FLAKE ORIENTATION EFFECTS ON PHYSICAL AND MECHANICAL PROPERTIES OF SWEETGUM FLAKEBOARD

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ABSTRACT

Research was initiated to determine the effect of flake orientation on the physical and mechanical properties of flakeboard. The panel fabrication techniques investigated were single-layer panels with random and oriented flake distribution, three-layer, five-layer, and seven-layer panels. Single-layer oriented panels had panel directional property ratios of 11.8 and 12.9 for bending strength and modulus of elasticity (MOE). In the single-layer construction, the bending strength and MOE for the random panels were slightly less than that of the average for the two directions of the oriented panel. Compared to the random panels, multi-layer panels had higher bending properties. Also, the MOE was influenced more than the bending strength by a change in fabrication pattern. Internal bond was unaltered with the panel construction variability. Multi-layered panels did not have a decrease in dimensional change properties as compared with random single-layer panels.

The development of oriented strandboard (OSB) has revolutionized the structural wood composite industry. It has been predicted that OSB will soon surpass plywood as the dominant panel in the huge North American sheathing market (7). In fact, total OSB production in the United States and Canada was greater than plywood for the first time in 1999 (1). Moreover, demand for engineered wood products, including OSB, was expected to grow 300 to 400 percent between 1992 and 2000 (20).

As the name implies, OSB derives its mechanical and physical properties from cross-aligned flakes in alternate panel layers. It has previously been hypothesized that improvements in the mechanical and physical properties of OSB can be realized by an optimal flake orientation during panel fabrication (3,5, 6,12). Geimer et al. (8) stated that flake alignment in face layers of oriented structural flakeboard is considered one of the most important variables for control of panel stiffness.

McNatt et al. (15) investigated the effects of flake alignment on strandboard performance. As expected, they found face strand alignment improved bending strength and stiffness in the aligned direction. However, neither cross alignment of core strands nor unidirectional alignment of strands throughout the panel thickness improved panel performance when compared to aligned face strands and random core strands. Other researchers have developed models to predict improvements in bending property by aligning flakes (4), and others have used Von Mises probability functions to characterize flake orientation (9,17). Recent research has shown a programmed robot can form well-defined and reproducible three-layer oriented flakeboards (23). Xu reported that improving the percent alignment increases MOE-parallel and decreases MOE-perpendicular, but the decrease of MOE-perpendicular levels off after the percent alignment exceeds approximately 50 percent (24).

Research addressing the importance of flake alignment on stiffness and di-

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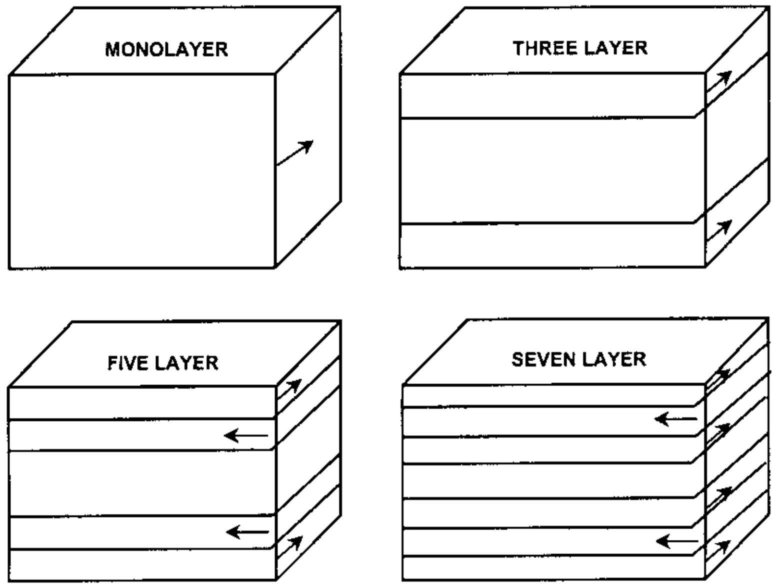
mensional stability of wood composite panels has not been restricted to flakeboard. Previous research has shown that alignment of particles is important in particleboard properties (18,22), and others have shown that fiber alignment is influential in determining the properties of high-density, dry-formed hardboard (19).

Research on the mechanical and physical properties of both multi-layered cross-oriented boards and homogenous boards provides a basis to optimize properties and is therefore important in view of the continued emergence of OSB in the sheathing market and its competitiveness in other markets. Therefore, the principal objectives of this study were to determine the effect of flake arrangement in homogeneous panels and the effect of several oriented layers. Hankinson's formula was used to obtain predicted panel property values as a comparison against observed panel property values.

