

Density Profile and Fiber Alignment in Fiberboard From Three Southern Hardwoods

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Abstract

Density profile and fiber orientation were evaluated for their effects on selected mechanical properties of medium density fiberboard. Bending MOE and modulus of rigidity were predicted from density profiles established by x-ray radiography. Orthotropic ratios ranged from 1.19 to 2.32 for electrically aligned fiberboards from three southern hardwoods. Off-axis tensile and compressive behavior was best described by Hankinson's formula when compared with other methods. Results indicate that oriented fiberboards have mechanical properties superior to boards of equal density but with randomly placed fibers; woody raw material can be best utilized as structural panels, therefore, in boards with oriented fibers.

MAT-FORMED PARTICLEBOARD was introduced into the United States and Canada about 25 years ago and has experienced spectacular growth in the past 10 years (Vajda 1975). However, growing pulpmill demand for low-grade wood waste and increasing utilization of wood waste as fuel are causing some changes in the particleboard industry. Medium density fiberboard (MDF), a recently developed product, has emerged as a major competitor because it can be manufactured from wood waste and low-grade hardwoods unsuitable for pulping or conventional particleboard. MDF is a dry-formed panel product

manufactured from lignocellulosic fibers bonded together with a synthetic resin, mat-formed, and compressed to desired density (31 to 50 lb./ft.³) while the binder is cured under heat and pressure (NPA 1973).

Density profile and degree of fiber orientation strongly influence the mechanical properties of MDF (Woodson 1976a; Talbott 1974). The present study investigated the effects of these two variables on selected mechanical properties of MDF manufactured from three southern hardwoods. Special emphasis was given to developing a nondestructive x-ray technique for determining density profile and predicting elastic moduli.

Experimental Procedure

Raw Material

Species were selected to cover the range of specific gravities occurring in the southern hardwoods and to represent a substantial percentage of the available supply. At least eight trees each of sweetgum (*Liquidambar styraciflua* L.), southern red oak (*Quercus falcata* Michx.), and mockernut hickory (*Carya tomentosa* Nutt.) were collected from different sites in central Louisiana. Information about the collection of

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materials and preparation of the fiber has been outlined in a previous study (Woodson 1976a) and will not be reported here.

Mat and Board Formation

Two techniques were used to form the experimental boards. One technique yielded sweetgum boards with random fiber orientation (random boards) and either uniform density through the thickness or gradient density (high-density faces and low-density cores). The other technique yielded fiberboards with electrically aligned fibers (oriented boards) made from each of the three species.

Random boards.—Sweetgum fibers were blended with 8 percent resin solids (Allied Chemical Fiberbond binder) and 1 percent wax solids (Hercules Inc. Paracol 404N), then brushed through 3/4-inch hardware cloth mounted on top of a forming box to form mats 18 inches wide, and 20 inches long. Uniform-density boards 1/2 inch thick were made in the following manner: mats were placed in an unheated hot press, compressed to thickness stops, and allowed to remain under pressure until oil-heated platens in the press attained a temperature of 285°F. Time for temperature to rise from 72°F to 285°F averaged 1 hour and 15 minutes. For boards with a density gradient, mats were prepressed at room temperature with a pressure of 300 psi and hot-pressed in an oil-heated press at 335°F and 480 psi. Press time was 9 minutes; closing time was about 30 seconds. These random boards were made at several densities:

Uniform boards

Density, g/cm³ 0.5, 0.6, 0.7, 0.8, 0.9, 1.0

Replications 3

Gradient boards

Density, g/cm³ 0.5, 0.6, 0.7, 0.8

Replications 3

Oriented boards.—Dry fibers from sweetgum, southern red oak, or hickory were blended with 10 percent powdered phenolic resin (Bakelite BRP 4425) and passed through a vibrating screen into an electrical field for fiber alignment, as described by Talbott and Stefanakos (1972) and Talbott (1974). Boards 12 inches wide, 15 inches long, and 3/8 inch thick were pressed in an electrically heated hot press at 420°F; closing time was 1 minute, and total press time was 5 minutes. This slow closing time results in a sinusoidal density profile with maximum density located beneath the surface. Four boards of each species were made with densities of 0.67 and 0.75 g/cm³ to determine properties parallel or perpendicular to the fiber alignment (principal-axis test). In a separate experiment (off-axis test), 12 sweetgum boards were made at each of the two densities and cut to yield specimens with orientation angles of 0, 15, 30, 45, 60, and 90 degrees. In addition, four sweetgum boards were pressed under these same conditions but with random fiber alignment for comparison with oriented boards.

