THE INFLUENCE OF FINES CONTENT AND PANEL DENSITY ON PROPERTIES OF MIXED HARDWOOD ORIENTED STRANDBOARD[1]

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ABSTRACT

Single- and three-layer mixed hardwood oriented strandboard (OSB) with various wood fines contents and panel densities were manufactured using phenol-formaldehyde (PF) resin as binder. The effects of fines level and density on the panel properties were studied. Mathematical models based on lamination theories were used to predict properties of three-layer panels, including effective modulus (EM), linear expansion (LE), and swelling stresses using single-layer data as model input. The model's prediction was compared with actual experimental data.

For single-layer panels, parallel bending modulus and strength decreased, while the perpendicular values increased as fines increased in the panels. LE and thickness swelling increased with the increase of fines contents. Regression analysis indicated that bending properties and LE were highly correlated with fines content and panel density. The results of three-layer boards with a small fixed amount of fines in the face layers showed that the bending properties varied little in the parallel direction and decreased in the perpendicular direction as fines in the core layer increased. Parallel LE decreased and the perpendicular value increased with the increase of fines in the core layer. Predicted EM and LE agreed well with the experimental data. Shifting a certain amount of fines from core to face layers led to more balanced panel properties along the two principal directions. Predicted swelling stresses decreased with the increase of fines levels in the boards.

Keywords: Mixed hardwood; OSB, linear expansion, effective modulus, fines, modeling.

INTRODUCTION

As one of the primary structural composites, OSB is gaining increased use in both residential and commercial applications. Continuing growth of OSB is exerting undue pressure on both the environment and resource (Schuler et al. 2001; Han et. al 2006). The increasing use of small-diameter softwood and hardwood trees in OSB production has potentially positive implication for sustainable development of OSB and forest management.

It is well known that the strength of OSB is influenced by orientation of strands, which is

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highly related to strand dimensions and shape (Kruse et al. 2000; Nishimura et al. 2004). The flaking of small-diameter and low-quality materials from both softwood and hardwood species generates low-quality flakes and a large amount of wood fines (i.e., small wood particles). Commercial OSB is manufactured with a significant amount of fines placed in the core layer. The use of fines can help reduce raw material cost for OSB production. However, the fines in a mat change internal mat structure and influence panel properties. A large amount of fines in a given board leads to decreased mechanical and increased linear expansion (LE) properties along the cross-machine direction due to random distribution of the fines in the core layer (Maloney 1977; Wu 2003; Han et al. 2006). The structural composite industry faces common problems on how to generate flakes with a minimum amount of fines, and how to best utilize them in the furnish. A better understanding of the effect of varying amounts of fines and their location in different parts of the panel on board properties is thus highly needed (EWRF 2001; Han et al. 2006).

Barnes (2000) developed sets of equations accounting for the effects of wood content, adhesive amount, in-plane strand orientation, strand length, strand thickness, fines content, and orienter set-up parameters. In his model, the relationship between the proportion of non-orientable fines material and strength properties was inversely linear. More recently, Barnes (2002) developed a model on the effect of fines content on the strength properties of oriented strand composites from aspen. It was reported that increasing fines content reduced bending strength properties of the composite in a linear relationship when the boards were made with evenly distributed fines and strands. However, Barnes's model equations were developed using only limited wood species (i.e., aspen, western red cedar, and Douglas-fir). Very limited fundamental studies on the effect of varying amounts of fines and their location in the panel on mat structure and final board properties have been done.

OSB can be considered as laminated composite panel made of strand layers of different density and orientation, where lamination theories (e.g., Bodig and Jayne 1993) are applied to predict three-layer board properties using experimental data from single-layer boards. Hunt et al. (1979) and Hoover et al. (1992) used transformed section analysis in predicting layered structural composites for industrial and commercial roof decking based on experimental properties of strand layers. Wu (1999) investigated the effects of panel processing variables on mechanical and dimensional stability properties of single-layer OSB. The experimental data formed a database of layer properties that were used to model LE and effective modulus (EM) of three-layer, cross-laminated OSB as influenced by panel shelling ratios (Lee and Wu 2002). The effect of fines at different locations across panel thickness on panel properties can be handled in a similar fashion using lamination theories. However, this effect has not been dealt with previously.

The objective of this work was a) to investigate experimentally the effects of fines content and panel density on structural properties of single- and three-layer OSB from small-diameter mixed hardwood species; and b) to simulate the effects of fines on the properties of three-layer panels.

MATERIALS AND METHODS

Raw materials

Commercial OSB face and core materials (i.e., fines) were obtained from a local OSB mill. The furnish contained materials from both high- and low-density species groups from small-diameter mixed hardwood trees (e.g., oak, cottonwood, hackberry, etc.). The face flakes had average length of 120 mm with 0.8-mm thickness, and random width. The fines contained about 50% of materials between 5.0 mm and 38.0 mm in length, with the rest below 5.0 mm. All materials were kiln-dried to 3% moisture content (MC) prior to the panel manufacturing. Commercial liquid phenol-formaldehyde (PF) resin and wax with solid contents of 48% and 45%, respectively, were used.

Board fabrication

Two types of panels were fabricated (Table 1). Single-layer OSBs (570 × 500 × 6 mm) were made by evenly distributing fines through the panel thickness at loading levels of 0, 10, 20, 30, and 100% with target panel densities of 0.55, 0.65, 0.75, and 0.95g/cm^3 (i.e., Groups A, B, C, and D, respectively). The three-layer boards contained about 2.75% fines in the face layers for all panels. The fines content in the core layer varied from 0, 10, 20, 30, and 45% based on the total flake weight in the panel. All three-layer panels (570 × 500 × 12 mm) were constructed with a face and core flake weight ratio (i.e., shelling ratio) of 55% to 45% (i.e., 1.22). All fines material was uniformly distributed within the face and core layers. For both types of boards, the PF resin and wax were applied to the strands at 4% and 1% loading levels, respectively, based on the oven-dried weight of the strands. Mats were manually formed using a specially designed forming box to control the strand alignment level. The formed mats were hot-pressed to the target thickness at a temperature of 190°C for 2.5 and 4 min for single- and three-layer boards, respectively. Two replicates were used for each condition, and a total of 50 boards were manufactured. The panels were trimmed and conditioned at 25 °C and 65% relative humidity to reach an MC level of 6% before testing.