MATERIALS AND METHODS

Sweetgum (*Liquidambar styraciflua* L.) flakes for all boards were made by clipping 3/8-inch widths from rotary-peeled veneer strips measuring 0.0381 cm (0.015 in.) thick and 7.62 cm (3 in.) along the grain. Previous research by Hse et al. (11) has indicated that decent panel properties are obtained with a face flake 3 inches long by 0.015 inch thick and random width (approximately 3/8-in. width is most desirable). Core flakes should be slightly thicker: 0.025 inch. Other processing parameters were also identified to improve panel properties. Panels were fabricated with single layers (i.e., oriented in one direction or all random), three layers, five layers, and seven layers (**Fig. 1**). All panel types were replicated three times. Oriented single-layer boards were all fabricated in one forming direction; then the cutting pattern was skewed to yield specimens with the preferred angle. Board fabrication consisted of drying all flakes to an average moisture content (MC) of 3 percent and then applying 6.5 percent of a liquid phenol-formaldehyde resin based on ovendry weight of the flakes. No wax was applied to the panels. Panels were pressed in the 50.8-cm^2 (20-$in.^2$) platen laboratory press at 168.3°C (335°F) for 6 minutes. The press was closed to stops as soon as possible with 3447 kPa (500 psi) mat pressure. The



Board Type	Oriented Layer Weight	Oriented Layer Thickness	Core Weight	Core Thickness
	(%)	In.	(%)	In.
MONOLAYER	100	1/2		
THREE LAYER	12.5	1/16	75	3/8
FIVE LAYER	12.5	1/16	50	1/4
SEVEN LAYER	12.5	1/16	25	1/8

Figure 1. — Panel fabrication technique for single-layer and multi-layer panels.

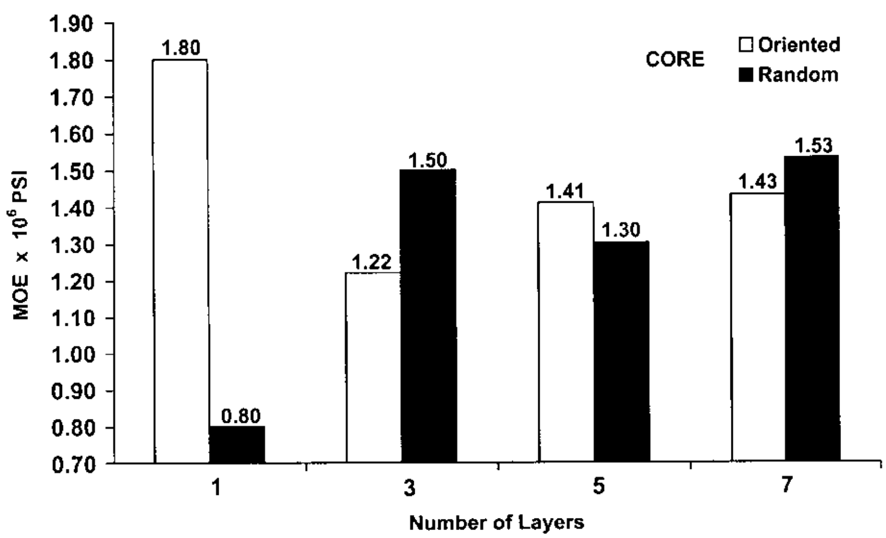


Figure 2. — MOE of panels fabricated with different layers as affected by core construction.

TABLE 1. — Fabrication and strength properties of single-layer and multi-layer flakeboards fabricated with sweetgum and veneer flakes.

Board type	Material volume by weight		Density[a]		MC[b]	MOR[c,d]		MOE[c,e]		IB[f]	
	Faces	Core									
	-------- (%) --------		(pcf)	(kg/m³)	(%)	(psi)	(kPa)	(1,000 psi)	(MPa)	(psi)	(kPa)
Single-layer											
Random	100	0	44.9	719	5.9	8,028	55,351	820.3	5656	261	1800
Oriented											
0 degrees	100	0	42.0	673	5.1	15,142	104,400	1,799.0	12,404	254	1751
30 degrees	100	0	42.3	678	5.1	5,366	36,997	733.0	5054	231	1593
60 degrees	100	0	43.1	690	5.0	1,943	13,397	230.5	1589	233	1606
90 degrees	100	0	41.0	657	5.9	1,288	8880	139.5	962	218	1503
Three-layer (oriented faces)											
Random core	12.5	75	45.9	735	5.9	8,524	58,771	1,539.3	10,613	279	1924
Oriented core	12.5	75	47.1	754	5.5	8,425	58,088	1,215.0	8377	292	2013
Five-layer (oriented faces)											
Random core	12.5	50	45.6	730	5.1	9,575	66,017	1,303.8	8989	285	1965
Oriented core	12.5	50	47.0	753	5.1	10,345	71,326	1,411.4	9731	306	2110
Seven-layer (oriented faces)											
Random core	12.5	25	46.2	740	5.3	10,992	75,787	1,526.3	10,523	284	1958
Oriented core	12.5	25	46.5	745	5.5	10,567	72,857	1,429.3	9855	278	1917

