a number of n measured density points, SG_{DP} (j = 1 . . . n). The density values at these points were averaged to get the mean density for the layer, SG_L(i).
2. The layer density and other panel parameters (i.e., resin content and concentration parameter) were used to calculate model parameters A(i) and M_v(i) in Nelson's sorption isotherm using regression equations established by Wu and Ren (2000) for each sub-layer.

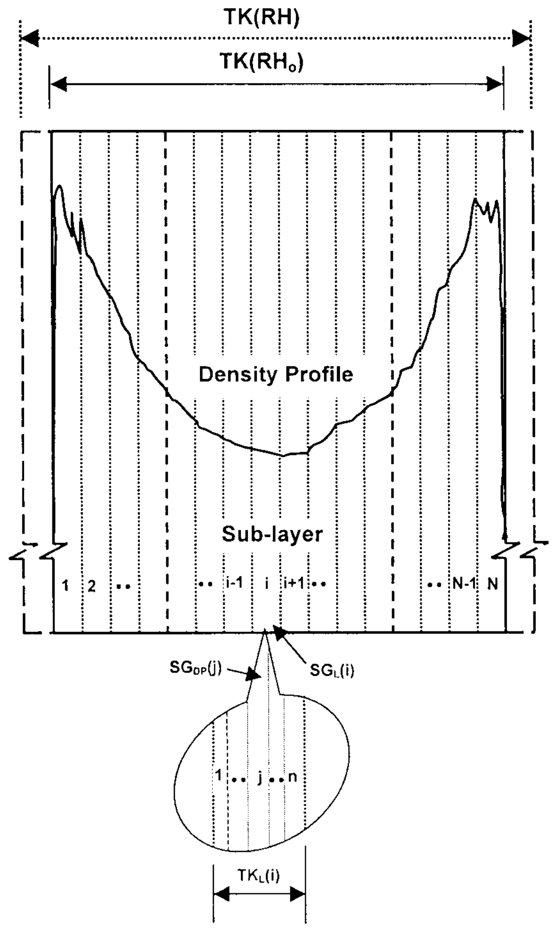

FIG. 1. Schematic of layer division across panel thickness for modeling panel TS. Variables used are: TK—panel thickness, TK_L—sub-layer thickness, RH—relative humidity, RH_0—reference relative humidity, I—index for sub-layer, N—total number of sub-layers, j—index for measured density points, n—total number of measured density points within a sub-layer, SG_L—sub-layer specific gravity, and SG_{DP}—measured density point within a sub-layer.

3. Starting at a reference RH level (RH_0), the EMC of each sub-layer, MC(i, RH_0), was calculated using the Nelson's sorption isotherm. The details of the procedure for calculating EMC distribution across board thickness can be found from Wu and Ren (2000).
4. RH level was increased. EMC distribution corresponding to the new RH, MC(i, RH), was recalculated, from which the EMC change in relation to the reference condition for each layer was evaluated:

$$\Delta MC(i, RH) = MC(i, RH) - MC(i, RH_O) \qquad (4)$$

5. TSR for each layer, TSR(i, RH), was calculated using characterized Eq. (3) from the single-layer, uniform density boards.
6. Layer thickness swelling was calculated as:

$$TS(i, RH) = TSR(i, RH) \times \Delta MC(i, RH) \qquad (5)$$

7. Total panel thickness swelling was calculated:

$$TTS(RH) = \frac{\sum_{i=1}^{N} TS(i, RH)}{N} \qquad (6)$$

8. The calculation was shifted back to Step 4 and the process was repeated. A FORTRAN program was developed using Microsoft FORTRAN PowerStation 4.0 to implement the above algorithm. The procedure yielded distributions of EMC, TS rate, and TS for a given RH exposure condition.

RESULTS AND DISCUSSIONS

Thickness swelling data

Measured TS (%) and EMC (%) data at the selected RH levels are summarized in Table 1 for single-layer boards and Table 2 for three-layer boards. Also shown in Table 1 and Table 2 are the manufacturing variables for various panels listed. TS and EMC values shown are means of eight specimens for each board type. TS was zero at the initial dry condition. Typical plots showing TS as a function of moisture content change, MCC, are shown in Fig. 2a for the single-layer boards and Fig. 2b for the three-layer boards. In both graphs, the TS curve starts at zero percent MC change (i.e., initial dry condition). The last data point (i.e., oven-dry condition) shows a negative MC change indicating an MC decrease from the initial dry condition. Thus, the absolute value of the last MC change was the beginning MC for the boards. The effects of moisture cycling on TS are clearly seen from the graphs. For each adsorption cycle, TS increased with increase in board MC. For each desorption cycle, TS decreased with MC decrease. However, board thickness did not return to the beginning value after each cycle as indicated by the residual TS at a similar EMC level between adsorption and desorption. This behavior is similar to sorption hysteresis shown in a previous paper (Wu and Ren 2000) and is thus defined as thickness swelling hysteresis. The largest TS hysteresis (or residual TS) occurred after the first sorption cycle. There was a small amount of increase in the residual TS after each of the two additional sorption cycles. As a result, the TS hysteresis loop moved up as the number of cycles increased (Fig. 2a and 2b). This clearly indicates the damaging effect of the cyclic humidity exposure on board quality. As permanent residual TS increased, there was an increased amount of bond failure in the panel.

