

Fiberboards from Loblolly Pine Refiner Groundwood:

Aspects of Fiber Morphology

Abstract

In tests with *Pinus taeda* L., most properties of wet-formed hardboard were improved by using fiber refined from wood having short, slender tracheids with thin walls. A theoretical analysis suggested that the fibers fail in bending while under stress induced by the pressing operation. Such bending failures improve conditions for hydrogen bonding, thus improving board properties. Tracheids having narrow diameters and thin walls flex easily and collapse readily. Short tracheids are more desirable than long tracheids because of a greater number of fiber crossings per unit weight in the pulp mat.

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A PREVIOUS PAPER (3) examined the interrelationships between gross wood characteristics and the physical properties of fiberboards made from loblolly pine. Wood specific gravity, proportion of latewood, and growth rate were shown to affect the strength of boards in tension and bending, as well as their dimensional stability. For the refining conditions and formation procedures employed, and after allowance for the effect of board specific gravity, most properties were improved by using fiber refined from dense wood having low latewood content. Because earlywood near the pith is relatively dense, and because the latewood content of loblolly pine characteristically is at a minimum near the pith, corewood appeared to be a desirable raw material from a strength standpoint.

Gross wood characteristics, being reasonably easy to measure, are useful in identifying wood types. It is difficult however, to interpret them in terms of their causal relationships with board properties. For example, wood specific gravity is, in part, determined by the morphological characteristics of earlywood and latewood tracheids and the proportions of each tissue type (4). Therefore, a study was made of the interrelationships between fiber morphology and the physical properties of boards.

Procedure

The detailed procedures for selection of trees, wood preparation and classification, refining, chip sampling, and board formation and testing have all been described previously (3). All morphological characteristics were

measured on samples used in the earlier study and were correlated with the board properties determined in that study (3).

Wood was selected and stratified into 12 categories. Two growth rates (less than six rings per inch and more than six rings per inch), two specific gravities (less than 0.49 and more than 0.49), and three radial positions in the tree (0 to 10, 11 to 20, and 21 to 30 rings from the pith) were considered in a factorial design. The wood in each category was chipped and the chips randomly divided into four within-sample replications. A subsample was drawn from each replication for determination of fiber characteristics.

Four morphological properties were measured for both earlywood and latewood—single cell-wall thickness, radial lumen diameter, radial tracheid width, and tracheid length—and correlated with seven board properties.

Tracheid length was determined from 40 chips randomly selected from each subsample. Chips were dissected into earlywood and latewood slivers and macerated in a 50/50 solution of 30 percent hydrogen peroxide and glacial acetic acid for 48 hours at 50°C. Samples of the macerated material were mounted in water on 10 glass slides. With a calibrated projection

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The author acknowledges the assistance of the Roy O. Martin Lumber Co., Alexandria, La.; R. A. Leask and J. Adams, Bauer Bros. Co., Springfield, Ohio; and D. Bower, statistician, Southern Forest Experiment Station, New Orleans, La.

This paper was received for publication in September 1968.

microscope (X40), five tracheids were measured on each slide—the five unbroken tracheids lying adjacent to a dot on the center of the projection screen. Thus, 50 observations were made on each replicate.

On other macerated tracheids, single cell-wall thickness, lumen diameter, and tracheid diameter for both earlywood and latewood were separately determined by viewing the radial fiber surface. Fifty observations of each dimension were made at the midpoint of the tracheids (five observations on each of 10 slides) with a compound microscope equipped with a Filar eyepiece. Radial surfaces were identified by the presence of pits. Thickness of both cell walls was measured and the results averaged for each observation.

Boards were manufactured in three density classes of approximately 0.45, 0.60, and 0.80 (low, medium, and high). Partly on the basis of results in the first study, it seemed likely that the relations between fiber morphology and board properties would be similar for the three board-density classes. The assumption was tested and found to be valid. Therefore this paper deals only with boards of the 0.60 density class.

Processing the Data

Since a hardboard is a composite of both earlywood and latewood fibers, a weighting system was employed to describe average morphological characteristics, e.g., average earlywood-latewood tracheid length.