Test Specimens

All boards were trimmed with equal sides having a length equal to 29 times the thickness, conditioned at 50 percent relative humidity and 72°F, and tested for

modulus of rigidity (ASTM D805-63) before samples were prepared for static bending, tension, and compression (ASTM D 1037-72a). Each property measurement was replicated three times. Compression specimens were prepared by laminating two matched pieces to yield final dimensions of 3/4 inch by 3/4 inch by 3-1/4 inch and tested without lateral support. Stacked, two-element, foil strain gages (1/2-in. gage length) were bonded to selected sets of randomly oriented tension and compression specimens to measure the deformations to be used in calculating Poisson's ratio. Modulus of elasticity (MOE) (tension and compression) was calculated from deformations measured with a strain gage extensometer having a gage length of 2 inches. Moisture content (MC) averaged 3.5 percent for oriented specimens and 7 percent for random specimens. Density values were calculated from the weight and volume of complete specimens at time of test. To facilitate comparisons, mechanical properties were adjusted to a common density of 0.70 g/cm³ by linear regression analysis of experimental data.

Results and Discussion

Random Boards

Gradient specimens had face densities 33 to 40 percent greater than core density and a 16 to 24 percent difference between face density and average density. Bending strength of gradient specimens was 32 percent greater than that of uniform-density specimens (Table 1). Tensile strength of gradient specimens was 12 percent greater than that of uniform-density specimens. Analysis of strain gage data from uniform-density tensile specimens indicated that strain at failure ranged from 0.6 percent for low-density specimens to 0.9 percent for high-density specimens. In gradient specimens, maximum strain was not an average of strain for high-density faces and low-density core; it was weighted more toward the strain of the faces. Compressive strength was not affected in any important way by density profile. Data for strain at failure were not available for compression specimens; therefore, analysis of their inelastic behavior was not made.

Modulus of rigidity and bending modulus of elasticity were 24 and 23 percent greater for gradient specimens than for uniform-density specimens (Table

Table 1.—STRENGTH AND ELASTIC MODULI FOR RANDOM 1/2-INCH SWEETGUM FIBERBOARDS ADJUSTED TO A COMMON DENSITY OF 0.70 g/cm³ AND CONTAINING 8 PERCENT RESIN.

Property	Density profile	
	Uniform (psi)	Gradient (psi)
Bending MOR	3,580	4,750
Tensile strength	2,742	3,058
Compressive strength	2,225	2,268
Modulus of rigidity	147,000	182,000
MOE		
Bending	373,000	460,000
Tensile	404,000	421,000
Compression	355,000	360,000
Poisson's ratio	0.386	0.386

1). Tensile and compressive MOE were both unaffected (statistically at the 0.01 level) by density profile. Strain gages attached to tension specimens with uniform density profiles indicated that Poisson's ratio did not vary with densities over the range from 0.6 to 1.0 g/cm³. Conversely, linear regression analysis indicated that all other strength and elastic properties were positively correlated with density. Thus the values (Table 1) were adjusted to a common density of 0.70 g/cm³ from the regression equations. The regressions were all highly significant and accounted for 90 to 99 percent of the total variation. For a more detailed account, the reader is referred to the author's doctoral dissertation (Woodson 1976b).

Density Profile Measurement

Knowledge of density variation through board thickness is important to supplement results of routine particleboard or fiberboard tests (Plath and Schnitzler 1974). The usual procedure is to plane successive thin layers from the board surface and calculate the density of material removed. This procedure, however, is time consuming and does not provide a continuum of data points. Nearn and Bassett (1968) suggested using x-ray radiography to study the subtle changes in density profile. In the present study, x-ray radiography was used to establish density profiles (Fig. 1) for subsequent prediction of elastic moduli. More detailed information about the x-ray technique may be found in previous studies (Woodson 1976a and b).