TABLE 1. *Experimental variables for panel manufacturing.*

Experimental variables	Panel manufacturing conditions: 1-layer board	3-layer board
Panel size (mm)	570 × 500 × 6	570 × 500 × 12
Density (g/cm^3)	0.55, 0.65, 0.75, 0.95	0.65
Fines content (%)	0, 10, 20, 30, 100	2.75, 12.75, 22.75, 32.75, 47.75
Resin and amount	Liquid PF 4%	Liquid PF 4%
Replication	Two at each condition	Two at each condition

Testing procedure and data analysis

Flake alignment distribution and density profile.—Flake alignment angles from board surfaces were measured using image analysis with 150 flakes randomly selected on each side of the board for all panel types (Han et al. 2006). The alignment angle of each strand was measured from −90° to 90° with 0° set as the principal machine direction. Strand alignment was described by a percent alignment (PA) proposed by Geimer (1976). This measures the average angle deviation from a reference angle of 45 degrees to the principal alignment direction of the test board:

$$PA(\%) = 100\% \times [45 - \theta]/45 \qquad (1)$$

where, θ is the average absolute alignment angle of each board based on measured angles over the range of −90° to 90°. The statistical cumulative distribution of strand alignment was done for each board based on a uniform interval of 10 degrees.

Density profile through the specimen thickness for both single- and three-layer boards (50 × 50 × thickness mm) was evaluated using a Quintek Density Profile QDP-01X. Six replicates were used, and the result was averaged for each group.

Physical and mechanical properties.—The properties evaluated for both single- and three-layer boards include modulus of elasticity (MOE) and modulus of rupture (MOR), internal bond (IB) strength, linear expansion, and thickness swelling (TS). Tests were conducted according to the ASTM Standard D1037 (ASTM 1998; Han et al. 2006). The panel properties from all single-layer boards were expressed as a function of fines loading level and panel density using SAS (SAS Institute 2002) and a power-form equation (Wu 1999) as:

$$P = a\, FL^{b}\, \rho^{c} \qquad (2)$$

where: P = property: LE (%), MOE (GPa), MOR (MPa), TS (%) or IB (MPa); FL = fines level (%); ρ = density (g/cm^3); and a, b, and c = regression constants. In fitting Eq. (2), natural logarithm transformation of both dependent variables (LE, MOE, MOR, TS, or IB) and independent variables (FL and ρ) was first performed. A multilinear regression analysis was then made with the transformed variables.

Three layer panel LE and EM properties.—The measured properties from single-layer panels were used to predict performance of the three-layer boards (i.e., LE and EM). The approach considers a three-layer OSB board as a multi-layer laminate with varying flake orientation between face and core and varying layer density from panel surface to panel center (Lee and Wu 2002). Under the swelling condition, internal stress and strain develop due to the variation of layer swelling potentials. Superimposing the components of the stress-induced deformation on the free expansion results in LE of the panel over a given MC change:

$$d\varepsilon_{LE} = \left[\int_0^{TK} [d_{\varepsilon FE}(i)\, E(i) dx]\right] \Big/ \left[\int_0^{TK} [E(i) dx]\right] \quad (3)$$

where $d\varepsilon_{LE}$ is panel linear expansion strain, E is elastic modulus (GPa) at a given MC condition, which varies across panel thickness due to density and strand alignment change at various positions, and i is the layer index in the board thickness direction, TK is the panel thickness (mm), and x is the coordinate across board thickness. The stress increment can be derived as:

$$d\sigma(i) = [d_{\varepsilon LE}(i) - d_{\varepsilon FE}(i)]E(i) \quad (4)$$

where $d\sigma$ is the stress increment (MPa) and $d\varepsilon_{FE}$ is free expansion strain. Equations (3) and (4) allow the determination of the internal stresses and panel LE under the swelling conditions. The analysis applies to both directions parallel and perpendicular to the major alignment direction of the face flakes.

The effective modulus (EM) of three-layer OSB for a given panel structure was modeled using an equation developed by Bodig and Jayne (1993).

$$EM = \frac{1}{I}\sum_{i=1}^{n} E^i[I_0^i + A^i\,(d^i)^2] \quad (5)$$

where EM is the effective MOE of three-layer OSB in either parallel or perpendicular direction (GPa), I is the moment of inertia of entire OSB panel (cm^4), E^i is the MOE of the ith sub-layer (GPa), $I_o{}^i$ is the moment of inertia of the ith sub-layer (cm^4), A^i is cross-sectional of the ith sub-layer (cm^2), and d^i is the distance between the centroid planes of individual layer and the panel (cm).

The effect of fines content and their distribution across panel thickness on panel LE and EM was simulated using Eqs. (3) and (5). This was done by first dividing the panel thickness and measured density distribution into three layers representing face, core, and face layers. The face and core layers were further divided into 6 (3 for each face layer) and 5 sub-layers of equal thickness, respectively. The division led to a layer thickness ratio of 1.2, which was approximately the same as the layer flake weight ratio between face and core layers used to manufacture the panel. The mean density of each sub-layer was evaluated based on measured density profile and number of density points within the sub-layer using numerical integration techniques. The layer properties of MOE and LE as a function of fines levels and layer density were determined using the regression results from single-layer panels (Eq. 2). The prediction of panel LE was done using layer LE data measured from oven-dry to vacuum pressure soaking condition. The predicted value was verified using three-layer board properties measured under the same condition. Simulation analysis was performed by varying amount of fines in the core layer and by shifting a certain amount of fines from core layer to face layer to study their effect on panel properties.

RESULTS AND DISCUSSIONS

Single-layer boards

Flake alignment and density profile.—Mean strand alignment levels of different board types are shown in Table 2. The PA values varied

TABLE 2. *Summary of single-layer panel property data at various fines and density levels.*