If the dimensions of cells in the tangential direction are assumed constant at unity, it can be shown that a given average morphological property for the earlywood

and latewood composite is a function of the number of cells per unit volume of each tissue type and their respective volume percentages. From this analysis, the following weighting equation was developed:

$$P = \frac{\left[\frac{(1-LW)(P_e)}{(ET)(ETD)} \right] + \left[\frac{(LW)(P_l)}{(LT)(LTD)} \right]}{\left[\frac{(1-LW)}{(ET)(ETD)} \right] + \left[\frac{(LW)}{(LT)(LTD)} \right]}$$

Where

- P = a weighted morphological characteristic of the earlywood-latewood composite
- P_e = a morphological characteristic of earlywood
- P_l = a morphological characteristic of latewood
- LW = proportion of latewood
- ET = earlywood tracheid length (millimeters)
- ETD = earlywood tracheid diameter (micrometers)
- LT = latewood tracheid length (millimeters)
- LTD = latewood tracheid diameter (micrometers)

The morphological characteristics of the wood samples were derived by this weighting procedure. The proportion-of-latewood values used in the equation were those obtained in the earlier study.

The drainage and formation characteristics of the pulps were such that accurate control of board density was not possible. Therefore the specific gravity of the

Table 1. — WEIGHTED WOOD CHARACTERISTICS AND BOARD PROPERTIES FOR BOARDS OF MEDIUM DENSITY.^a

Position in tree (Rings from pith)	Unextracted chip specific gravity	Rings per inch	Cell-wall thickness ^b		Lumen dia. ^b	Tracheid width ^b	Tracheid length ^b	Tension		Bending			Dimensional change				
			μm	μm				μm	mm	Max. stress	Board specific gravity	Max. stress	Board specific gravity	Stress at PL	MOE	MOR	Board specific gravity
			μm	μm	μm	mm	Psi		Psi		Psi	Psi	Psi		%	%	
0-10	.431	4.75	6.3	36.8	49.2	3.85	2,187	0.672	17.9	0.663	1,610	487,795	3,340	0.672	0.535	8.96	0.677
0-10	.456	10.13	6.2	33.4	45.7	3.79	1,713	.635	20.6	.610	1,377	441,713	3,029	.635	.542	8.51	.637
0-10	.494	4.47	6.5	31.5	44.3	3.61	2,436	.709	19.8	.690	1,953	585,329	4,117	.709	.557	8.57	.764
0-10	.535	12.39	6.5	29.2	42.2	3.43	2,013	.671	23.4	.655	1,673	517,502	3,541	.670	.504	7.42	.670
11-20	.442	5.52	6.6	36.7	49.7	4.26	1,800	.658	17.8	.654	1,295	403,027	2,838	.658	.532	9.15	.667
11-20	.466	6.84	6.6	34.8	47.9	4.22	1,754	.673	20.3	.655	1,269	407,398	2,815	.673	.500	9.50	.683
11-20	.510	4.78	7.5	29.2	44.2	4.11	1,745	.637	20.0	.647	1,105	332,293	2,482	.637	.542	8.89	.649
11-20	.531	8.34	7.3	28.9	43.5	4.02	2,074	.693	24.5	.665	1,474	434,573	3,195	.693	.522	8.45	.685
21-30	.470	5.21	7.4	33.9	48.2	4.37	1,870	.680	20.2	.646	1,373	412,814	2,953	.680	.550	9.08	.673
21-30	.449	8.15	6.9	31.9	45.6	4.19	1,720	.660	18.6	.649	1,228	388,605	2,733	.660	.542	9.18	.653
21-30	.517	6.30	7.3	30.3	44.8	3.93	1,808	.677	20.8	.656	1,234	377,752	2,784	.677	.537	8.55	.679
21-30	.534	9.86	7.9	27.3	43.1	3.96	1,952	.676	24.8	.665	1,413	426,728	2,928	.676	.512	9.31	.679

^aEach numerical value is the average of four replications except that the values for rings per inch are based on one observation.