Statistical correlation analysis was performed to demonstrate the effect of panel processing variables on total TS at various RH exposure levels. The test results are summarized in Table 3 for the single-layer boards and Table 4 for the three-layer boards. As shown in Table 3, the effect of density on the total TS of the single-layer, uniform density boards was not significant at the 93% RH level in all three cycles. This was due to the fact that, even though high-density boards tended to swell more because of their larger swelling potentials, the MC level reached at a given RH level, especially at RH levels above 85%, was lower compared to the low-density boards

TABLE 1. *Measured TS and EMC at the selected levels of relative humidity for the single-layer boards.*

Board Type[b]	Specific Gravity	k[c]	TS (EMC) at the Specified Relative Humidity Condition[a]							
				1st Adsorption Cycle		2nd Adsorption Cycle		3rd Adsorption Cycle		
			Initial Dry	32%	93%	32%	93%	32%	93%	End 32%
4% RC										
HAL	0.58	11.52	0 (5.4)	0.9 (7.9)	16.6 (24.3)	8.9 (8.7)	17.7 (23.1)	9.9 (8.0)	19.2 (23.5)	11.0 (7.9)
	0.84	9.47	0 (5.8)	1.3 (8.1)	17.6 (21.6)	6.7 (8.5)	19.1 (21.1)	7.2 (7.9)	21.2 (21.6)	10.9 (7.7)
	1.05	9.05	0 (6.1)	0.7 (7.5)	15.8 (19.8)	5.1 (8.3)	16.5 (19.0)	5.9 (7.8)	18.4 (19.2)	7.2 (7.5)
	1.23	8.67	0 (6.1)	0.3 (7.0)	16.7 (19.4)	5.5 (8.0)	18.4 (19.4)	6.7 (7.7)	19.5 (19.5)	7.5 (7.3)
LAL	0.62	2.35	0 (6.1)	0.6 (7.4)	21.7 (23.2)	11.2 (8.4)	20.2 (22.5)	12.1 (7.9)	20.4 (21.9)	12.6 (7.9)
	0.81	2.50	0 (6.8)	0.4 (7.6)	15.9 (21.0)	6.1 (8.3)	16.3 (19.9)	6.4 (7.9)	19.1 (20.9)	7.7 (7.7)
	1.01	2.29	0 (7.5)	0.2 (8.0)	15.1 (19.6)	4.7 (8.3)	15.7 (18.9)	5.5 (8.0)	18.0 (20.2)	6.9 (7.7)
	1.20	2.42	0 (6.9)	0.2 (7.2)	13.8 (18.6)	3.6 (8.0)	14.0 (18.4)	4.2 (7.7)	13.5 (18.4)	4.6 (8.1)
RAL	0.59	0.15	0 (6.3)	0.5 (7.4)	19.4 (22.5)	11.1 (8.4)	20.8 (22.6)	12.2 (7.9)	22.1 (21.5)	11.9 (7.8)
	0.80	0.21	0 (6.6)	0.7 (7.9)	20.8 (22.3)	9.9 (8.7)	21.6 (22.0)	11.2 (8.1)	24.0 (22.6)	12.4 (7.7)
	0.95	0.15	0 (6.6)	0.4 (7.6)	21.7 (21.1)	9.8 (8.3)	22.6 (20.6)	11.4 (7.8)	25.5 (20.9)	12.8 (7.8)
6% RC										
HAL	0.59	9.69	0 (5.3)	0.9 (7.7)	17.1 (24.1)	8.9 (8.6)	16.8 (22.9)	9.6 (8.0)	17.3 (23.6)	8.6 (7.8)
	0.84	9.73	0 (6.2)	0.9 (8.3)	16.8 (22.1)	6.1 (8.7)	17.2 (21.4)	6.9 (8.2)	20.9 (22.4)	7.9 (7.8)
	1.03	8.49	0 (6.8)	0.5 (8.0)	13.1 (20.3)	3.3 (8.5)	14.2 (20.0)	3.9 (7.9)	15.9 (20.0)	5.3 (7.7)
	1.23	7.06	0 (6.4)	0.7 (7.3)	15.9 (20.2)	5.1 (8.1)	16.8 (19.5)	5.4 (7.6)	18.7 (20.0)	6.2 (7.3)
LAL	0.62	2.18	0 (7.3)	0.1 (8.0)	16.0 (23.9)	7.7 (8.6)	20.2 (22.5)	8.0 (8.0)	18.1 (22.8)	8.4 (7.7)
	0.83	2.36	0 (7.8)	0.4 (8.3)	15.4 (21.3)	6.4 (8.6)	16.3 (19.9)	6.6 (8.1)	17.2 (21.4)	7.4 (7.8)
	1.01	2.29	0 (8.3)	0.3 (8.6)	16.6 (21.3)	5.1 (8.6)	15.7 (18.9)	6.2 (8.2)	18.9 (20.7)	7.4 (8.2)
	1.15	2.33	0 (7.5)	0.5 (8.2)	18.8 (20.8)	7.6 (8.5)	14.0 (18.4)	9.1 (8.0)	22.0 (19.9)	10.3 (7.9)
RAL	0.56	0.10	0 (7.7)	0.3 (8.3)	15.1 (23.7)	7.0 (8.8)	14.9 (23.3)	8.0 (8.1)	15.7 (23.0)	6.8 (7.9)
	0.74	0.13	0 (7.7)	0.5 (8.3)	16.9 (22.0)	7.0 (8.8)	17.6 (21.5)	8.2 (7.9)	17.2 (21.0)	8.2 (7.7)
	0.97	0.04	0 (8.4)	0.5 (8.8)	13.8 (20.5)	3.0 (8.5)	13.7 (20.1)	3.5 (7.8)	13.9 (19.7)	4.2 (7.9)