			Parallel					Perpendicular								
			Bending			LE		Bending			LE		Internal bond strength		Thickness swelling[c]	
Target density group[a]	Fines level (%)	PA[b] (%)	Density (g/cm³)	MOR (MPa)	MOE (GPa)	Density (g/cm³)	LE (%)	Density (g/cm³)	MOR (MPa)	MOE (GPa)	Density (g/cm³)	LE (%)	Density (g/cm³)	IB (MPa)	Density (g/cm³)	TS* (%)
A	0	71.88	0.66	29.07	6.56	0.64	0.07	0.68	5.28	0.95	0.69	1.85	0.74	0.14	0.64	36.98
		(3.57)	(0.02)	(3.36)	(0.67)	(0.01)	(0.03)	(0.08)	(0.05)	(0.24)	(0.10)	(0.42)	(0.07)	(0.01)	(0.02)	(4.58)
	10	69.48	0.67	26.79	5.11	0.66	0.18	0.60	6.28	0.99	0.68	2.06	0.68	0.16	0.55	46.60
		(2.45)	(0.02)	(4.34)	(0.14)	(0.00)	(0.04)	(0.00)	(1.07)	(0.02)	(0.03)	(0.17)	(0.17)	(0.03)	(0.04)	(7.30)
	20	69.08	0.62	26.48	5.16	0.62	0.15	0.68	6.48	1.26	0.76	1.39	0.71	0.34	0.71	52.50
		(3.91)	(0.07)	(0.78)	(1.07)	(0.04)	(0.00)	(0.02)	(3.21)	(0.32)	(0.05)	(0.07)	(0.10)	(0.01)	(0.02)	(3.54)
	30	66.83	0.62	22.86	4.38	0.65	0.19	0.70	8.93	1.39	0.75	1.48	0.73	0.33	0.66	57.68
		(4.44)	(0.09)	(1.12)	(0.93)	(0.02)	(0.03)	(0.06)	(0.54)	(0.42)	(0.03)	(0.25)	(0.05)	(0.03)	(0.03)	(0.98)
	100	—	0.60	10.00	1.72	0.62	0.62	0.60	10.00	1.72	0.62	0.62	0.70	0.34	0.60	64.07
			(0.06)	(2.55)	(0.42)	(0.04)	().15)	(0.06)	(2.55)	(0.42)	(0.04)	(0.15)	(0.08)	(0.02)	(0.01)	(1.24)
B	0	72.88	0.75	51.03	10.19	0.71	0.14	0.74	3.55	0.96	0.73	2.70	0.78	0.50	0.72	32.74
		(3.24)	(0.10)	(3.56)	(3.43)	(0.08)	(0.00)	(0.04)	(0.15)	(0.00)	(0.01)	(0.08)	(0.06)	(0.11)	(0.08)	(4.52)
	10	71.96	0.78	60.52	8.97	0.64	0.06	0.77	6.55	1.05	0.81	2.90	0.79	0.55	0.73	35.88
		(6.45)	(0.04)	(5.17)	(1.54)	(0.06)	(0.08)	(0.01)	(0.78)	(0.20)	(0.01)	(0.18)	(0.07)	(0.27)	(0.01)	(2.10)
	20	69.27	0.80	72.66	8.60	0.77	0.04	0.71	7.45	1.05	0.73	2.47	0.88	0.54	0.73	44.69
		(4.70)	(0.00)	(7.02)	(0.74)	(0.00)	(0.00)	(0.12)	(0.10)	(0.19)	(0.00)	(0.06)	(0.03)	(0.17)	(0.03)	(6.14)
	30	63.18	0.75	33.66	6.16	0.70	0.08	0.69	7.83	1.38	0.78	2.17	0.81	0.53	0.73	41.82
		(5.25)	(0.09)	(7.51)	(1.62)	(0.02)	(0.02)	(0.06)	(2.68)	(0.66)	(0.04)	(0.62)	(0.06)	(0.19)	(0.03)	(6.84)
	100	—	0.71	12.81	2.40	0.71	0.81	0.71	12.81	2.40	0.71	0.81	0.72	0.45	0.69	56.34
			(0.05)	(3.29)	(0.90)	(0.07)	(0.30)	(0.05)	(4.29)	(0.90)	(0.07)	(0.30)	(0.04)	(0.09)	(0.02)	(0.32)
C	0	70.85	0.82	56.28	9.73	0.77	0.15	0.83	9.48	1.56	0.85	2.20	0.82	0.41	0.74	27.04
		(2.67)	(0.03)	(7.71)	(0.12)	(0.04)	(0.03)	(0.03)	(3.36)	(0.51)	(0.04)	(0.81)	(0.08)	(0.03)	(0.02)	(8.55)
	10	69.66	0.70	39.90	7.23	0.77	0.14	0.81	9.10	1.35	0.86	2.47	0.84	0.30	0.81	40.39
		(11.01)	(0.05)	(7.66)	(0.85)	(0.05)	(0.01)	(0.02)	(3.41)	(0.32)	(0.09)	(0.60)	(0.08)	(0.07)	(0.03)	(8.62)
	20	66.14	0.79	35.14	7.55	0.77	0.20	0.72	12.28	1.56	0.86	1.99	0.79	0.41	0.76	40.56
		(5.90)	(0.04)	(7.17)	(0.25)	(0.08)	().00)	(0.02)	(4.29)	(0.40)	(0.07)	(0.00)	(0.02)	(0.06)	(0.03)	(0.50)
	30	64.87	0.82	38.62	6.97	0.78	0.17	0.81	10.90	1.69	0.74	1.47	0.84	0.41	0.79	42.69
		(9.83)	(0.06)	(4.39)	(1.75)	(0.07)	(0.01)	(0.03)	(1.66)	(0.21)	(0.01)	(0.12)	(0.04)	(0.06)	(0.04)	(3.60)
	100	—	0.79	21.24	3.52	0.79	0.59	0.79	21.24	3.52	0.79	0.59	0.80	0.41	0.73	64.50
			(0.02)	(2.63)	(0.49)	(0.04)	(0.10)	(0.02)	(2.63)	(0.49)	(0.04)	(0.10)	(0.05)	(0.05)	(0.01)	(3.23)
D	0	69.41	0.82	59.45	15.83	0.79	0.05	0.77	8.83	2.29	0.86	3.83	0.85	0.49	0.77	35.10
		(5.16)	(0.01)	(7.41)	(1.33)	(0.04)	(0.02)	(0.01)	(0.00)	(0.26)	(0.02)	(0.00)	(0.07)	(0.11)	(0.00)	(1.49)
	10	65.95	0.81	52.76	17.18	0.86	0.06	0.81	13.55	4.30	0.93	2.93	0.87	0.54	0.85	34.82
		(9.01)	(0.06)	(8.09)	(1.98)	(0.04)	(0.02)	(0.06)	(0.73)	(0.33)	(0.07)	(0.26)	(0.05)	(0.07)	(0.02)	(3.81)
	20	66.59	0.79	39.69	14.22	0.79	0.17	0.75	9.62	3.57	0.83	1.75	0.84	0.40	0.75	47.19
		(4.93)	(0.00)	(8.92)	(0.25)	(0.03)	(0.02)	(0.00)	(2.49)	(1.02)	(0.02)	(0.10)	(0.06)	(0.08)	(0.03)	(7.18)
	30	63.98	0.78	41.86	13.32	0.78	0.23	0.76	13.83	3.48	0.83	1.69	0.84	0.42	0.75	53.63
		(9.45)	(0.00)	(8.19)	(1.45)	(0.02)	(0.09)	(0.03)	(1.02)	(0.63)	(0.04)	(0.14)	(0.06)	(0.11)	(0.02)	(2.26)
	100	—	0.80	18.90	6.69	0.82	0.96	0.80	18.90	6.69	0.82	0.96	0.89	0.49	0.82	65.58
			(0.02)	(2.73)	(1.10)	(0.02)	(0.09)	(0.02)	(2.73)	(1.10)	(0.02)	(0.09)	(0.03)	(0.11)	(0.00)	(2.79)

[a] Target density group: A: 0.55 g/cm³; B: 0.65 g/cm³; C: 0.75 g/cm³; and D: 0.95 g/cm³

[b] PA represents the average value of percent alignment of the strands from both sides of the panel. Values in parentheses are standard deviations.