The relationship between recorder output and actual density was established by placing calibration samples (uniform-density specimens at various densities from 0.5 to 1.0 g/cm³) on the x-ray film each time a set of specimens was exposed. These calibration samples were the same thickness as the specimens to be examined and thus gave indexes for determining the actual density at any given point in the density profile. By measuring the light transmission (in millivolt output) through exposed film, it was possible to relate actual density of uniform-density specimens to the film density. This relationship (Fig. 2) appeared to be linear in the density range of 0.5 g/cm³ to 1.0 g/cm³ (density refers to actual specimen density). The calibration curve can be viewed as a characteristic curve, where specimen density is considered as an indicator of relative exposure and millivolt output is considered a measure of the film density. The relation

DENSITY

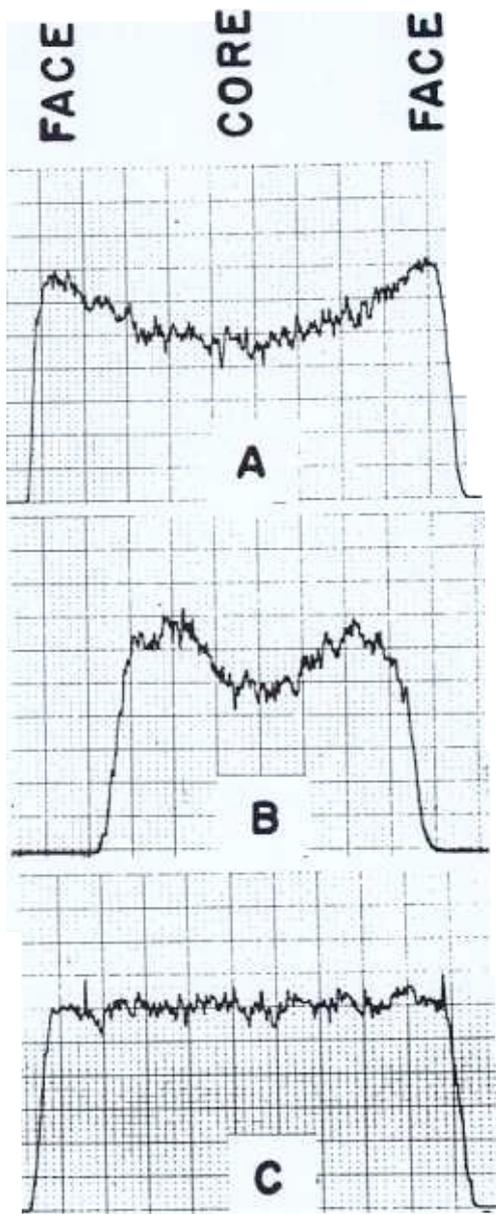


Figure 1.—Typical density profiles of fiberboards formed under three different pressing regimes. A) Parabolic density profile with maximum density located in the faces. B) Sinusoidal density profile with maximum density located beneath the surface. C) Special uniform density profile without density contrast face to core.

