INFLUENCE OF JUVENILE WOOD ON DIMENSIONAL STABILITY AND TENSILE PROPERTIES OF FLAKEBOARD[1]

Robert L. Geimer
Forest Products Technologist

Victoria L. Herian
Statistician

and

Danping Xu
Visiting Scientist

USDA Forest Service
Forest Products Laboratory
Madison WI 53705

(Received September 1996)

ABSTRACT

The purpose of this study was to determine if juvenile wood adversely affects the linear expansion, water adsorption, and thickness swell of aligned flakeboard. Literature on juvenile wood properties and their effects on product performance was reviewed. Veneer and lumber cut from 35-year-old plantation-grown loblolly pine were segregated by age and used to manufacture plywood and flakeboard. As expected, longitudinal linear expansion of the juvenile (0 to 12 years old) veneer was greater than that of mature (13+ years old) veneer. At several levels of humidity exposure, linear expansion of symmetrical cross-laminated plywood made from the juvenile veneer was greater than that of plywood made from mature veneer. Significant increases in the linear expansion of three-layer cross-oriented flakeboard were also attributed to juvenile wood. Differences in the linear expansion of single-layer directional aligned flakeboards made from juvenile wood and from mature wood were not statistically significant for the most part. Analysis did show that test results were affected by tree-to-tree variation in wood age and sample variations. Accurate predictions of dimensional stability in three-layer cross-aligned panels were made using tensile and linear expansion properties derived from the directional flakeboard.

Keywords: Juvenile wood, flakeboard alignment, linear expansion, dimensional stability, tensile strength.

INTRODUCTION

Forest plantations and intensively managed stands represent an ever-increasing portion of the wood needed to supply the world's expanding human population. However, the short rotations and rapid tree growth associated with plantations increase the percentage of juvenile wood in harvested timber. The detrimental effects of juvenile wood on the properties of solid wood products and paper have been extensively assessed. However, studies have shown that strength deficiencies attributed to juvenile wood are often slight or nonexistent in fiber, particle, and flake composites as a result of interacting fabrication variables such as particle geometry and compaction ratios.

Research on the influence of juvenile wood on the dimensional stability of composites is

[1] The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin. This article was written and prepared by U.S. Government employees on official time, and it is therefore in the public domain and not subject to copyright.

Wood and Fiber Science, 29(2), 1997, pp. 103–120

limited and does not adequately describe its effect on oriented flakeboard. A model based on the directional linear expansion and tensile modulus of elasticity (MOE) of each composite layer (Heebink et al. 1964) could be useful in predicting the linear expansion of cross-oriented flakeboard. In particular, the linear expansion of a balanced cross-laminated composite panel is very similar to the linear expansion of the layers measured in the parallel-to-grain direction. Information on the dimensional stability of both layered cross-oriented boards and homogeneous board made with unidirectional oriented flakes is important in view of the prominence of oriented strandboard (OSB) in the sheathing market and the emergence of composite lumber.

BACKGROUND

Characteristics of juvenile wood

Juvenile wood exists in every tree. It is classified as that portion of the xylem, surrounding the pith in a cylindrical column, whose cells have not fully matured. The failure of cells to mature is attributed to the prolonged influence of the apical meristem on lateral cambium wood formation (Panshin and de Zeeuw 1980). During part of its early growth, the entire tree consists of juvenile wood. In a large tree stem, juvenile wood is a core of approximately uniform diameter along the length. Above a certain height, the stem consists entirely of juvenile wood. The actual number of growth rings in the juvenile core depends upon how juvenile wood is anatomically defined (Bendtsen 1978). Compared to mature wood, the juvenile wood of conifers is characterized by lower specific gravity, shorter tracheids, larger fibril angle, lower transverse shrinkage, higher longitudinal shrinkage, lower strength, lower percentage of latewood, higher moisture content, thinner cell walls, larger lumen diameters, and less cellulose but higher lignin content. However, the demarcation between juvenile and mature wood is never clear because of the gradual nonlinear change in properties with time. Researchers generally agree that the juvenile core occurs in the first 5 to 20 growth rings, depending mostly upon species (Erickson and Arima 1974; Goggans 1961; Hallock 1968; Isebrands and Hunt 1975; Rendle and Phillips 1957; Zobel et al. 1972; Shiokura 1982; Bendtsen 1978, 1986).