[c] TS is the value at 24.5 mm from the sample edge.

from 63% to 73%. In general, PA value decreased with the increase of fines level in the panels. This was due to the increased difficulty for controlling strand orientation during hand-forming process with the high fines-level boards. The cumulative distributions of alignment angles for the boards with different fines contents are shown in Fig. 1 (a). Typical strand alignment distribution curves are observed for all evaluated panels. About 85% to 90% flakes for different panels were aligned within −30° to 30° from the panel's principal direction, in–dicating good control of strand orientation in the mat-forming process. The boards with lower fines contents had superior alignment distribution compared with other panels with more wood fines. This result agrees well with the PA values of the panels at different fines contents.

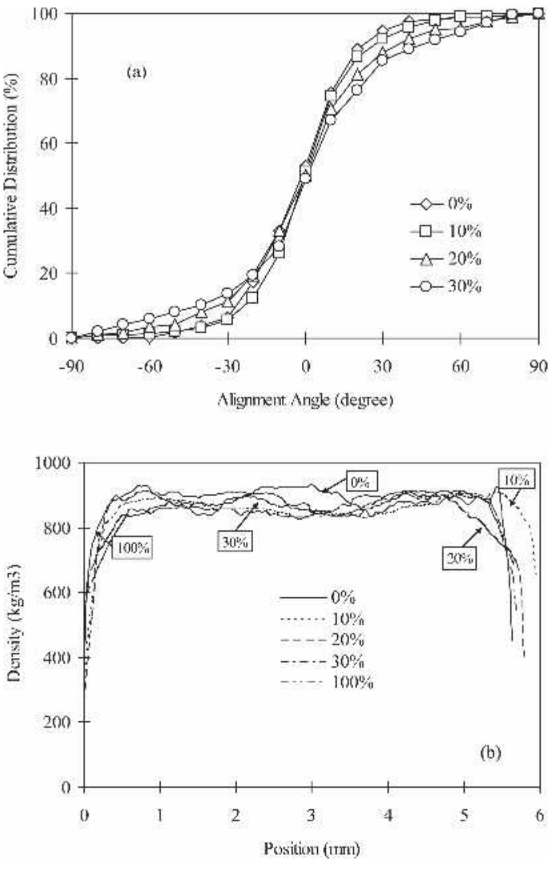

FIG. 1. Cumulative distribution of flake alignment angles (a) and density profile across panel thickness (b) at various fines loading levels for single-layer mixed hardwood OSB.

Typical density profiles across panel thickness at various fines content levels are shown in Fig. 1 (b). In general, all boards had relatively uniform through-thickness density profile due to small panel thickness and rapid heat transfer from panel surface to the core layer during pressing. The fines contents had very little effect on density profiles. High-density panels showed significant springback because of more compression sets developed during hot-pressing. This can be seen from Table 2 as Group D boards did not meet the target density level. The result indicates the difficulty in making high-density thin panels at the resin content level used.

Effect of fines level and panel density on mechanical properties.—Bending modulus (i.e., MOE) and strength (i.e., MOR) for the single-layer OSB with various fines content levels are summarized in Table 2. The relationships between the bending properties, fines level, and panel densities are plotted in three-dimensional graphs in Fig. 2. There was a distinct difference of MOE and MOR along the parallel and perpendicular directions associated with the strand alignment. The property difference decreased with the increase of fines contents, indicating that adding fines resulted in a better balance of bending properties in the two directions. The higher density boards showed a bigger property difference between the two directions.

There was a general decreasing trend in the parallel MOE and MOR with the increase of fines loading levels. This result agrees with those of Barnes (2002) from aspen OSB that increasing fines content reduced bending strength. The reduction of bending performances is likely due to the increase of non-oriented materials along the direction and the decrease of aligned strands that contribute to a superior bending property. The decrease of MOR and MOE was more significant for the boards with higher board densities. For the boards with lower densities, MOE and MOR decreased very little as fines content increased to 20%. A further