^b μm = micrometer = 10^{-3} millimeters = 10^{-6} meters.

medium-density boards was considered in developing stepwise multiple regression equations relating hard-board properties and morphological characteristics. In the analysis the effects of board density and the square of board density were considered first. Morphological factors were then accepted by the usual stepwise criteria. All equations were of the type: $y = b_0 + bx_1 + bx_2 + \dots$ where y is a dependent variable, e.g., modulus of elasticity, modulus of rupture; b_i , a regression coefficient; and x_i , an independent variable, e.g., weighted average tracheid length, weighted average cell-wall thickness. All equations were tested at the 95 percent level of probability, and all variables included were significant at that level.

Table 2. — MULTIPLE REGRESSION EQUATIONS DEVELOPED TO ESTIMATE BOARD PROPERTIES.¹

Variable	Coefficient	Cumulative R ²	Standard error of estimate
Equation 1. Maximum stress, tension parallel (psi)			
	b ₀	786.5718	
(BG)	b ₁	—210.5061	.583
(BG) ²	b ₂	4,186.4811	.592
(TL) ²	b ₃	38.0156	.684
			168
Equation 2. Maximum stress, tension perpendicular (psi)			
	b ₀	—49.1934	
(BG)	b ₁	270 9175	.001
(BG) ²	b ₂	—210.5355	.042
(LD)	b ₃	—0.4368	.219
			3.1
Equation 3. Stress at PL in bending (psi)			
	b ₀	3,469.7360	
(BG)	b ₁	—5,445 9997	.466
(BG) ²	b ₂	8,417.5693	.498
(TL) (CWT)	b ₃	—1,847.0007	.622
(TD)			
(TD — LD)	b ₄	—208.6679	.680
			192
Equation 4. MOR in bending (psi)			
	b ₀	3,963.9965	
(BG)	b ₁	4,022 0525	.558
(BG) ²	b ₂	6,352.2598	.587
(TD)	b ₃	—606.6188	.790
(TD — LD)	b ₄	—36 5260	.821
(CWT) ²			
(TL)	b ₅	—20,246.1189	.843
(TD)			
			273
Equation 5. MOE in bending (psi)			
	b ₀	2,012,648 3150	
(BG)	b ₁	—4,467,736.4260	.535
(BG) ²	b ₂	4,797,955.4690	.603
(TL) (CWT)	b ₃	—625,763.7390	.747
(TD)			
(TD — LD)	b ₄	—71,209.6330	.815
			45,545
Equation 6. Dimensional change parallel to surface (%)			
	b ₀	0.7031	
(BG)	b ₁	—0.6722	.092
(BG) ²	b ₂	—10.6150	.104
			0.03
Equation 7. Dimensional change perpendicular to surface (%)			
	b ₀	2.3858	
(BG)	b ₁	6.1893	.000
(BG) ²	b ₂	—2.4849	.026
(TD ² — LD ²) (TL)	b ₃	0 0009	.360
			.57

¹BG = board specific gravity (ovendry weight and volume at test); TL = tracheid length (mm.); CWT = cell wall thickness (μm); TD = tracheid diameter (μm); LD = lumen diameter (μm).

cient; and x_i , an independent variable, e.g., weighted average tracheid length, weighted average cell-wall thickness. All equations were tested at the 95 percent level of probability, and all variables included were significant at that level.

The single variables included in the analysis were:

BG = board specific gravity

TL = weighted average tracheid length (millimeters)

CWT = weighted average cell-wall thickness (micrometers)

LD = weighted average lumen diameter (micrometers)

TD = weighted average tracheid diameter (micrometers).

Various combinations and transformations of the single variables were selected to include functions indicative of bending strength and resistance to collapse.

The transformations were:

$$(LD)/(TD)$$

$$\frac{1}{(TD)}$$

$$(TL)/(TD)$$

$$(TD)/(TD - LD)$$

$$(BG)^2$$

$$(TL)^2$$

$$(LD)^2$$

$$(CWT)^2$$

$$(TD)^2$$

$$[(TD)^2 - (LD)^2] (TL)$$

$$(TL) (CWT)$$

$$(TD)$$

$$2 (CWT)$$

$$(LD)$$

Results

Table 1 summarizes morphological characteristics and board properties for the 12 wood categories. Board properties are those from the previous paper. The values are carried to an extreme number of places to permit the present statistical manipulation and are not intended as

absolute measures of strength. The averaged values are accurate to no more than four significant digits.