[a] Based on ovendry weight and nominal volume.
[b] Moisture content.
[c] Values given with face flake orientation.
[d] Modulus of rupture; represents 12 observations.
[e] Modulus of elasticity; represents 12 observations.
[f] Internal bond; represents 30 observations.

target board density based on ovendry weight and nominal volume was 721 kg/m³ (45 pcf). The target thickness was 0.5 inch. Although the panel fabrication conditions used in the study are outside current commercial practices, they were deemed acceptable to illustrate the desired comparisons.

The study contained two experiments: 1) single-layer panels with various angles of orientation; and 2) multi-layer panels with 12.5 percent of flakes oriented in each face, and with varying interior layering. The press size only allowed bending samples of multi-layered panels to be obtained for one panel direction. The direction selected corresponded to the major axis of orientation or 2.4-m (8-ft.) direction of a conventional sheathing product. Oriented panels were constructed employing the forming modulator described by Hse and Price (10).

Each panel type was replicated three times. After panel fabrication, all panels were conditioned to 50 percent relative humidity (RH) and 22°C (72°F) before evaluation. When possible, American Society for Testing and Materials (ASTM) Standard D 1037-96a (2) was used for property evaluation. However, the 7.62-cm- (3-in.-) wide specimens were tested in bending over a 40.64-cm (16-in.) test span. Dimensional stability measurements were obtained on 10.16-cm² (4-in.²) specimens subjected to either submergence in boiling water for 5 hours or a 24-hour vacuum-pressure-soak (VPS) cycle. The VPS cycle consisted of placing the specimen in water under vacuum for 1/2 hour followed by 23.5 hours of 448 kPa (65 psi) pressure at room temperature. For both durability tests, specimens were weighed and all three dimensions measured for water absorption, thickness swell, length change, and width change.

RESULTS AND DISCUSSION

MECHANICAL PROPERTIES

The single-layer oriented panels were randomly divided into the various test groups, which showed slight density variation. Bending strength (MOR) and modulus of elasticity (MOE) averaged 11.8 and 12.9 times greater, respectively, in the oriented direction (0-degree direction) than in the across-parallel direction (90-degree direction) (**Table 1**). Mean MOE values are presented in **Figure 2**. These values are partially influenced by the 90-degree direction group having 16.0 kg/m³ (1.0 pcf) lower density. Thus, dividing the property by the density to obtain a specific property value, ratios of 11.5:1 and 12.6:1 for specific MOR and MOE, respectively, were obtained. With good-quality flakes and alignment, a ratio in excess of 10:1 should be obtainable for both bending properties.

Hankinson's formula was employed to calculate theoretical MOR and MOE values for panels manufactured with 30- and 60-degree flake orientation. Hankinson's formula was developed for computing the tensile strength of wood σ_γ in which the direction of the grain is inclined at an angle γ to the direction of the load:

$$\sigma_\gamma = \frac{\sigma_{\|}\sigma_{\perp}}{\sigma_{\|} \times \sin^n \gamma + \sigma_{\perp} \times \cos^n \gamma} \qquad [1]$$

where $\sigma_{\|}$ = tensile strength parallel to the grain ($\gamma = 0$); $\sigma_{\perp}$ = tensile strength perpendicular to the grain (γ = 90 degrees); n is a constant (14).