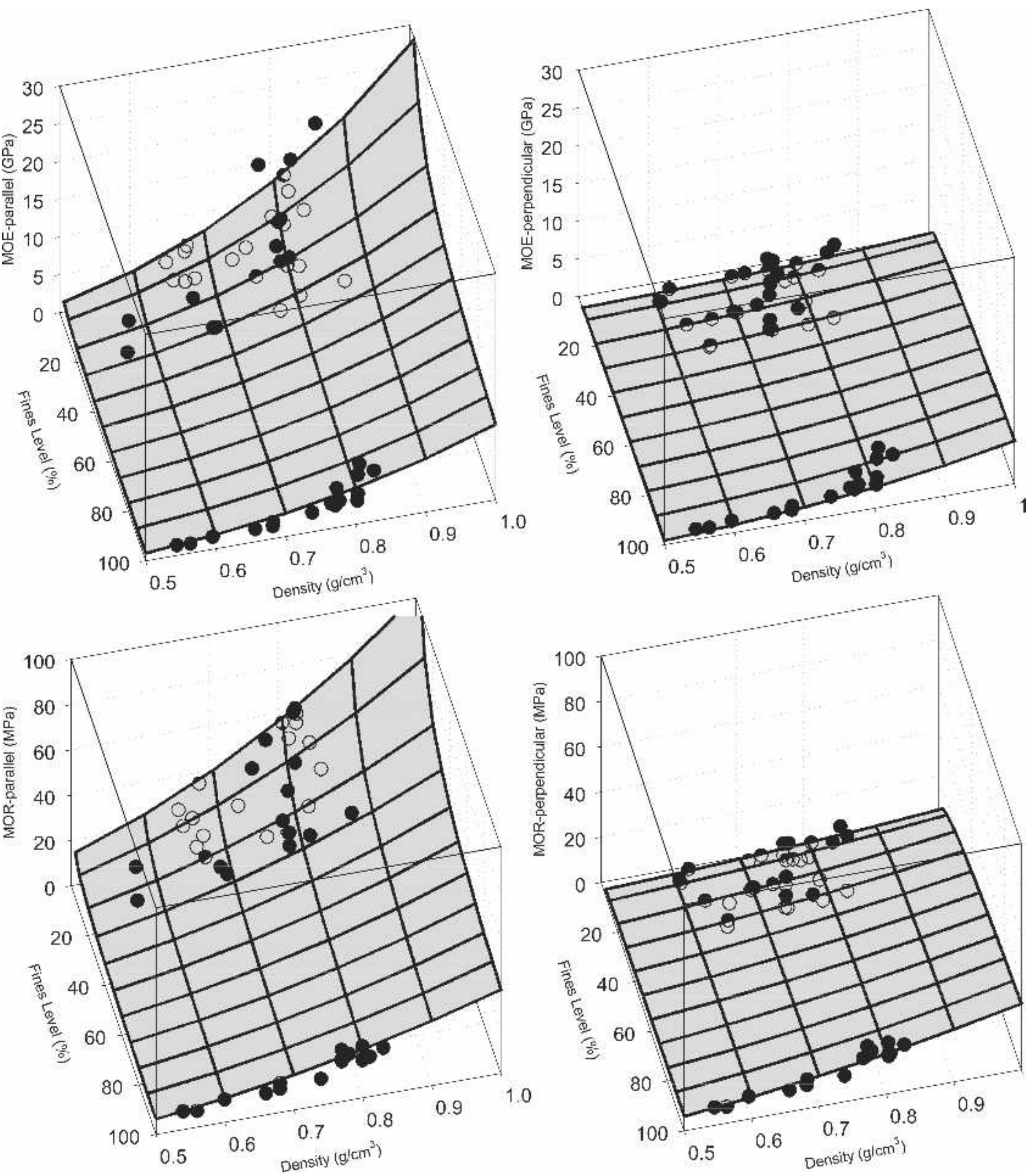

FIG. 2. Bending modulus of elasticity (MOE) and strength (MOR) of single-layer mixed hardwood OSB as a function of fines level and panel density. The symbols show the original data, and the mesh shows the regression fits.

increase of the fines led to reduced bending properties. The boards with 100% fines had the lowest MOE and MOR values. The inferior bending properties of pure fines boards were due to the random orientation of small strands in the boards. The bending properties in the perpendicular direction slightly increased with the increase of fines contents in the boards. This is attributed to the increase of the strands aligned in this direction. At a certain fines level, all bending properties were enhanced with increasing board densities.

IB strength data of the panels as a function of fines content and board density are summarized in Table 2 and plotted in Fig. 3. For Group A boards, IB strength increased with the increase of fines up to the 20% loading level. IB values were enhanced slightly for Group B boards as fines content increased up to 10%. This indicates that fines can be used to fill the voids in the low-density boards, improving IB performance. Further increase of the fines led to little change of the IB values, which could be due to less resin coverage on the surfaces of small flakes, reducing the effect of filled voids. For the boards with higher target density levels (i.e., Groups C and D), the IB values showed not much variation as fines content increased. This could be related to the fact of lower void volume in the high-density boards.

Effect of fines level and panel density on physical properties.—LE data for the boards are summarized in Table 2 and plotted in Fig. 4. Similar to the results of MOE and MOR, distinct difference in LE values along the parallel and perpendicular directions appeared. The perpendicular LE values were higher than the parallel LE, indicating the effect of strand alignment. The difference between LE values was reduced with increase of fines content in the boards. And this reduction was more pronounced for the boards at higher density levels. For Group C boards, the perpendicular LE value was reduced from 2.2% at the 0% fines level to less than 1.5% at 30% fines content. This means that us-

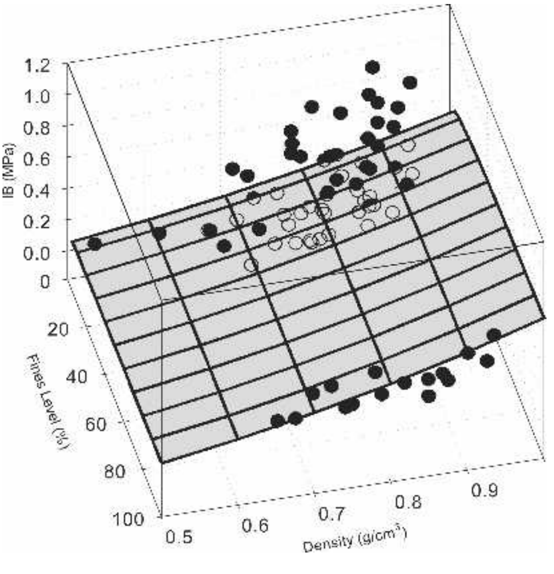

FIG. 3. Internal bond (IB) strength of single-layer mixed hardwood OSB as a function of fines level and panel density. The symbols show the original data, and the mesh shows the regression fits.

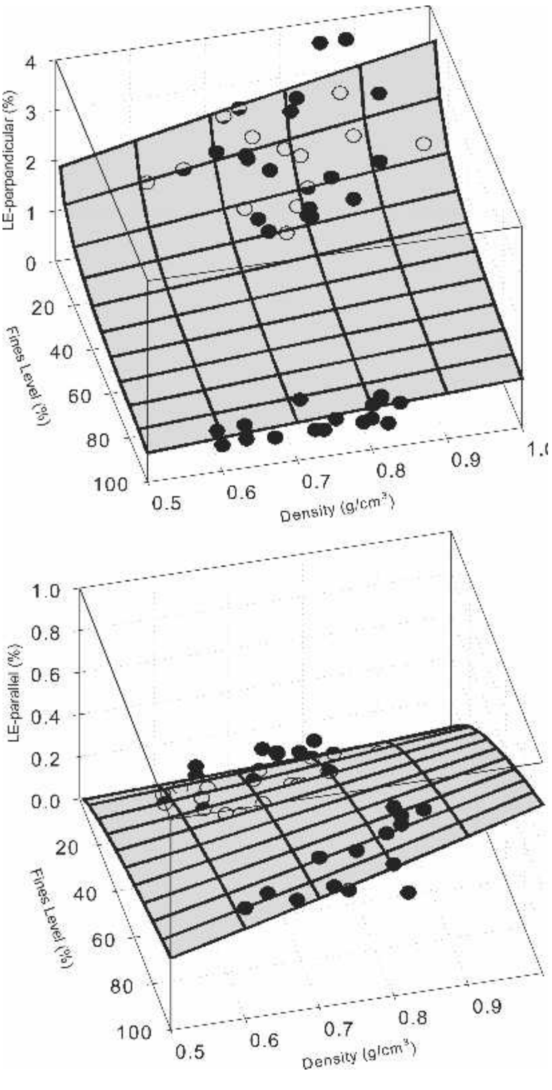

FIG. 4. Linear expansion (LE) of single-layer mixed hardwood OSB as a function of fines level and panel density. The symbols show the original data, and the mesh shows the regression fits.

ing fines can help balance parallel and perpendicular LE values. OSB made of 100% wood fines had similar LE values in both directions. The effect of panel density on LE values varied with material directions. At the 0% fines level, the perpendicular LE increased and the parallel LE varied little with the increase of panel density (Table 2). The result in the perpendicular direction agrees with earlier research by Wu (1999). Wu's data showed that for the single-layer aligned boards, there was an increase in the perpendicular LE and a decrease in the parallel LE with increase in panel density from 0.55 to 1.15g/cm^3 (Wu 1999). The result of less density dependence of the parallel LE could be due to the small density range (0.60–0.90g/cm^3) used in the study.