[a] TS (%) and EMC (%) are mean values of eight specimens for each board type.
[b] HAL—high alignment level, LAL—low alignment level, RAL—random alignment level, RC—resin content.
[c] k—concentration parameter.

TABLE 2. *Measured TS and EMC at the selected levels of relative humidity for the three-layer boards.*

Board Type[b]	FWR[c]	Specific Gravity	k[d]	TS (EMC) at the Specified Relative Humidity Condition[a]: Initial Dry	1st Adsorption Cycle: 32%	1st Adsorption Cycle: 93%	2nd Adsorption Cycle: 32%	2nd Adsorption Cycle: 93%	3rd Adsorption Cycle: 32%	3rd Adsorption Cycle: 94%	End 32%
4% RC											
HAL	0.3	0.75	6.35	0 (5.6)	0.6 (6.5)	25.0 (21.6)	10.9 (7.8)	21.3 (20.5)	12.5 (7.6)	23.4 (20.5)	13.8 (7.7)
	0.4	0.76	5.02	0 (5.2)	0.7 (6.4)	26.2 (21.6)	11.6 (7.8)	23.4 (20.3)	13.4 (7.6)	24.0 (19.8)	14.4 (7.8)
	0.5	0.76	6.57	0 (5.4)	0.8 (6.8)	23.6 (21.8)	9.9 (7.9)	21.0 (20.5)	11.5 (7.5)	20.8 (19.9)	12.0 (7.7)
	0.6	0.75	6.62	0 (5.2)	0.7 (6.8)	25.9 (22.3)	11.4 (8.2)	23.6 (21.4)	13.3 (7.7)	21.8 (21.3)	14.2 (7.5)
LAL	0.3	0.74	1.54	0 (6.6)	0.2 (6.9)	23.7 (21.7)	12.4 (8.2)	23.3 (20.7)	14.0 (7.7)	24.1 (20.7)	15.2 (7.9)
	0.4	0.74	1.51	0 (6.7)	0.1 (6.9)	22.1 (21.6)	10.6 (8.2)	21.7 (21.1)	12.2 (7.7)	22.8 (21.3)	13.5 (7.9)
	0.5	0.74	1.84	0 (6.7)	0.0 (7.0)	21.4 (21.9)	10.6 (8.3)	21.8 (21.6)	12.4 (7.7)	24.3 (22.2)	13.8 (7.7)
	0.6	0.72	1.32	0 (6.1)	0.2 (6.9)	24.7 (22.6)	13.1 (8.2)	25.9 (23.0)	15.6 (7.7)	24.4 (21.1)	15.7 (7.7)
6% RC											
HAL	0.3	0.73	5.78	0 (5.7)	0.6 (6.8)	20.4 (22.7)	8.3 (8.6)	19.2 (22.2)	9.2 (8.1)	19.1 (22.1)	9.5 (7.8)
	0.4	0.75	6.09	0 (6.1)	0.6 (7.4)	23.5 (22.4)	10.2 (8.6)	21.4 (21.7)	11.8 (8.1)	22.8 (22.2)	12.6 (7.9)
	0.5	0.76	6.44	0 (5.6)	0.5 (7.9)	21.7 (21.4)	9.1 (8.3)	20.1 (20.6)	10.3 (7.8)	20.9 (21.4)	11.6 (7.7)
	0.6	0.75	7.00	0 (5.7)	0.6 (7.8)	20.3 (22.0)	7.3 (8.3)	18.2 (21.5)	8.5 (7.8)	21.5 (21.8)	9.7 (7.8)
LAL	0.3	0.71	1.47	0 (6.5)	0.1 (6.8)	19.8 (23.1)	8.8 (8.3)	19.4 (22.5)	10.2 (7.9)	20.8 (22.0)	10.5 (7.8)
	0.4	0.75	1.67	0 (6.2)	0.6 (7.4)	21.1 (22.6)	9.5 (8.5)	21.0 (21.8)	11.1 (7.9)	21.8 (22.1)	12.2 (7.8)
	0.5	0.71	1.79	0 (7.0)	0.6 (7.0)	21.2 (23.3)	8.7 (8.7)	19.5 (22.4)	10.1 (8.1)	20.0 (23.5)	10.9 (7.8)
	0.6	0.73	1.61	0 (6.9)	0.4 (7.4)	23.1 (22.9)	9.4 (8.4)	20.1 (21.9)	11.0 (8.0)	21.8 (22.4)	11.7 (7.7)

[a] TS (%) and EMC (%) are mean values of eight specimens for each board type.
[b] HAL—high alignment level, LAL—low alignment level, and RC—resin content.
[c] FWR—flake weight ratio.
[d] k—concentration parameter.