Juvenile wood can be either sapwood or heartwood (Krahmer 1986). Reaction wood (tension wood in hardwood and compression wood in softwood) that appears during the first few years of growth is difficult to separate from juvenile wood since their properties are somewhat similar (Zobel et al. 1972; Zobel and Blair 1976; Isebrands and Bendtsen 1972; Isebrands and Parham 1974; Olson et al. 1947). Limited evidence suggests that the extent of juvenility in terms of differences in anatomical characteristics is less in hardwoods than in conifers (Boyd 1968). Although juvenile wood is not always associated with fast growth, it usually characterizes plantation-grown trees; mechanical properties of lumber suffer from the combination of juvenile wood and low density (Pearson and Gilmore 1971, 1980; Senft et al. 1985).

Properties of lumber made from juvenile wood

Tensile strength, bending modulus of rupture (MOR), and bending MOE of juvenile wood are inferior to that of mature wood because of high fibril angle, short tracheid length, and low specific gravity (Panshin and de Zeeuw 1980; Smith and Briggs 1986). Reduction in selected mechanical properties of parallel laminated veneer made from larch containing juvenile wood was reported by Jo et al. (1981). Members fabricated with 100% juvenile wood had 90% of the compression strength, 70% of the bending strength, and 70 to 80% of the block shear strength of members made with 100% mature wood.

The high fibril angle found in juvenile wood causes up to 10 times as much shrinkage along the grain as found in mature wood (Meylan 1968) and is often responsible for severe warp in lumber. Weak joints, warped panels, and uneven floors can also be attributed to juvenile wood shrinkage characteristics.

Properties of composite boards made from juvenile wood

Several studies have investigated the influence of juvenile wood on composite board properties. Stefaniak (1981, 1985) manufactured particleboards at specific gravity (SG) values of 0.5, 0.6, and 0.7 from (a) crown branches more than 15 years old, (b) mature stem wood, and (c) juvenile stem wood. Tests showed that particleboards made from juvenile wood had better strength properties (bending MOE, MOR, and internal bond) and lower water adsorption and thickness swell than particleboards made from mature wood. Boards made from branch wood had better bending MOR but poorer bending MOE and internal bond properties and poorer (higher) water adsorption and thickness swell properties than did boards made from mature wood.

The linear expansion of Douglas-fir flakeboard made from branches (a) 25 to 102 mm in diameter and (b) <25 mm in diameter was 0.74 and 1.33%, respectively, when measured from an oven-dry condition (OD) to one of complete water saturation (Lehmann and Geimer 1974). In contrast, the linear expansion of control boards made from mature wood was 0.20%. Bending and internal bond properties of the branch wood boards were also poorer than that of the control boards.

In studies of flakeboard from short-rotation (6-year-old), intensively cultured hybrid poplar clones, bending MOE >3,100 MPa and bending MOR >27 MPa were obtained in a homogeneous, randomly distributed flakeboard (Geimer and Crist 1980). Alignment of face flakes increased MOE and MOR in the direction of alignment to maximum values of 6,550 and 48 MPa, respectively. These values compare very favorably to the minimum MOE of 3,102 MPa and MOR of 17 MPa prescribed in the American National Standards (National Particleboard Association 1989) for exterior waferboard. Boards made from 7-year-old, intensively cultured hybrid poplar had reduced bending but increased internal bond properties compared to boards made from the 6-year-old material (Geimer 1986). Boards made from 7-year-old tamarack and jack pine had poorer mechanical properties and were less durable than boards made from the 7-year-old poplar hybrid clones grown under the same conditions (Geimer 1986).