Figure 5 shows the effect of fines content and board density on 24-hour water soaking TS of the panels. TS values increased with increasing fines contents in the panel. For Group C boards, the TS value at a 30% fines level increased to more than 40% from 27% at the 0% fines level. The boards with 100% fines had the highest TS

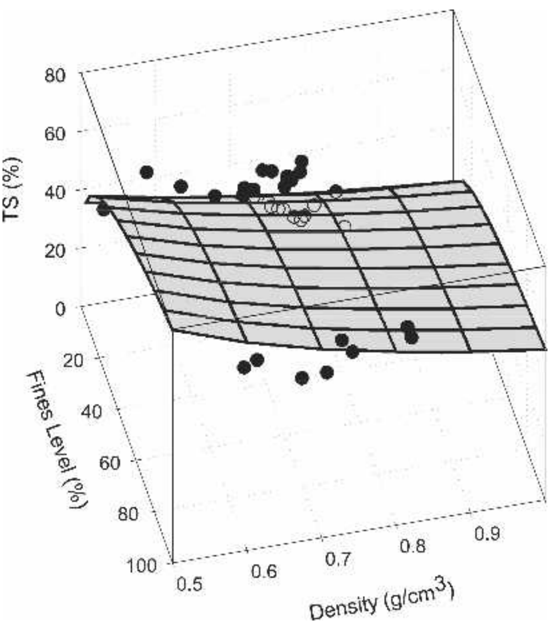

FIG. 5. Thickness swelling (TS) of single-layer mixed hardwood OSB as a function of fines level and panel density. The symbols show the original data, and the mesh shows the regression fits.

values. Thus fines can cause significant TS problems for OSB. The high TS of boards made with more wood fines was likely due to the more water absorption of the panels resulting from the larger surface area of small wood particles. Board density did not show much effect on the TS. It is known that high-density boards have high compaction ratio, and can absorb more water compared with low-density boards at the equilibrium state (Kelly 1977). However, the reduced porosity in the high-density boards prevented rapid liquid water penetration throughout the board. Consequently, the diffusion path of the water into the individual component flakes was much longer and the subsequent rate of TS was reduced in high-density material (Kelly 1977).

Regression analysis.—The regression results on the relationships among fines content, panel density, and various board properties are summarized in Table 3. Typical mesh plots of the fitted lines based on the regression equations in Table 3 are shown in Figs. 2–5. Regression analysis at the 5% significance level revealed that fines content in the model was a significant variable on all the panel properties except IB. Panel density showed a significant effect on bending properties and IB, but not on LE and TS. In general, the power form relationship fitted LE data better compared with the MOE and MOR data. This can be seen from Table 3 as the coefficients of determination of the regression models for LE are higher than those for MOE and MOR. IB had very low correlation coefficients, because of the large variation in IB data as shown in Fig. 3. The analytical functions established provide an approach to generate layer properties for three-layer panels.

Three-layer boards

Panel properties.—The panel properties for three-layer OSB constructed with a 2.75% fines level in the face layers and various fines contents in the core are summarized in Table 4. The percent alignment of the strands varied from 62% to 70%. Flake alignment showed little difference for panels with various fines levels because the

TABLE 3. *Regression results on the relationships between single-layer panel properties (P), fines levels (FL), and density (ρ). Model:* $P = a\,FL^b\rho^c$

Material direction	Properties	Regression constants			
		a	b	c	r^2
Parallel	LE (%)	0.0458	0.6219	1.2258	0.82
	MOE (GPa)	51.4678	–0.3608	3.2833	0.89
	MOR (MPa)	194.0230	0.3583	2.4173	0.79
Perpendicular	LE (%)	6.9875	–0.4249	0.7462	0.77
	MOE (GPa)	2.4323	0.2986	3.5205	0.83
	MOR (MPa)	8.5483	0.2892	2.1183	0.92
Combined	TS (%)	17.7993	0.2317	0.6276	0.60
	*B (MPa)	0.5423	0.0610	2.1207	0.31

fines content in the face layers was held constant for all panels. Figure 6 illustrates the effect of fines on the vertical density profile of the panels. Three-layer boards had significant density gradients compared to single-layer panels. As was true for single-layer panels, fines contents showed very little effect on the density profiles for the three-layer OSB.

Generally, there was no consistent variation on the bending properties as fines contents increased in the core layer (Table 4). This is due to the fact that the bending properties are mainly controlled by the face layer properties where the fines were held constant for all panels in this study. An increasing trend of IB strength was observed as the fines loading level increased up to 30%. This indicates that fines can be used to fill the voids in the core layer where the density was low, hence improving IB performance. IB values of the boards with 45% fines content (i.e., core layer made of 100% fines) showed no further increase, probably due to the poor bonding resulting from less resin coverage on the surfaces of wood fines at the higher loading levels.

Table 4 shows a significant trend of increased perpendicular LE and decreased parallel LE with the increase of fines content in the core layer. Thus, high levels of wood fines can cause a poor balance of LE values along the two principal directions without using high resin loading levels. The perpendicular LE well exceeded the prevailing industrial standards of commercial OSB at the high fines loading levels. In general, there was not much variation on TS values as fines increased to the 30% level. A further increase of fines to 45% increased TS. The increase of TS of boards made with more wood fines was due to the more water absorption of the panels resulting from the larger surface area of small wood particles.