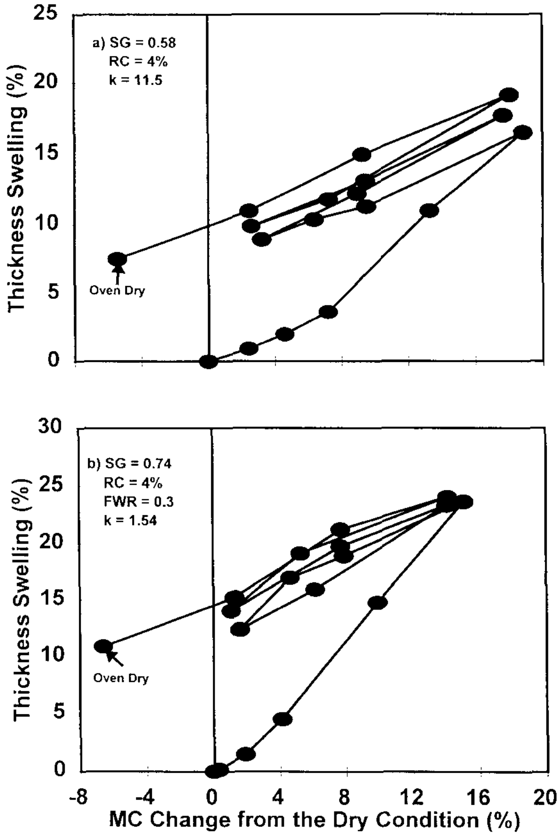

FIG. 2. Typical thickness swelling hysteresis loops as a function of moisture content change under cyclic exposure conditions. a) single-layer boards and b) three-layer boards.

(Wu and Ren 2000). As a result, the total TS reached in those high-density boards was not necessarily larger. At the 32% RH level, the effect of density on the residual TS was significant for all three exposure cycles. High-density boards had significantly less residual TS. The effect of resin content on the total TS was significant at all exposure conditions. Thus, increase in resin content significantly reduced the amount of TS. Effects of flake alignment level (k) on the TS were generally not significant, as shown in Table 3.

For all three-layer boards (Table 4), panel density tended to have a positive effect on TS, but the effect was not significant except at two RH exposure levels. In studying the relationship between thickness swelling and panel density, Liu and McNatt (1991) showed that TS varied from point to point in flakeboards, but no definite relationship between TS and density was found. The current results agreed with their findings. Similar to the single-layer boards, the effect of resin content was significant at all exposure levels, indicating that boards made with higher resin content had smaller TS for a given exposure condition. Flake alignment level showed a negative effect on the swelling. This implies that an increase in flake alignment level (i.e., better forming the mat) will lead to less TS and thus a more stable panel. Flake weight ratio, FWR, used to make three-layer boards did not show significant effect on TS.

Thickness swelling rate from the initial adsorption cycle

Thickness swelling rate, TSR (%TS/%MC), from the initial adsorption cycle was calculated for each board type. Typical plots showing TSR as a function of moisture content are shown in Fig. 3a for the single-layer boards and Fig. 3b for the three-layer boards. As shown, the swelling rate reached over 2% per percent MC change for some of the boards.

TSR generally increased with an increase in panel MC level. This indicates that MC increases at the higher MC range (e.g., above 15%) led to a larger amount of TS. For the single-layer, uniform-density boards, high-density boards had a larger swelling rate compared to low-density boards at the same resin content level. For the three-layer boards, flake weight ratio had no obvious effect on the TSR-MC curve. The swelling rate curves for some panels, especially low-density single-layer boards, leveled off at the MC levels above about 15%, indicating a similar swelling rate in the MC range. Regression analysis was carried out to establish correlations among the TSR, MC, and panel processing variables. The model is:

TABLE 3. *Effects of SG, RC, and k on total thickness swelling at 93% and 32% RH levels for single-layer, uniform-density boards. Data shown are p-values*[a].