Dimitri et al. (1981) fabricated three-layer, 19-mm particleboards with various proportions of chipped crown wood (up to 30%) and stem wood. Most boards met German DIN standards for density, bending strength, and internal bond. Negative effects of crown wood were more pronounced when the wood was used in the surface layer, rather than the middle layer.

In studies on Douglas-fir stem wood, Wasniewski (1989) found a 10% increase in bending MOE and MOR of randomly distributed flakeboard as wood age increased from 1 to 50 years. This was compared to a 30 to 40% increase found with lumber specimens. The effect of wood age was thought to be moderated by changes in packing density and horizontal density gradients associated with thinner flakes and lower density of the younger material. A decrease in the linear expansion of the random flakeboard, as wood age increased, was attributed to change in fibril angle. However, increases in thickness swell with wood age were related to differences in production parameters such as flake thickness.

Pugel et al. (1990a, b) manufactured composite panels from mature wood, the juvenile core (first 10 rings from the pith), branches (no bark), tops of 40- to 50-year-old loblolly pine, and 8-year-old fast-grown trees. Flakeboard, particleboard, and fiberboard constructed to SG values of 0.640 and 0.705 were evaluated for internal bond, MOE, and MOR. The results showed that composite boards made from juvenile wood had mechanical properties similar to boards made from mature wood. Thickness swell and linear expansion of the flakeboard made from juvenile core material were similar to those properties measured in mature wood. However, thickness swell and linear expansion of all board types made from fast-grown trees were significantly higher than those of boards made from mature wood. Pugel theorizes that board properties are determined from not only the anatomical properties of the wood (i.e., juvenile wood characteristics) but also the production variations (i.e., compaction ratio, density gradient, and particle size), which can be affected by wood age.

Prediction of linear expansion in composite panels

The general relation of linear expansion to flake type, flake alignment, specific gravity, and moisture content has been documented (Geimer 1976, 1982). However, prediction of linear expansion in a composite board is quite complex and has been related to MOE of the wood as measured in both the parallel-to-grain and perpendicular-to-grain directions (Heebink et al. 1964) and to the stress at proportional limit in lateral compression (Talbott et al. 1979). Maloney et al. (1981) used equations to predict moisture-induced dimensional movement in particleboard laminated with veneer faces.

Linear expansion values of plywood panels are predicted using an equation developed by Heebink et al. (1964):

$$\epsilon = \frac{m_w E_w + m_x E_x}{E_w + E_x} \quad (1)$$

where

ϵ = linear expansion of panel (mm/mm),

m_w, m_x = coefficients of expansion or strain (mm/mm) of individual plies over defined range of moisture change in longitudinal and transverse-to-grain directions, respectively, and

E_w, E_x = tensile MOE in longitudinal and transverse-to-grain directions, respectively.

Heebink's model was proposed for balanced plywood panels having equal amounts of veneer oriented with the grain parallel to both panel directions. Results that use the model for three-layer OSB will be somewhat affected by the presence of a vertical density gradient. Heebink's research showed that the linear expansion of a balanced cross-laminated veneer panel will be very similar to the linear expansion of the veneer in the parallel-to-grain direction.

OBJECTIVE

The objective of this research was to determine the effect of juvenile wood on the dimensional stability of three-layer cross-oriented flakeboard. Specifically, the dimensional stability properties of the flakeboard were compared to those of plywood. Furthermore, linear expansion properties of the three-layer boards were predicted using linear expansion and tensile data derived from both veneer and single-layer directional oriented flakeboard.