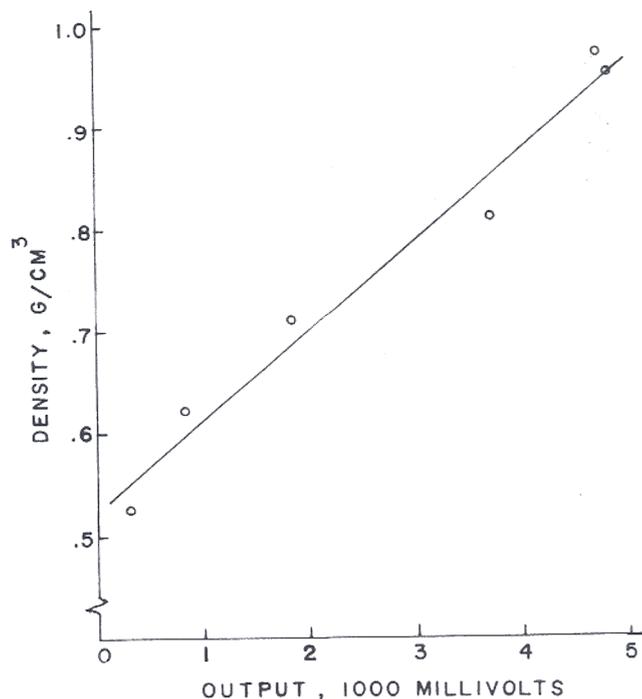


Figure 2.—Calibration curve for actual density versus light transmission as recorded from scanning densitometer.

is valid over the range of densities shown in Figure 2 and holds only for specimens exposed on this particular film. The relation cannot be assumed because the density range over which it is valid depends on the film used and on the processing conditions (Eastman Kodak 1969).

Predicting Elastic Moduli

Since modulus of rigidity and bending MOE were sensitive to density profile, further analysis of plate shear and bending specimens was appropriate to see how well predictions could be made for both elastic moduli from the x-ray density profiles.

The usual technique for analyzing a finite number of distinct layers for bending MOE is to construct a section of one material on which the resisting forces are the same as on the original section. Such a section is called an equivalent, or transformed, section and is frequently used to reduce a beam of several materials to an equivalent beam of one material so that usual elastic formulas apply. The transformation is accomplished by changing the width of a cross section parallel to the neutral axis in the ratio of elastic moduli of the material. For a beam with discrete layers of known elastic moduli, the effective elastic moduli (E_{eff}) can be expressed as

$$E_{eff} = \frac{\sum E_i I_i}{I}$$

where

E_i = MOE of each layer

I_i = moment of inertia of each layer about the neutral axis

I = moment of inertia of the entire beam about its neutral axis before the transformation.

It was convenient for prediction purposes to consider only boards with parabolic density profiles (Fig. 1A.) and with layer densities within the range of the calibration samples. Thus, the profile of the board cross section (Fig. 1A.) was divided into 16 layers (eight on each side of the center line) and the average density of each layer was calculated by using the calibration curve (Fig. 2). From the linear regressions established previously between density and the elastic moduli (uniform-density specimens), it was possible to use the standard summation equation to compute effective bending MOE and effective modulus of rigidity (G_{eff}). Predictions (Table 2) were quite variable with E_{eff} varying from 13 percent below to 8 percent

above and G_{eff} ranging from 3 percent above to 19 percent below the actual values. Overall, the predicted values averaged 3 percent less than the measured values.

The familiar summation technique is adequate for analyzing a finite number of layers. However, integral equations are necessary if a more general expression for an infinite number of layers is desired. For comparative purposes, an expression for effective bending MOE (E_{eff}) was derived by 1) establishing continuous functions for density profiles, 2) determining the effective density by transformed section, and 3) substituting this effective density into linear regressions relating MOE to density. The following expression was derived for a fiberboard with a parabolic density profile of the form $D_y = D_o + ay^k$:

$$E_{eff} = \alpha + \beta \left[D_o + \frac{3at^k}{2^{k+3}} \right]$$

The coefficients α and β were estimated by linear regression relating MOE to density; a and k were estimated by the nonlinear model for density profile; core density (D_o) and board thickness (t) were measured. Predictions from the general expression were similar to those obtained by using the summation technique and were generally less than experimental values. All random and oriented boards were made from matched fiber populations. Results, therefore, are not due to differences in furnish characteristics.

Oriented Boards

Principal-axis properties.—Average moduli of rigidity (adjusted to density of 0.70 g/cm³) for sweetgum, southern red oak, and hickory specimens were 173,000, 180,000, and 146,000 psi. Sweetgum specimens produced the greatest orthotropic ratios (ratio of property at 0° to the property at 90°) and also produced the greatest strength and elastic moduli for random and parallel fiber orientation (Table 3). Southern red oak, however, appeared to maintain the greatest strength and stiffness in the cross fiber direction.