	1st Cycle		2nd Cycle		3rd Cycle	
Factor[b]	93% RH	32% RH	93% RH	32% RH	93% RH	32% RH
SG	0.1026	0.0001	0.9752	0.0001	0.8253	0.0001
	(−)*	(−)	(+)*	(−)	(+)*	(−)
RC	0.0001	0.0001	0.0002	0.0001	0.0001	0.0001
	(−)	(−)	(−)	(−)	(−)	(−)
k	0.0208	0.0824	0.0749	0.0392	0.4073	0.3055
	(−)	(−)*	(−)*	(−)	(−)*	(−)*

[a] The "−" sign means negative effect, the "+" sign means positive effect, and the "*" sign means that the effect is not significant at the 0.05 significance level.
[b] SG—specific gravity, RC—resin content, and k—flake orientation concentration parameter.

$$TSR_{1st\ ADS} = 0.0827MC^{1.1592}SG^{0.3664}k^{-0.0234}RC^{-0.2727} \quad R^2 = 0.49 \tag{7}$$

for the single-layer boards and

$$TSR_{1st\ ADS} = 0.2474MC^{0.9809}SG^{1.146}RC^{-0.3353} \quad R^2 = 0.52 \tag{8}$$

for the three-layer boards. In both Eqs. (7) and (8), TSR is in %TS/%MC, MC is in percent, and RC is in percent. Equations (7) and (8) allow the prediction of thickness swelling rate as a function of panel processing variables. As shown, TSR for both single- and three-layer boards was correlated positively with MC and panel density, and negatively with resin content.

The mean TSR for the RH change from 32% to 93% was calculated for both single- and three-layer boards. Multi-linear regression analysis was performed using SAS PROC REG (SAS Institute Inc. 1996) to demonstrate the effect of panel processing variables on the mean TSR values from the first adsorption cycle. For the single-layer boards, panel density had the most significant positive effect on the TSR ($p = 0.0001$, standardized parameter of estimates = 0.4104, and Type II partial correlation coefficient = 0.1994). TSR increased with panel density at all density levels. Resin content had a significant negative effect on TSR ($p = 0.0002$, standardized parameter of estimates = −0.2425 and Type II partial correlation coefficient = 0.0807). Thus, increase in panel resin content level will significantly reduce the thickness swelling rate as expected. The flake alignment level also showed signif-

TABLE 4. *Effects of SG, RC, k and SR on total thickness swelling at 93% and 32% RH levles for three-layer boards with density gradient. Data shown are p-values*[a].

	1st Cycle		2nd Cycle		3rd Cycle	
Factor[b]	93% RH	32% RH	93% RH	32% RH	93% RH	32% RH
SG	0.0287	0.3478	0.2741	0.6171	0.0003	0.0976
	(+)	(+)*	(+)*	(+)*	(+)	(+)*
RC	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	(−)	(−)	(−)	(−)	(−)	(−)
k	0.2466	0.0080	0.0133	0.0032	0.0224	0.0043
	(+)*	(−)	(−)	(−)	(−)	(−)
FWR	0.1608	0.0985	0.1658	0.4258	0.2309	0.4694
	(+)*	(+)*	(+)*	(+)*	(+)*	(+)*

[a] The " " sign means negative effect, the "+" sign means positive effect, and the "*" sign means that the effect is not significant at the 0.05 significance level.
[b] SG—specific gravity, RC—resin content, k—flake orientation concentration parameter, and FWR—flake weight ratio between face and core layers used to manufacture three-layer boards.

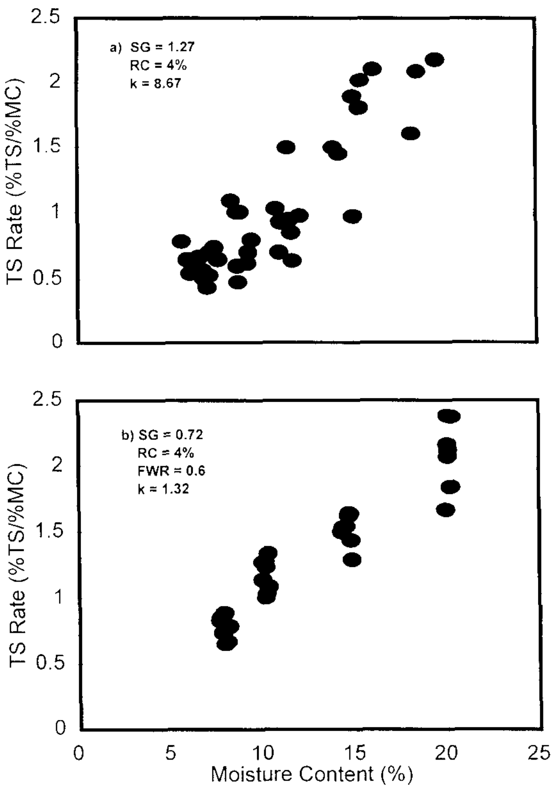

FIG. 3. Typical thickness swelling rate from the first adsorption cycle (i.e., 35% to 93% RH) as a function of sample moisture content. a) single-layer boards and b) three-layer boards.