PROCEDURES

Research direction

The wood used in this study was obtained from 35-year-old loblolly pines grown on the Whitehall Forest Plantation, School of Forestry, University of Georgia, in Clark County, Georgia. Juvenile (defined in this study as the first 12 growth rings) and mature wood were characterized by specific gravity and fiber length measurements. Tensile MOE and linear expansion in the longitudinal and transverse (when possible) directions were measured in veneer cut from both juvenile and mature wood. Both of these properties were measured following exposure to different conditions:

1. oven-dry
2. 30% relative humidity (30 RH)
3. 60% relative humidity (60 RH)
4. 90% relative humidity (90 RH)
5. vacuum-pressure-soak (VPS) treatment
6. VPS followed by final oven-drying (VPS-OD)

Likewise, tensile MOE, tensile MOR, and linear expansion values were determined for single-layer, random, and oriented (30 and 70% aligned, Geimer 1976) flakeboard made from mature and juvenile wood. Finally, linear expansion values were obtained for both plywood and three-layer cross-oriented flakeboard at all exposure levels.

Statistical analysis of variance (ANOVA) tests were developed for changes in the three dimensional stability properties of water adsorption, linear expansion, and thickness swell from the oven-dry state to the five other exposure conditions. A randomized block design with subsampling was used to analyze the veneer and plywood data. The blocking factor consisted of the four trees from which the material was collected. The same design was used to analyze the flakeboard when the data from specimens cut parallel (Pa) to the long panel dimension were studied separately from the data from specimens cut perpendicular (Pe) to the long panel dimension. Because the Pa and Pe specimens were cut from the same panel, a split-plot design with subsampling was used to analyze the flakeboard data when the Pa and Pe specimens were grouped.

Wood characterization

A 50-mm slice was cut from 5-m-long butt logs of four loblolly pine trees. The slices were segregated by age: the first 12 growth rings were categorized as juvenile wood, and the remainder of the stem was categorized as mature wood. Volume and weight measurements were used to determine the specific gravity of the components. Match-sized specimens were then cut from each growth ring using the material sliced from one of the trees. These specimens were then macerated and measured for average fiber length. Fiber length measurements were also obtained for the 4th, 8th, 12th, and 16th ring on the other three trees.

Veneer

Sample preparation.—Bolts, 1.2 m long, were cut from the lower portion of the four loblolly pine butt logs. Tree diameter at breast height measured 37.3, 39.6, 40.6, and 43.7 cm. Each bolt was marked on the ends to denote the periphery of the 12th growth ring and then sawn lengthwise in half. One half was sliced to produce the necessary 1.60-mm-thick veneer for MOE and dimensional stability (DS) tests and for plywood construction; the other half was used to fabricate flakeboard. Six veneers were selected from each of four locations in the log: juvenile-radial, juvenile-tangential, mature-radial, and mature-tangential (Fig. 1A). Veneers containing both juvenile and mature wood were cut lengthwise to separate the two ages of wood. The veneers were then cut crosswise to provide material for testing and for the construction of plywood (Fig. 1B). Test specimens were cut as shown in Fig. 1C.

Each bolt supplied six sets of specimens for dimensional stability tests (DS specimens). The material was classified according to age, cutting direction, and fiber orientation; i.e., mature-tangential-longitudinal, mature-tangential-transverse, mature-radial-longitudinal, juvenile-tangential-longitudinal, juvenile-radial-longitudinal, and juvenile-radial-transverse. (Note that the size of the transverse-to-grain veneer did not allow for juvenile-tangential-transverse and mature-radial-transverse specimens.) The sets of specimens, handled as a group of six sample replications, were measured for linear expansion and water adsorption after successive equilibration exposure to OD, 30 RH, 60 RH, 90 RH, VPS, and VPS-OD conditions.

Six sets of six samples each were similarly cut from the veneers to determine tensile MOE. However, because of the destructive nature of the test, only one sample from each set was exposed to each environmental condition.

Testing.—Staples were driven into the DS specimens 25.4 cm apart and used as the basis for measuring linear expansion. Measurements were made using optical equipment capable of measuring to the nearest 0.0025 mm. Specimens were weighed and measured after equilibration to each condition.