Density profile can have as great an effect on bending properties as fiber orientation. Values for bending strength and bending MOE for random oriented hickory specimens are 10 percent greater than those for highly oriented specimens (0° orientation). Further analysis revealed that density profiles of the random specimens bonded with liquid urea resin (values in parentheses) were parabolic (i.e., similar to Fig. 1A) and the profiles for oriented specimens bonded with phenolic resin were sinusoidal (similar to Fig. 1B). Thus, the density profile completely masked the effect of orientation. Similarly, sweetgum specimens made with random fiber orientation and two resin types had different density profiles and therefore different bending properties (Table 3).

The difference in resin type appears to have affected tensile strength but not tensile MOE. Sweetgum specimens bonded with liquid urea and with random orientation (3,378 psi) yielded maximum stress values 25 percent less than those bonded with phenolic powder and random orientation (4,503 psi). Tensile strength is sensitive to interfiber bonding; it is

Table 2. — SPECIMEN DENSITY AND PREDICTED AND EXPERIMENTAL ELASTIC MODULI FOR 1/2-INCH SWEETGUM FIBERBOARDS.

Overall average density of specimens (g/cm ³)			Effective elastic moduli (1,000 psi)			
Static bending	Plate shear	X-ray	E_{eff}		G_{eff}	
			Predicted	Actual	Predicted	Actual
0.75	0.75	0.76	545	507	203	201
.72	.72	.70	463	465	176	184
.77	.76	.79	584	538	216	210
.92	.87	.91	683	718	249	250
.89	.88	.85	646	742	236	291
.86	.85	.84	654	716	239	241

Table 3.—STRENGTH AND ELASTIC MODULI OF 3/8-INCH FIBERBOARDS¹ FROM THREE SOUTHERN HARDWOODS WITH RANDOM, PARALLEL (0°), AND PERPENDICULAR (90°) FIBER ORIENTATION.

Species and orientation	Bending MOR (psi)	Tensile strength (psi)	Compressive strength (psi)	Elastic moduli (1,000 psi)		
				Bending	Tension	Compression
Sweetgum						
0°	7,001	5,565	4,322	678	711	651
Random ²	5,717	4,503	3,756	456	488	462
Random	(6,143) ³	(3,378)	—	(556)	(492)	—
90°	3,818	2,926	2,769	292	314	303
So. red oak						
0°	6,637	4,890	3,682	607	654	621
Random	(5,412)	(3,188)	—	(542)	(487)	—
90°	4,588	3,550	3,099	362	390	361
Hickory						
0°	5,097	4,416	3,530	456	562	522
Random	(5,628)	(2,825)	—	(501)	(448)	—
90°	3,551	2,776	2,546	286	310	304

¹Values adjusted to density of 0.70 g/cm³.

²Four boards with random fiber orientation made as controls for oriented fiberboard tests.

³Values in parentheses indicate values taken from a previous study (Woodson 1976) in which fibers were bonded with liquid urea resin; all other values derived from specimens bonded with phenolic powder.

therefore probable that differences are related to resin distribution.

Off-axis properties.—Sweetgum specimens prepared with orientation at angles of 0, 15, 30, 45, 60, and 90 degrees to the direction of applied load were subjected to uniaxial tension and compression to determine effects of fiber orientation. Experimental values were compared to predicted strengths from the maximum stress theory, distortional energy theory, and Hankinson's formula. A mathematical summary of these theories follows.

The maximum stress theory states that, for a given orientation (θ) in relation to the X_1 axis, the critical value for uniaxial strength is given by the lowest value (σ_θ) of the following:

$$\sigma_\theta = \sigma_{11} / \cos^2 \theta$$

$$\sigma_\theta = \sigma_{22} / \sin^2 \theta$$

$$\sigma_\theta = \sigma_{12} / \sin \theta \cos \theta$$

where σ_{11} = axial strength; σ_{22} = transverse strength; σ_{12} = shear strength (Tsai 1966).