Predicted panel effective modulus and LE.—Predicted panel EM and LE of the three-layer OSB as a function of overall fines level are plotted in Fig. 7 (lines). Experimental data of measured MOE and LE for panels constructed with a 2.75% fines level in the face layers and various fines contents in the core are also shown in Fig. 7 (symbols) for comparison. The parallel EM varied little at all fines levels and there was only a slight decrease in the perpendicular EM as fines increased up to 10%. The general trend of the predicted parallel EM (solid line in Fig. 7a) was in agreement with the experimental data. The discrepancy of actual values along the parallel direction may be due to differences in actual alignment level and localized density variation between the single- and three-layer boards, where the single-layer data were used to predict three-layer panel properties. The predicted EM in the perpendicular direction (solid line in Fig. 7b) matched well with the experimental data. As with experimental observation, predicted LE decreased in the parallel direction and increased in the perpendicular direction with the increase of fines in the core layer. The model's prediction of LE (solid lines in Figs. 7c and d) matched well with the experimental data in both directions.

Shifting a certain amount of fines from the core layer to face layer had a significant effect on both EM and LE (non-solid lines in Fig. 7).

TABLE 4. *Summary of panel property data for 3-layer mixed hardwoods OSB.*[a]

Target density	Fines level (%)	PA[b] (%)	Parallel Bending Density (g/cm^3)	Parallel Bending MOR (MPa)	Parallel Bending MOE (GPa)	Parallel LE Density (g/cm^3)	Parallel LE (%)	Perpendicular Bending Density (g/cm^3)	Perpendicular Bending MOR (MPa)	Perpendicular Bending MOE (GPa)	Perpendicular LE Density (g/cm^3)	Perpendicular LE (%)	Internal bond strength Density (g/cm^3)	Internal bond strength IB (MPa)	Thickness swelling[c] Density (g/cm^3)	Thickness swelling[c] TS* (%)
	2.75	62.23	0.71	45.15a	9.28a	0.67	0.22a	0.67	21.81a	2.20ab	0.67	0.67b	0.72	0.16b	0.62	43.85a
		(11.88)	(0.07)	(6.65)	(1.19)	(0.01)	(0.05)	(0.06)	(4.43)	(0.21)	(0.03)	(0.04)	(0.05)	(0.05)	(0.03)	(4.64)
	12.75	65.39	0.68	50.90a	9.75a	0.69	0.18a	0.66	25.95a	2.01ab	0.64	0.87b	0.73	0.27b	0.64	37.55a
0.65		(5.23)	(0.00)	(6.18)	(1.89)	(0.08)	(0.01)	(0.00)	(2.79)	(0.35)	(0.02)	(0.08)	(0.09)	(0.08)	(0.00)	(0.96)
(g/cm^3)	22.75	70.40	0.68	45.01a	8.60a	0.66	0.17a	0.73	31.68a	1.96a	0.68	0.83b	0.73	0.30b	0.63	41.19a
		(5.71)	(0.07)	(0.20)	(0.32)	(0.08)	(0.07)	(0.04)	(3.18)	(0.04)	(0.01)	(0.04)	(0.08)	(0.05)	(0.00)	(1.34)
	32.75	62.36	0.71	51.77a	9.75a	0.65	0.16a	0.72	30.33a	1.56ab	0.67	0.91b	0.74	0.36a	0.63	41.46a
		(5.66)	(0.08)	(4.03)	(0.91)	(0.01)	(0.01)	(0.02)	(6.27)	(0.25)	(0.03)	(0.09)	(0.04)	(0.06)	(0.06)	(3.85)
	47.75	65.88	0.66	44.32a	9.50a	0.63	0.12a	0.67	21.17a	1.46b	0.63	1.32a	0.72	0.31b	0.63	49.18a
		(7.14)	(0.01)	(4.81)	(0.03)	(0.03)	(0.00)	(0.01)	(5.60)	(0.07)	(0.00)	(0.17)	(0.07)	(0.05)	(0.01)	(3.43)

[a] PA represents the average value of percent alignment of the strands from both sides of the panel. Values in parentheses are standard deviations. TS is the value at 24.5 mm from the sample edge. Same letter denotes statistically similar results at the 5% confidence level.

With increased fines level in the face layer (i.e., changed surface layer properties), parallel EM decreased and perpendicular EM increased. At the same time, parallel LE increased and perpendicular LE decreased. For EM, the effect was more pronounced at the lower fines levels (less than 5%). For LE, the effect was more consistent throughout all loading levels (up to 10%). The predicted EM and LE in both directions reached much similar values for boards with high fines loading levels as the fines level in the face layer increased to the 10% level. This clearly indicates that shifting fines from core to face layers can effectively balance the EM and LE properties in two directions without changing resin loading.

Large perpendicular LE has been observed with commercial OSB (Wu 2003), especially for mixed hardwood OSB due to the amount of fines in the core layer. Redistributing fines between core and face layers could provide a balanced solution to the panel properties.

Predicted swelling stress.—Predicted swelling stresses as a function of fines levels for 3-layer panels are shown in Fig. 8. Similar swelling stress distributions are observed for all the tested panels. For the parallel specimens, two face layers were subjected to tension and the core layer was subjected to compression. In these specimens, the face layers had flakes oriented along the parallel direction and the core

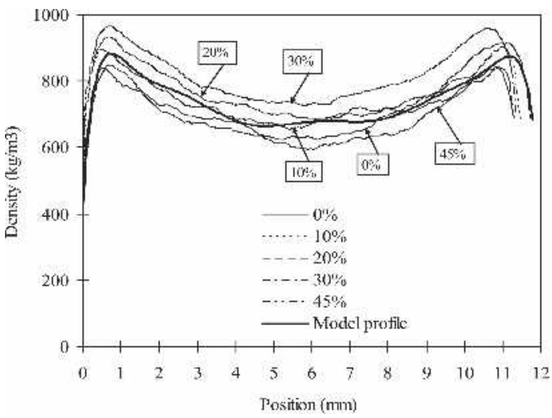

FIG. 6. Density profile across panel thickness at various fines loading levels in the core layer for three-layer mixed hardwood OSB. The model density profile was used for simulation of panel properties.