Tensile MOE specimens were prepared as

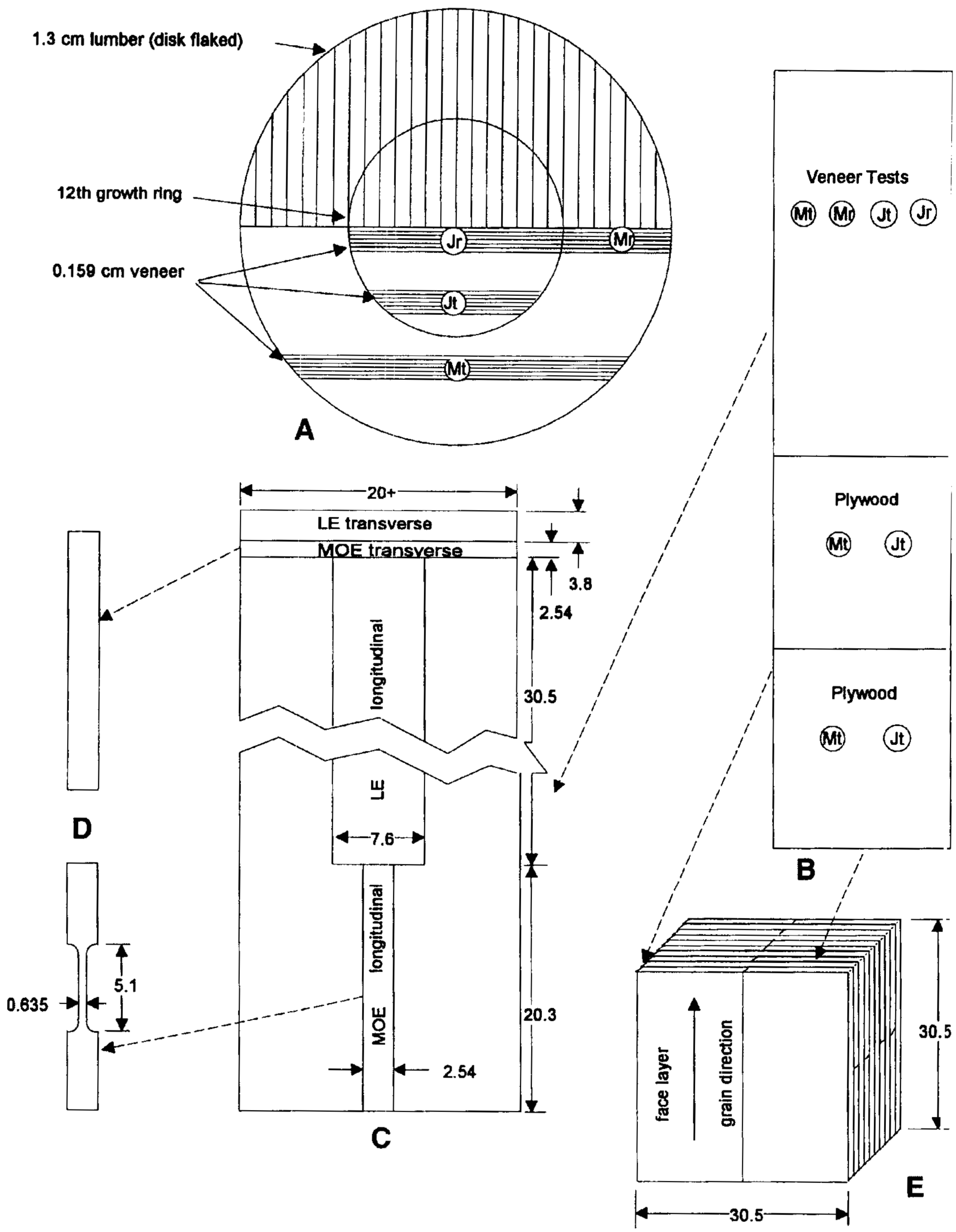

FIG. 1. Log cutting pattern. (A) Position of veneer and lumber in log; Jr, juvenile—radial; Mr, mature—radial; Jt, juvenile—tangential; Mt, mature—tangential. (B) Allocation of veneer for test specimens and plywood. (C) Cutting pattern for veneer test specimens. (D) Veneer tension specimens. (E) Plywood layup. Dimensions in centimeters.

shown in Fig. 1D and tested according to ASTM D805-72 (ASTM 1972), following equilibration to constant weight at each exposure condition. Machine cross-head movement was used to indicate specimen elongation, and the specimens were loaded to their breaking point.