This formula should also be applicable to composite materials comprised of various flake orientations tested under static bending conditions. Kollmann (13) showed that the formula is correct when the exponents of the trigonometric terms are between 1.5 and 2. Using Hankinson's formula exponent of 2, and

TABLE 2. — *Comparison of experimental and calculated MOE and MOR mean values. Experimental values were determined using Hankinson's formula.*

Flake orientation	MOR		MOE	
	Experimental	Calculated	Experimental	Calculated
	(psi)		(1,000 psi)	
30	5,366	4,105	733.0	452.7
60	1,943	1,670	230.5	181.3
	(kPa)		(MPa)	
30	36,997	28,303	5054	3121
60	13,397	11,514	1589	1250

TABLE 3. — *Ratios of experimentally determined MOE to calculated MOE of flakeboard.*

Core	Three-layer	Five-layer	Seven-layer
Oriented	1.10	1.08	1.12
Random	1.12	1.10	1.18

TABLE 4. — *Flakeboard bending stress based on the transformed section.*

Core	Three-layer		Five-layer		Seven-layer	
	Rectangular section	Transformed section	Rectangular section	Transformed section	Rectangular section	Transformed section
	(psi)					
Oriented	8,425	13,786	10,345	14,247	10,567	14,848
Random	8,524	11,118	9,575	14,581	10,992	15,314
	(kPa)					
Oriented	58,088	95,051	71,326	98,230	72,857	102,373
Random	58,771	76,656	66,017	100,532	75,787	105,586

the properties of boards with 0- and 90-degree flake orientation, the bending properties of boards with 30- and 60-degree flake orientation were predicted (**Table 2**). Specific properties were obtained by dividing the MOR and MOE by the board density.

For a single-layer oriented panel, Price (16) showed the best strength theory for a tensile test was Hankinson's formula. Price further showed that an n of 2.15 in the formula yielded the best Hankinson's fit. Panels with random construction had tensile strengths equivalent to oriented specimens with an off-axis orientation of approximately 20 degrees. In our current study, with our 0- and 90-degree bending strength or specific bending strength data in Hankinson's formula and the exponential factor equal to 2.0, strengths were calculated for values with random monolayer panel values. The results show that a panel with a flake orientation offset of greater than 20 degrees would have less strength than a panel comprised of flakes with random orientation. Using Hankinson's formula, a 28-degree off-axis specimen when n = 2.5 approximated the MOE of the random panel. However, the modulus data indicate the same phenomena as our strength data; that is, panel flake orientation greater than 20 degrees will yield an MOE value less than a panel with random flake orientation.

In the three-layer panel, with only 25 percent of the flakes (i.e., 12.5% per face) oriented and the remainder in the core randomized, MOR increased by only 6 percent (**Table 1**), but the MOE increased by 88 percent. When the remaining 75 percent of flake volume was cross-oriented in the core, MOE was greater than for random panels, but less than for panels with oriented faces and random cores. Decreasing the core volume and increasing the number of oriented layers (five- and seven-layer panels) yielded additional MOR increases while MOE depended on the core construction. The three-layer and seven-layer random core panels had the greatest MOE values (**Fig. 2**). However, as the number of layers increased, the oriented core panels had an increase in MOE but only exceeded the random core panels values for five-layer construction.

Based on 12,411 MPa (1.8×10^6 psi), 965 MPa (0.14×10^6 psi), and 5516 MPa (0.80×10^6 psi) for parallel, perpendicular, and random single-layer MOE values, respectively, an apparent modulus MOE_c in bending was calculated as follows:

$$MOE_c = \frac{1}{I}\sum_{i=1}^{n} MOE_i I_i \qquad [2]$$

where I = moment of inertia based on the full cross section; MOE_i = MOE of the ith ply; I_i = moment of inertia of the ith ply about the centroid of the full cross section.

For comparison, a ratio of the experimentally determined MOE to the calculated MOE was obtained (**Table 3**). Since all the ratios are greater than one, the calculated values were lower than the experimental.

The monolayer MOE values were also employed for obtaining a transformed section and moment of inertia evaluation. Bending stresses based on the transformed section are shown in **Table 4**. With the transformed sections, the three-layer random core panel had a 26 percent increase above a monolayer random panel and yielded a smaller value than the three-layer oriented core panel. Five-layer panels had the opposite effect, i.e., random core had the highest stress of the transformed section values and oriented core the highest of rectangular sections.