Several of the morphological characteristics were correlated. For the 48 observations, lumen diameter was negatively correlated with cell-wall thickness ($r = -0.621$) and positively correlated with tracheid diameter ($r = 0.938$). Tracheid diameter was also positively correlated with tracheid length ($r = 0.429$). All other correlations were low (<0.323).

Table 2 lists multiple regression equations which most accurately describe the strength and stability of boards in terms of board specific gravity and weighted average morphological characteristics. The effect of specific gravity on board properties has been discussed in the previous paper (3) and will not be repeated here.

The relationships are charted in Figure 1. The graphs were drawn by substituting a range of values for the variable on the X axis and fixing the remaining variables at their mean values or at the indicated levels. The relations plotted consider only the range of variation contained within the range of all remaining variables.

The best equation for maximum stress in tension parallel to the surface (Equation 1) accounted for 68 percent of the total variation with a standard error of 168. After the positive effect of board gravity had been accounted for, stress was negatively related to the square of tracheid length (Fig. 1,A); *i.e.*, within the range of experimental data, stress was increased by using fiber refined from wood having short tracheids.

Maximum stress in tension perpendicular to the surface was related to lumen diameter after the effect of board density had been considered (Equation 2). As charted in Figure 1,B, maximum stress increased with decreasing lumen diameter. This property was equally well related to cell-wall thickness; it increased with decreasing wall thickness.

The best multiple regression equation for stress at the proportional limit in bending accounted for 68 percent of the total variation with a standard error of 192 (Equation 3). After board density had been considered, stress was a complex function of tracheid length, cell-wall thickness, tracheid diameter, and lumen diameter. Lumen diameter varied with tracheid diameter by the lineal regression equation:

$$LD = -27.7597 + 1.3080 (TD) \quad (R^2 = 0.893)$$

As shown in Figure 1,C, bending stress increased with decreasing tracheid length for all levels of cell-wall thickness and tracheid diameter. The level of the relationship of stress to tracheid length increased and the slope decreased with decreasing cell-wall thickness, whereas both the level and slope increased with decreasing tracheid diameter.

All variables considered, stress at the proportional limit in bending was greatest in boards made from fiber refined from wood having short tracheids with slender diameters and thin walls.

Equation 4 accounted for 84 percent of the variation in modulus of rupture (MOR). The standard error of the estimate was 273. With the positive effect of board