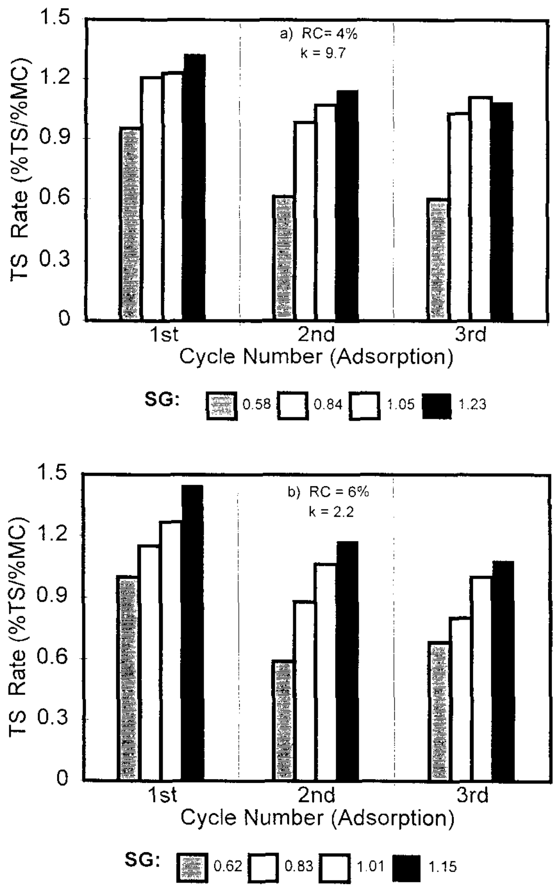

FIG. 4. A comparison of thickness swelling rate from the three adsorption cycles (i.e., 35% to 93% RH) for the single-layer boards. a) 4% resin content and high alignment level and b) 6% resin content and low alignment level.

icant negative effect on TSR ($p = 0.0001$, standardized parameter of estimates = −0.3967 and Type II partial correlation coefficient = 0.1882). This indicates that an increase in panel alignment level will help reduce the swelling rate. For all three-layer boards, resin content was the only variable that significantly affected mean TSR value ($p = 0.0001$, standardized parameter of estimates = −0.572, and Type II partial correlation coefficient = 0.3272). Flake weight ratio ($p = 0.7154$, standardized parameter of estimates = 0.01607 and Type II partial correlation coefficient = 0.00038) and flake alignment level ($p = 0.828$, standardized parameter of estimates = 0.02698 and Type II partial correlation coefficient = 0.001076) did not show a significant effect on the mean TSR value.

Comparison of TS rate under cyclic exposure conditions

A comparison of the mean TSR from the three adsorption cycles (i.e., 32% → 93% RH) is shown in Fig. 4 for the single-layer, uniform density boards at various density levels. It can be seen from Fig. 4 that

a) even though high-density boards did not show a significantly larger total TS as discussed in the previous section, their swelling rate (or swelling potential) was larger compared with that of the low-density boards, and

b) mean TSR value from the first adsorption cycle was the largest for all board types. Subsequent adsorption cycles led to significantly smaller TSR values. There was more reduction in TSR value for low-density boards at both resin content levels (Fig. 4).

The observation a) implies that low-density boards had a smaller swelling potential, thus a better long-term TS resistant properties than high-density boards. Therefore, reducing panel density does not only reduce manufacturing costs (raw materials and pressing costs), but also leads to a more stable product. Since low-density panels contain a substantial amount of voids, the effect of voids on panel stability and strength properties should be fully investigated. The observation b) implies that extreme precaution should be exercised to prevent the panel from taking moisture during the initial adsorption process. Moisture adsorption during the initial adsorption process will lead to a large total and residual (or nonrecoverable) thickness swelling of the product.

Comparisons of the TSR values from the three adsorption cycles (i.e., 32% → 93% RH) for three-layer boards with density gradient are shown in Fig. 5. Similar to the single-layer boards, the mean TSR value from the first adsorption cycle was the largest for all board types. Each of the two subsequent adsorption cycles led to a significantly smaller TSR value. There was about 50% reduction in TSR value from the first to the second or third adsorption cycle. Boards made with 6% resin content (Fig. 5b) had a significantly smaller swelling rate from all three exposure cycles compared with those made at the 4% resin content level (Fig. 5a). Flake weight ratio, FWR, which controls the layering structure for a three-layer board, did not make any significant influence on the mean swelling rate at all three exposure cycles.