For uniaxial strength σ_θ at arbitrary orientation (θ), the distortional energy theory states that

$$\frac{1}{(\sigma_\theta)^2} = \frac{\cos^4 \theta}{\sigma_{11}^2} + \left[\frac{1}{\sigma_{12}^2} - \frac{1}{\sigma_{11}^2} \right] \cos^2 \theta \sin^2 \theta + \frac{\sin^4 \theta}{\sigma_{22}^2}$$

The maximum stress theory and the distortional energy theory require a value for shear strength in the calculation. It was necessary, therefore, to determine a value experimentally for use in the prediction equations. Four specimens evaluated by the panel shear test (ASTM D805-63) resulted in a shear strength of 1,672 psi (adjusted to density of 0.70 g/cm³).

Hankinson's formula is suitable for computing the tensile or compressive strength (N_θ) at an angle θ to the direction of load and is represented by the expression

$$N_\theta = \frac{\sigma_{11} \sigma_{22}}{\sigma_{11} \sin^\lambda \theta + \sigma_{22} \cos^\lambda \theta}$$

where λ = exponent normally assumed to be 2. A best fit for Hankinson's formula was determined by

selecting the value of the power λ which minimized the residual sum of squares. The best value of λ was 1.75 for tension (Fig. 3) and 1.88 for compression (Fig. 4). Hankinson's formula provided a better estimate of tensile and compressive strength than either the maximum stress theory or distortional energy theory (Figs. 3 and 4).

Experimental and theoretical elastic moduli are shown as a function of fiber orientation in Figure 5. Transformed values (E_θ) were calculated from the following equation (Hearmon 1948):

$$\frac{1}{E_\theta} = \frac{\cos^4 \theta}{E_{11}} + \left[\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_{11}} \right] \cos^2 \theta \sin^2 \theta + \frac{\sin^4 \theta}{E_{22}}$$

where

E_{11} = MOE in the principal direction

E_{22} = MOE transverse to the principal direction

ν_{12} = major Poisson's ratio (transverse contraction in X_2 direction due to axial extension in X_1 direction caused by a tensile force in the X_1 direction)

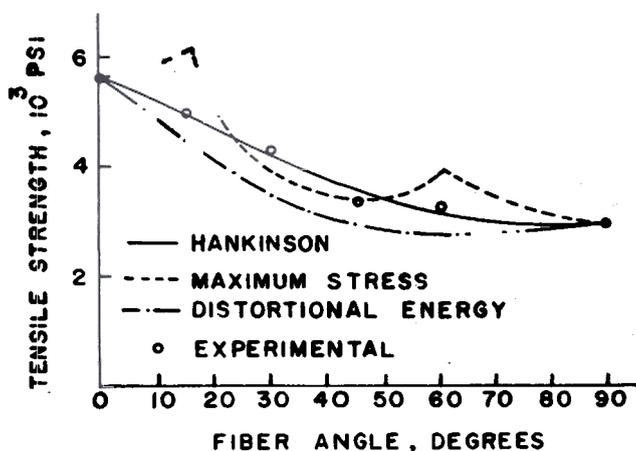


Figure 3.—Tensile strength as a function of fiber orientation based on Hankinson's formula (best fit), maximum stress theory, and distortional energy theory. Values adjusted to density of 0.70 g/cm³.