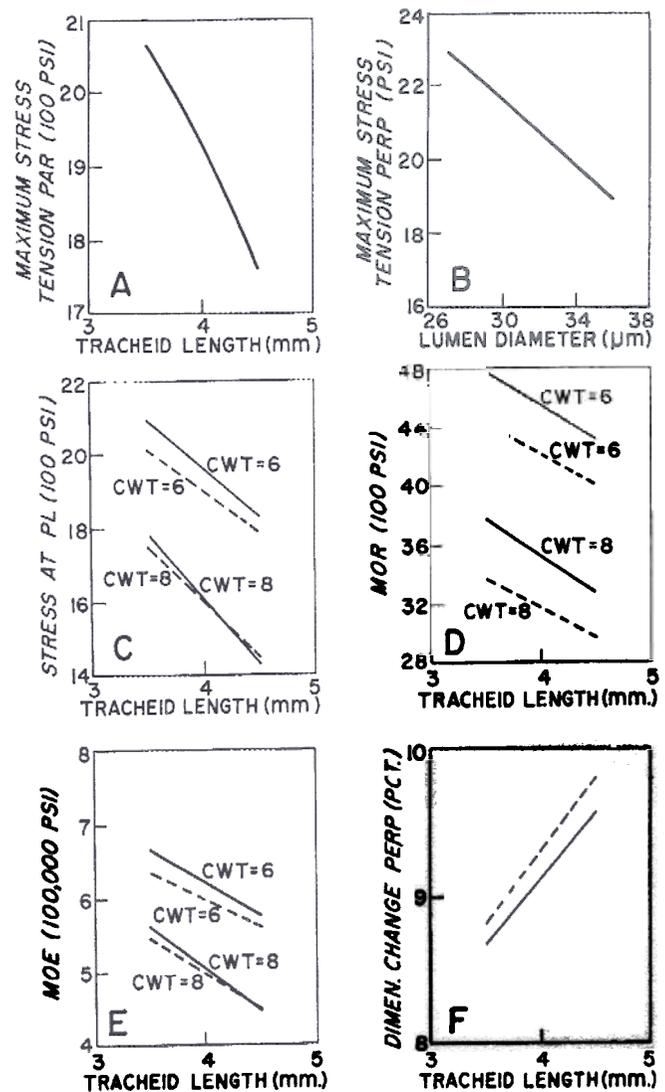


Figure 1. — Effect of tracheid length, cell-wall thickness, lumen diameter, and tracheid diameter on the strength and stability of fiberboard. Dotted lines plot tracheids having outside diameter of 49 micrometers (μm). Solid lines plot tracheids having outside diameter of 42 micrometers.

gravity allowed for, MOR was a complex function of lumen diameter, tracheid diameter, cell-wall thickness, and tracheid length. It increased with decreasing tracheid length for all levels of cell-wall thickness and tracheid diameter (Fig. 1,D). The level of the relationship of MOR to tracheid length increased with decreasing cell-wall thickness and decreasing tracheid diameter. The slope remained essentially unchanged. All factors considered, MOR was improved by using fiber refined from wood having short, slender tracheids with thin walls.

Modulus of elasticity (MOE) in bending was also related to a complex function of tracheid length, lumen diameter, tracheid diameter, and cell-wall thickness after the positive effect of board gravity had been considered. Equation 5 accounted for 82 percent of the variation with a standard error of 45,545. As shown in Figure 1,E, MOE increased with decreasing tracheid length for all

sampled levels of tracheid diameter and cell-wall thickness. The level of the relationship increased and the slope decreased with decreasing cell-wall thickness. In wood having thin cell walls (6 micrometers), the level and the slope increased with decreasing tracheid diameter. In wood having thick cell walls (8 micrometers), neither the level nor the slope differed significantly with tracheid diameter.

All variables considered, *MOE* in bending was greatest in boards made from fiber refined from wood having short, slender tracheids with thin walls.

After board gravity, no morphological characteristic was related to dimensional change parallel to the surface (Equation 6).

Equation 7 accounted for 36 percent of the dimensional change perpendicular to the surface; the standard error was 0.57. Tracheid diameter, lumen diameter, and tracheid length were significant morphological characteristics after board gravity had been considered. Dimensional change decreased with decreasing tracheid length (Fig. 1,F). For a given tracheid length it decreased with decreasing tracheid diameter. All factors considered, dimensional change perpendicular to the surface was least in boards made from fiber refined from wood having short, slender tracheids.

Discussion

Atack and May (1) have described three phases of mechanical breakdown during the double-disk refining of chips. The first phase, occurring in the breaker-bar section, produces slender, matchstick fragments whose major axes lie in the direction of the wood grain. In a

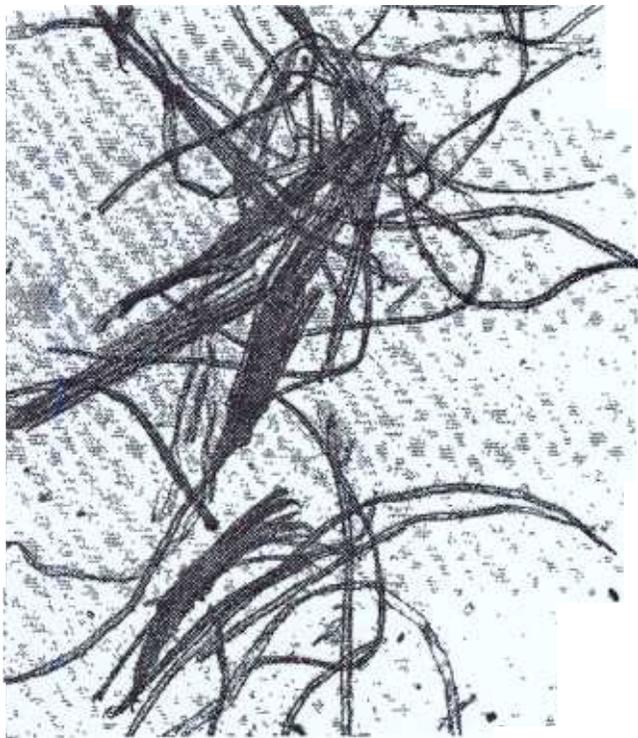


Figure 2. — Micrograph of typical pulp

second phase, these fragments are processed into partially or completely separated fibers. Last, the particles are refined into pulp of high specific surface area.