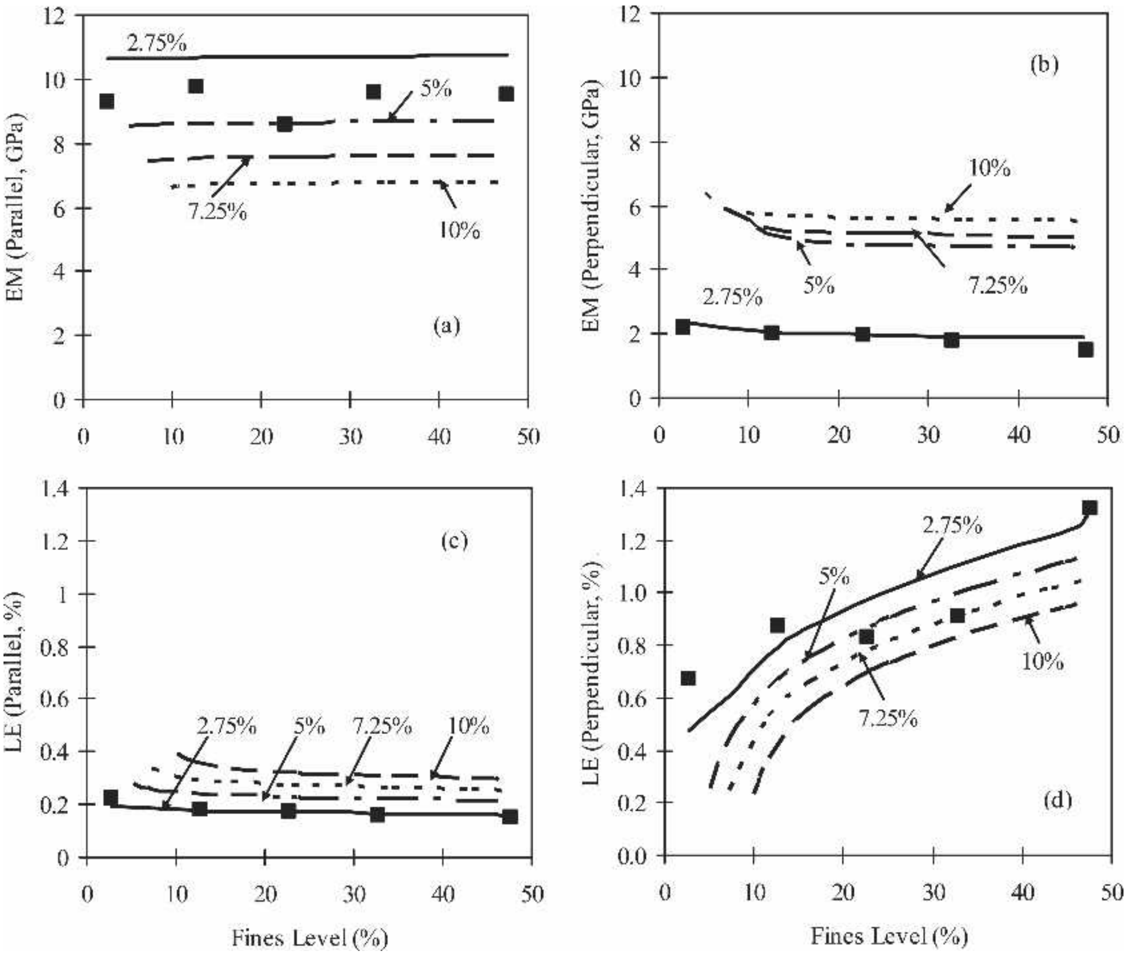

FIG. 7. Effective modulus (EM) and linear expansion (LE) as a function of fines levels. Symbols are measured data of panels with 2.75% fines in the face layers, and lines represent predicted values at different fines contents in the face layers.

layer had flakes oriented along the perpendicular direction. This led to a smaller free LE in the face layers and a larger free LE value for the core layer. During the swelling process, the core layer tried to swell to its potential, but was restricted by the face layers. This action put the core layer in compression. As a reaction, the face layers were under tension in order for the specimen to be at an equilibrium stress state. The opposite was true for the perpendicular specimens as seen in the graph. The relatively flat stress distribution in the core layer for both parallel and perpendicular specimens was likely due to a gradual density decrease towards to the centerline of the sample. The effect of fines on the magnitude of the swelling stresses is clearly seen in this graph. The magnitude of the swelling stress for both parallel and perpendicular specimens decreased with the increase of fines in the core layer. The reduced stresses were due to lower modulus values in the core layer resulting from increased fines contents.

SUMMARY AND CONCLUSIONS

The effects of fines and panel density on the properties of mixed hardwood OSB were investigated. For all single-layer boards, flake alignment levels decreased with the increase of fines

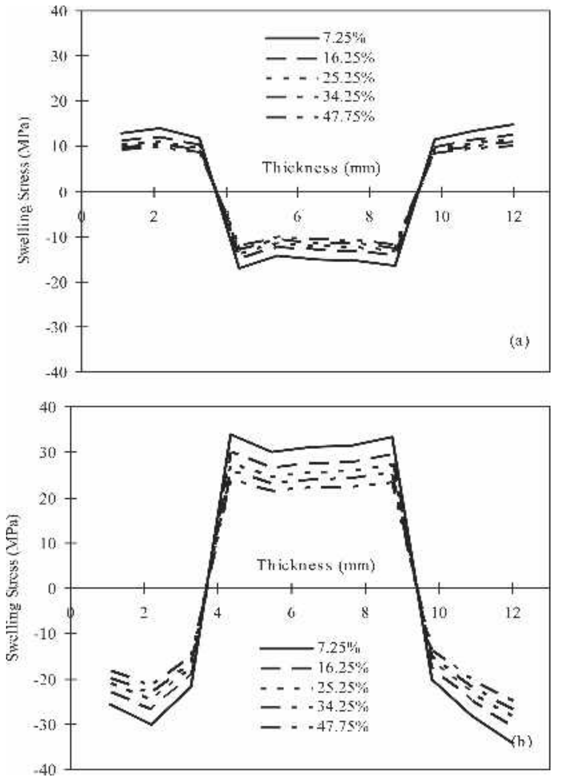

FIG. 8. Predicted internal stresses across panel thickness at selected fines levels. (a) parallel direction, and (b) perpendicular direction. The number shows total fines content in the panel.

content. Fines contents had little effect on the formation of density gradients in these panels. Parallel MOE and MOR decreased, while the perpendicular values increased with the increase of fines levels. IB strength was improved somewhat as fines increased to the 20% level. Both LE and TS increased with the increase of fines content in the panel. Regression analysis indicated that bending properties and LE were significantly correlated with fines content and panel density.

The results of three-layer boards with a small fixed amount of fines in the face layers showed that panel MOE and MOR varied little in the parallel direction and decreased in the perpendicular direction as fines in the core layer increased. At the same time, parallel LE decreased and perpendicular LE increased with the increase of fines in the core. Placing the major portion of the fines in the core layers therefore led to unbalanced panel properties along the two principal directions. Predicted EM and LE compared favorably with the experimental data. Shifting a certain amount of fines from core layer to face layer led to more balanced panel properties along the two directions. Predicted swelling stresses decreased with the increase of fines contents in the panel. The analysis provides an analytical tool for better utilizing fines in the panel and optimizing panel performances.

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