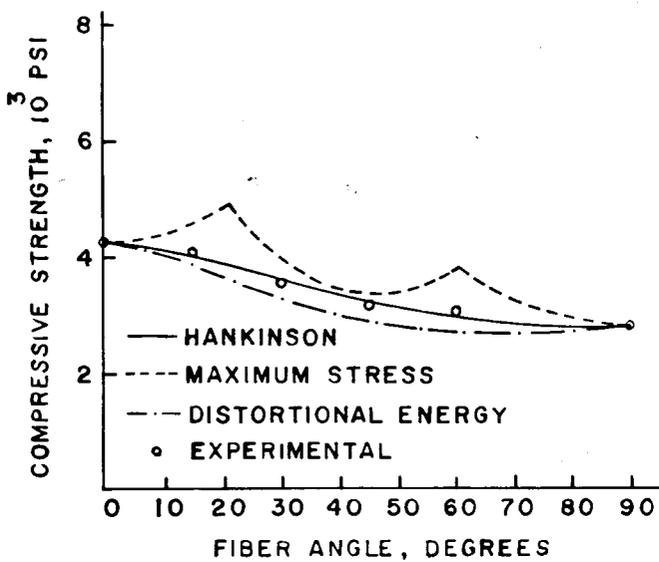


Figure 4.—Compressive strength as a function of fiber orientation based on Hankinson's formula (best fit), maximum stress theory, and distortional energy theory. Values adjusted to density of 0.70 g/cm³.

G_{12} = modulus of rigidity associated with shear deformations in the X_1 - X_2 plane.

Tensile and compressive MOEs were also compared to the best fit for Hankinson's formula (Fig. 5). Hankinson's formula proved to fit the experimental

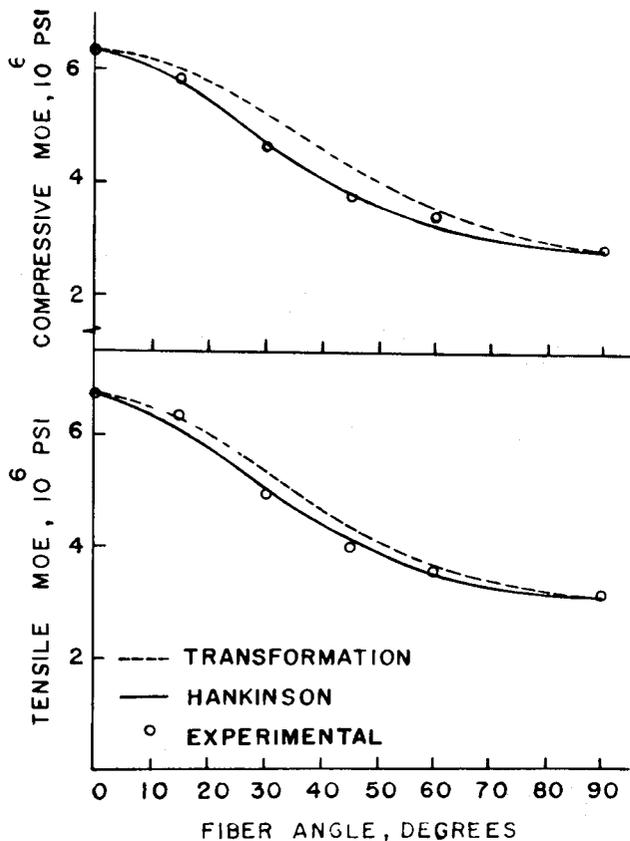


Figure 5.—Comparison of experimental and predicted tensile and compressive MOE as function of fiber orientation. Values adjusted to density of 0.70 g/cm³.

data better than the transformation equation. The best value of λ was 1.89 for tensile modulus and 1.90 for compressive modulus. The usual value for $\lambda = 2.00$ also gave a better fit than did the transformation equation.

Conclusions

The nondestructive x-ray technique for measuring density profile proved effective in predicting bending MOE and modulus of rigidity. Therefore, the technique could be used in commercial operations to supplement normal quality control procedures.

Although aligning fibers gave less improvement than that obtained with larger particles, the benefits were still substantial. Thus, oriented fiberboard with properties equal to those of random boards could be made at lower densities and with less raw material. Therefore, the technique may help extend the forest resource. In comparison with other methods, Hankinson's formula best described the tensile and compressive properties of sweetgum fiberboard tested at different angles of orientation.

Oriented fiberboard has great potential for structural use where the major axis of stress is in the direction of fiber orientation. Increasing strength through manipulation of density gradient also has promise, although boards with high face densities and low core densities will likely be weak in horizontal shear and will have low internal bond strength (Suchsland and Woodson 1976). In view of the high strength values obtained in experimental boards—both random and oriented—use of MDF as a structural material is a distinct possibility. Future research should focus on effects of long term loading to permit establishment of safety factors.

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