Particles of high surface area are produced by multi-pass operations at high levels of refining energy. In contrast, single-pass operations at low energy tend to yield only partially or completely separated fibers typical of those produced during the second phase of refining. The single-pass pulps were of this type (Fig. 2).

Boards of improved strength resulted when pulps were refined from wood with short, slender, thin-walled tracheids. It seems possible that the properties of fiberboards are determined through interaction of the hydrodynamic characteristics of fibers during mat formation, the forces exerted during mat pressing, and the morphological characteristics (cellular dimensions) of the fibers. Although an exact theoretical analysis is confounded by complex thermodynamic and chemical effects, an approximate solution can be developed that is in reasonable agreement with the observed morphological characteristics and board properties.

Consider that single-pass refining at low energy produces uniform, right-cylindrical, intact pulp fibers consisting of only the S_2 layer and having outside diameter d_o , inside diameter d_i , and length L (Fig. 3,A). Assume, as observed by Elias (2), that during formation of the wet mat the majority of the fibers orient themselves with their major axes perpendicular to the direction of water flow.

For these conditions, the resulting filtration-formed mat consists of layered, intact fibers whose major axes are parallel to the surface of the mat. Figure 3,B diagrams part of such a mat. When compressive forces F_c are applied during pressing, fibers of the mat are stressed as beams with concentrated loads. Under these conditions, an individual fiber may be analyzed as a hollow circular shaft stressed in bending.

If the undeformed fiber is considered to be held in mechanical equilibrium, Figure 3,C approximates the force relationship. Pressing force F_c is applied through an adjacent fiber and is resisted by reactive forces F_r of opposite sign. The state of stress of an element from the fiber's lower surface is pure tension. The maximum stress in tension for a hollow shaft in bending is

$$S_t = \left[\frac{32M}{d_o} \right] \left[\frac{1}{1 - (d_i/d_o)^4} \right] \quad [8]$$

Where

- S_t = maximum stress in tension
- M = bending moment
- d_o = outside diameter
- d_i = inside diameter

Equation 8 and Figure 3,D show that, for a given wall thickness and bending moment, a shaft with a small outside diameter develops greater stress than a large diameter shaft. For a given outside diameter, stress is greater in thin-walled than in thick-walled shafts. When the stress level exceeds the strength of the wall it

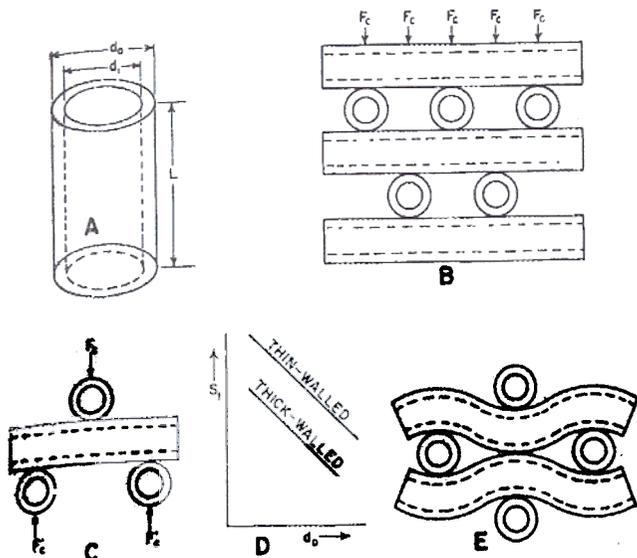


Figure 3. — Force relationships within fibers during pressing.

tension (or compression in the opposite wall), failure in bending occurs. Such bending failure tends to bring adjacent and overlapping fibers into contact (Fig. 3,E). As water is removed from the mat by heat and pressure, favorable conditions for hydrogen bonding between fiber surfaces are developed. Thus, thin-walled tracheids of small outside diameter are more desirable than thick-walled tracheids of large outside diameter, since they are more highly stressed in bending and are more conformable.