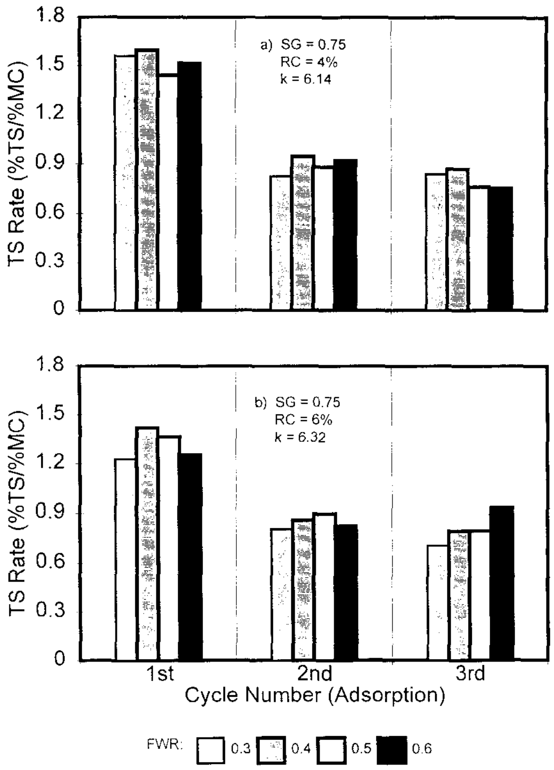

FIG. 5. A comparison of thickness swelling rate from the three adsorption cycles (i.e., 35% to 93% RH) at various shelling ratios for the three-layer boards. a) RC = 4% at high alignment level. b) RC = 6% at low alignment level.

Predicted TS of three-layer boards with density gradient

Prediction of TS was carried out only for the first adsorption cycle due to its dominant effect in controlling panel TS. Typical predicted TS curves as a function of MC change are shown in Fig. 6 in comparison with experimental data. As shown, the predicted TS compared well with the measurement over the entire MC range. Since the TS prediction was based on summing the TS of individual layers, the agreement between predicted and measured TS indicated that the interaction among flake layers across panel thickness played a less significant role on the final magnitude of TS in OSB.

Typical distributions of measured density, predicted EMC change, predicted TS rate, and TS across panel thickness are shown in Fig. 7. There were similar trends between density and TS rate distributions (Fig. 7a) and similar trends between TS and MC change (Fig. 7b). Both density (i.e., SG) and TS rate at the surface region were higher than those in the cen-

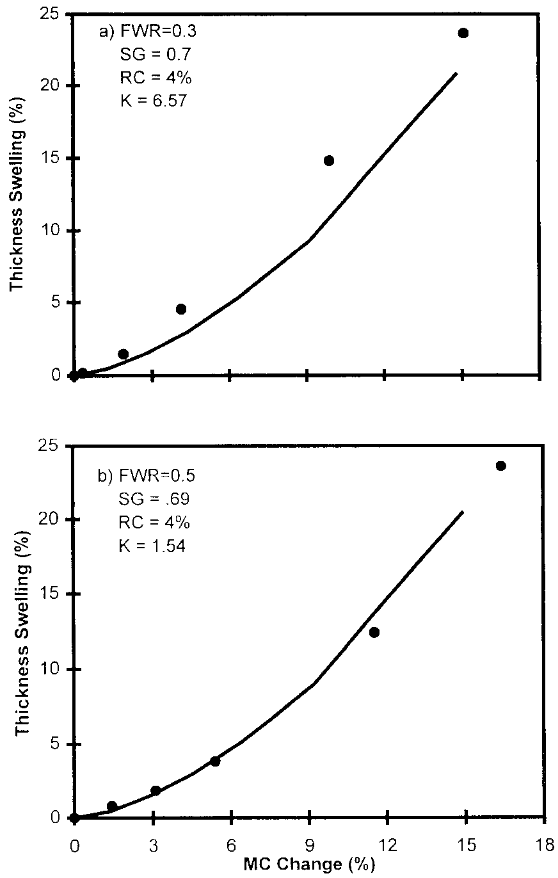

FIG. 6. A comparison of predicted and measured mean panel TS as a function of sample MC change for three-layer OSB panels. (a) FWR = 0.3 and low alignment level and (b) FWR = 0.5 and high alignment level.

ter. On the other hand, both TS and EMC change at the surface regions of the board were smaller than those in the center. The trend of TS is thus opposite to that of the density profile, which had higher values in the surface region. Xu and Winistorfer (1995) demonstrated a higher TS value in the surface region for OSB under direct water soaking, similar to the density profile. The difference was thought due to the exposure conditions used. Under high humidity exposure conditions, actual TS value of a flake layer depends on two factors, EMC change and TSR of the layer. Over a given exposure condition, the high-density face region had a smaller EMC change (Wu and Ren 2000) and a larger TSR compared to the low-density core. The net effect was the balance between the two opposing factors. At the high MC level, the effects of EMC reduction in the high-density face outweighed the effect of its larger swelling rate value. As a result, the face region had smaller TS than that of the core. Under water soaking conditions, however, all layers were assumed to reach saturation. The higher swelling rate in the high-density face region led to larger TS over the same amount of MC change. Thus, under long-term high humidity exposure, both EMC change and density distribution across board thickness were the important factors in controlling TS in OSB. Since the effect of density on EMC became smaller at the lower MC levels (Wu and Ren 2000), the TS difference between face and core layers decreased at the lower RH exposure levels.

CONCLUSIONS

Thickness swelling behavior of oriented strandboard under long-term cyclic RH exposure was investigated. From the study, the following conclusions were reached.