For both the apparent modulus and transformed section calculation, the assumption that each layer within the construction had the assigned MOE value based on the single-layer panel values was not verified. In fact, the single-layer values are strongly influenced by the properties of the densified surface layer. Yet, layers located within the panel would have a lower density and logically a lower than assumed MOE value. If a lower MOE_i value is assigned to each layer except the face, MOE_c would decrease, and a larger MOE ratio of the face layer to the other layers would result. Since the transformed section bending strength utilizes this MOE ratio, a larger ratio would yield an additional strength increase in the trans-

TABLE 5. — Dimensional stability properties of single-layer and multi-layer flakeboards fabricated with sweetgum veneer flakes.[a]

Board type	Boil test: Thickness change	Boil test: Weight change	Boil test: Width change	Boil test: Length change	24-hour VPS: Thickness change	24-hour VPS: Weight change	24-hour VPS: Width change	24-hour VPS: Length change
	(%)							
Single-layer								
Random	33.4	102.6	0.08	0.07	27.0	102.8	0.51	0.46
Oriented								
0 degrees	25.0	100.8	3.30	-0.20	23.8	101.3	3.48	0.30
30 degrees	27.1	72.2	2.48	0.71	22.9	100.8	2.96	1.15
60 degrees	27.9	94.0	0.57	2.28	23.8	98.9	1.21	2.88
90 degrees	29.6	92.6	-0.18	3.17	20.6	103.3	0.32	3.59
Three-layer (oriented faces)								
Random core	38.8	84.2	0.40	0.07	28.5	90.8	0.94	0.52
Oriented core	37.8	68.4	0.09	1.14	30.3	83.9	0.68	1.39
Five-layer (oriented faces)								
Random core	35.7	85.1	0.21	0.12	28.8	92.1	0.75	0.62
Oriented core	36.2	73.6	1.02	0.21	29.6	88.6	1.18	0.47
Seven-layer (oriented faces)								
Random core	34.5	74.2	0.36	0.13	28.9	89.7	0.90	0.57
Oriented core	36.7	77.1	0.25	0.40	30.1	87.3	0.76	0.79

[a] Length is direction oriented parallel to face flake orientation while width is perpendicular to face flake orientation; VPS = vacuum-pressure-soak.

formed section strength values. Thus, these calculations and comparisons are conservative. In the accurate prediction of flexural properties of composites, it is also worthy to mention that other factors, such as shear deflection, should be considered.

Panels made with these veneer flakes had good compaction without noticeable voids, and high internal bond strengths were obtained. The largest difference, 36 psi, within various panel groups occurred for panels evaluated with different angles of orientation. With this uniform furnish, the data indicate that panels fabricated at equivalent densities but differing layering and/or orientation regimes should have similar internal bond strengths.

Physical properties

Although two test methods were employed for measuring the panels' dimensional change, both methods yielded similar results (**Table 5**). Length change of the five-layer panels was the only trend that was not similar for both test methods. Based on the five-layer panel fabrication, a larger length change for the random core after the 24-hour water soak test would be reasonable. Also, an increase (positive change) of the oriented specimens rather than a decrease in specimen dimensions when subjected to a 5-hour boil test would be expected. Because of these inconsistencies in the boil test data, only the 24-hour water soak data will be discussed.

Thickness and weight changes were similar for the multi-layer panels. The slight differences were most likely the result of density variability. Also, density variability may have resulted in lower thickness change and higher weight change values for the single-layer panels. An inverse density correlation with these properties would be expected in several cases (21). For example, the amount of solid wood thickness swelling would be less with less wood substance, and swelling could fill void areas of low density composites. Also, void areas make good water traps that make weight changes greater in lower density panels.

Since the single-layer oriented specimens are cut from the same panels, each single-layer oriented specimen width corresponds to the length of another single-layer oriented specimen. For example, the 0-degree specimen width is the same direction as the 90-degree specimen length, and the 30-degree specimen width is the same direction as the 60-degree specimen length. Averaging the equivalent directions, oriented single-layer panels had length change values of 0.31, 1.18, 2.92, and 3.54 percent for 0, 30, 60, and 90 degrees, respectively. Therefore, a width-to-length (0 to 90 degrees) dimensional change ratio of 11.4 was obtained.

Randomization of the flakes in a single-layer panel slightly increased the length change and substantially decreased the width change, when compared with an oriented single-layer panel. Comparison of the average direction values (0.49% for a random panel with previously given average oriented panel values) indicates that a small amount of off-axis orientation would yield a panel with dimensional change in excess of the random panel property. Thus, without good orientation, a random panel may have better dimensional properties than an oriented panel.

Conclusions

Properties of panels can be tailored to approximate requirements by designing an appropriate layered construction. A property increase in one direction is usually obtained by lowering the property value in the other direction. Internal bond strength was not affected by panel fabrication method. MOE was more sensitive to different fabrication schemes than MOR. The reason that the multi-layered panels were not more stable than random monolayer panels can possibly be attributed, in part, to the small size of the specimens. A larger percentage of oriented flakes in the face layer of layered panels may alter these conclusions about panel stability.

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