In pulps refined from wood with short tracheids, the major portion of the weight is comprised of short fibers. Such pulps have more fiber crossings per unit weight than do pulps made from wood with long tracheids (2). Thus, in pulps from wood having short, slender, thin-walled tracheids, both the degree and the number of potential hydrogen bonds are increased, and it is reasonable to expect an accompanying improvement in board strength. This analysis of bending stresses in cylindrical fibers during pressing agrees with the experimental results in terms of optimum tracheid dimensions for improving properties of fiberboards.

In addition to failing in bending, the fibers diagrammed in Figure 3,B probably also fail as thin circular rings in direct compression, assuming an elliptical cross section. Such deformation again increases surface contact between fibers, and thereby the potential number of hydrogen bonds. The strain in a thin circular ring is directly proportional to its diameter and inversely proportional to the square of its wall thickness. Thus, for a given diameter, greater strain is developed in rings having thin walls than in rings having thick walls.

It is also possible that the chemical composition of wood may affect the properties of fiberboard. A regression analysis to test this hypothesis followed a sequence of first considering the effects of board gravity and morphological characteristics and then introducing chemical factors in stepwise fashion. Five chemical constituents were determined for each of the 48 categories

of wood samples used to manufacture the pulps. The constituents considered were hemicellulose, holocellulose, alpha-cellulose, lignin, and alcohol-benzene extractives.

Only one board property, maximum stress in tension parallel to the surface, proved related to wood chemical composition after the effects of fiber morphology had been considered. The equation was:

$$S_{tp} = -2871.3476 + 9901.9982(BG) - 3800.0017(BG)^2 \\ -20.0053(TL)^2 - 317.7213(EC) + \\ 10324.4808(EC/LI) \quad [9]$$

Where

S_{tp} = maximum stress in tension parallel to surface (psi)

EC = extractive content expressed as a percentage by weight of unextracted oven-dry wood

LI = lignin content expressed as a percentage by weight of extractive-free oven-dry wood.

Extractive content and the ratio of extractive content to lignin content proved significant after the effects of morphology were considered. From Equation 9 tensile strength parallel to the surface increases with increasing extractives. The level and the slope of the relationship increase with decreasing lignin content. Morphological characteristics and board gravity in this equation accounted for 68 percent of the variation with a standard error of 168. Chemical components accounted for an additional 10 percent. The standard error was 145.

It is possible that, under heat and pressure, extractives in the pulp polymerize to form resin-like compounds that may act as an adhesive between adjacent fibers. The positive effect of low lignin content on tensile strength may be due to reduced blocking of reactive sites necessary for hydrogen bonding.

Although no chemical constituent exhibited a significant effect on the other board properties, it should be noted that a considerable proportion of the total variation, particularly in bending, was accounted for when fiber morphology was specified (Table 2). Hence, from a statistical point of view, a relatively small percentage of the total variation remained unexplained. Extractives or other chemical constituents may affect board properties, but in this test the variation could not be detected after the effects of fiber morphology had been considered.

Literature Cited

1. ATACK, D., and W. D. MAY. 1963. Mechanical reduction of chips by double-disk refining. *Pulp Pap. Mag. Can.* 64(C): T75-T83, T118.
2. ELIAS, T. C. 1965. An investigation of the compression response of ideal unbonded fibrous structures by direct observation. Ph.D. Diss. Lawrence Univ. Appleton, Wis.
3. McMILLIN, C. W. 1968. Fiberboards from loblolly pine refiner groundwood: effects of gross wood characteristics and board density. *Forest Prod. J.* 18(8) 51-59.
4. ———. 1968. Morphological characteristics of loblolly pine wood as related to specific gravity, growth rate, and distance from pith. *Wood Sci. and Technol.* 2(3): 166-176.