1. TS hysteresis developed in all panels as a result of cyclic humidity exposure. The largest TS hysteresis (or residual TS) occurred during the initial adsorption cycle.
2. TS rate from the initial adsorption cycle increased with an increase in MC level and panel density, and decreased with increase in resin content. For the single-layer, uniform density boards, flake alignment level also showed a significant negative effect on the swelling rate. For the three-layer board with density gradient, both alignment level and shelling ratio did not have any significant effect on TSR.
3. The TS rate was the largest from the first adsorption cycle. The rate decreased significantly during the subsequent adsorption cycles. The general trend is similar for both single- and three-layer boards.
4. The predicted total TS matched experimental data well. The predicted TS distribution

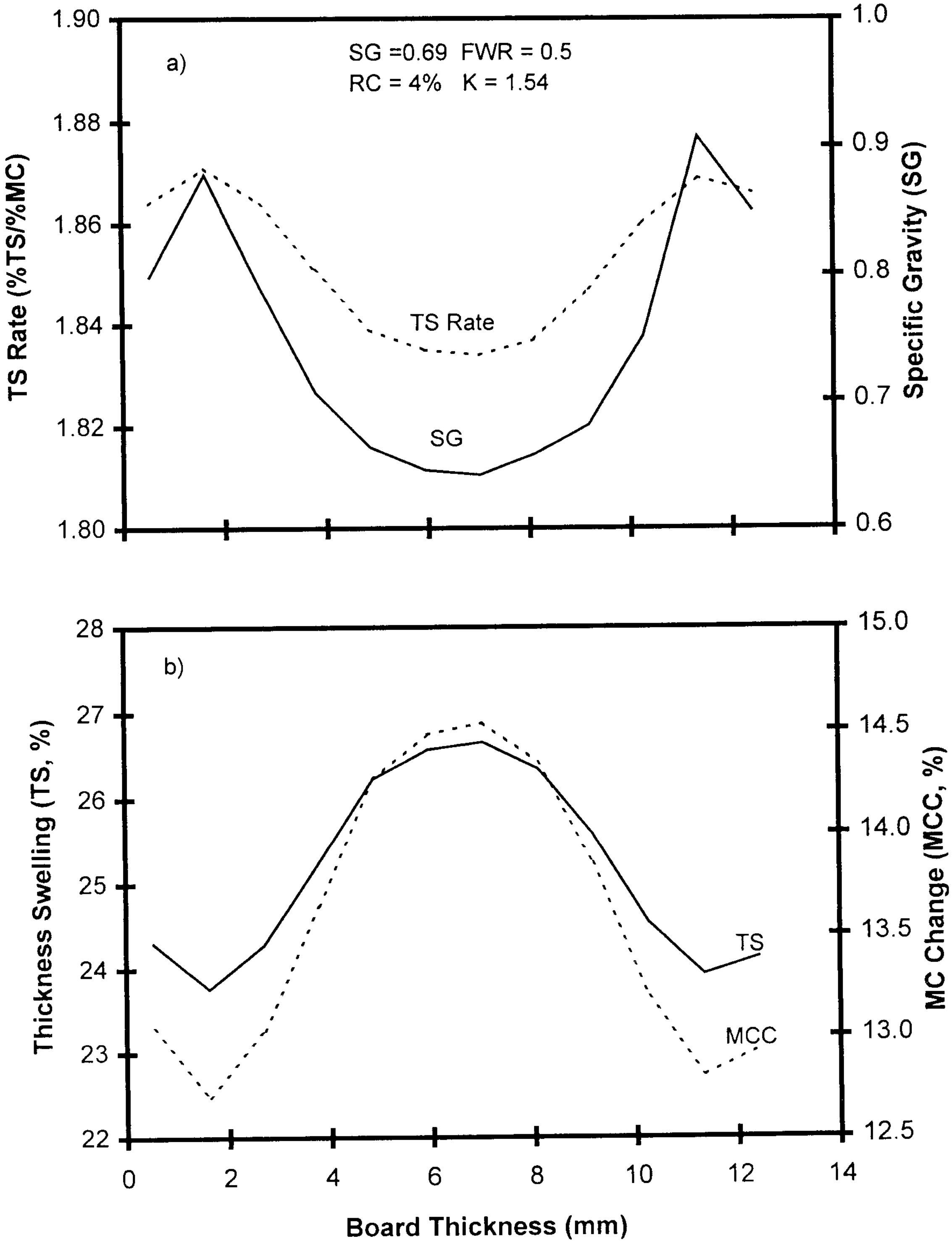

Fig. 7. Typical distributions of measured density (a), predicted TS rate (a), predicted MC change (b), and predicted TS (b) across panel thickness for three-layer OSB under RH exposure condition from 35% to 93%.

across panel thickness followed more closely the distribution of EMC change, instead of the vertical density profile. For a given RH exposure condition, TS was generally smaller in the high-density surface region compared to the low-density core because of smaller EMC changes in the face. The procedure developed provided a useful tool for analyzing the effect of panel processing parameters on TS behavior of OSB.

ACKNOWLEDGMENTS

This work is currently being supported by the USDA NRI Competitive Grant Program (97-35103-5055). The financial contribution to the project is gratefully acknowledged.

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