Statistical design.—The treatment structure for the veneer portion of the study was a 2 × 2 factorial that considered two cuts (radial and tangential) and two wood ages (mature and juvenile). Since the DS test was nondestructive, the analysis considered the same six pieces of veneer from each tree, tested at each exposure level.

Statistical analysis was conducted on only those veneers tested in the longitudinal-to-grain direction. The size of the transverse-to-grain veneer restricted testing to the two unique combinations of juvenile-radial and mature-tangential. Statistical analysis of these data was meaningless because there was no way of separating the effects of age and cut.

Plywood

Sample preparation.—Plywood was fabricated from tangentially sliced veneer (Fig. 1E). From each of the four trees, two eight-ply, 30.5- by 30.5-cm cross-laminated plywood boards were made from juvenile wood. Likewise, a total of eight boards were constructed from mature wood. Veneer was spread with phenol-formaldehyde resin at 0.244 kg/m^2 of single glue-line. Panels were pressed at 1.03 MPa pressure and 177°C for 15 min.

Testing.—Four 76- by 305-mm specimens were cut from each plywood panel and measured for changes in linear expansion (parallel to face-ply grain direction) after successive exposure to the same six exposure conditions used to determine veneer linear expansion. Measurements were obtained using the same optical system used for the veneer. Tensile properties were not determined for plywood.

Statistical design.—The treatment structure for the plywood portion of the study considered two wood ages (juvenile and mature). Since the DS test was nondestructive, the analysis considered the same four specimens from each of two boards tested at each exposure level.

Flakeboard

Sample preparation.—One-half of each bolt was ripped into 13-mm boards (Fig. 1A). Using the marks on the log ends denoting the 12th annual ring, the boards were ripped to separate juvenile and mature wood. Additional boards were cut from the remaining portion of each 5-m-long log to provide sufficient flake material. The boards were cross-cut into 50-mm-long slabs and fed into a disk flaker to obtain 0.5- by 13- by 50-mm flakes. The flakes were screened to eliminate material passing through a 3.2-mm mesh screen, dried to 4% moisture, and sprayed with 5% phenolic resin (solids content based on OD wood weight). Wax was not applied, as the intent of the study was to compare equilibrated dimensional stability of the boards rather than to retard the effect of moisture.

Six types of boards differing in flake alignment, layer construction, or specific gravity were constructed:

(1) Random orientation
(2) Single-layer, 30% alignment (30A)
(3) Single-layer, 30% alignment, high density (30A-HD)
(4) Single-layer, 70% alignment (70A)
(5) Three-layer, 30% cross-alignment (30XA)
(6) Three-layer, 70% cross-alignment (70XA)

The center layer comprised 50% of the weight of the three-layer balanced constructed boards. The degree of alignment was the same in both center and face layers, but the cardinal direction of alignment differed by 90°.

Two boards of each type were made from each tree, resulting in a total of 96 boards (two replications, six board types, two wood age groups, four trees). With the exception of those boards designated as high density (0.85 SG), all boards were constructed to 0.64 SG based on OD weight. The 600- by 700-mm mats, at 7% moisture content, were pressed for 7 min at 190°C to a target thickness of 13 mm.

Testing.—To obtain data on dimensional stability, four 76- by 305-mm specimens were cut from each of the random boards (two Pa and two Pe to the long panel direction). Six specimens were cut from each of the aligned boards (three Pa and three Pe to the face layer cardinal alignment direction, which was the long panel direction). These sample replications were then dried at 102°C for 24 h to establish an OD base for measuring linear expansion, water adsorption, and thickness swell. The specimens were then progressively conditioned at the 30 RH, 65 RH, and 90 RH exposures, subjected to VPS, and finally redried to the OD state. After equilibrium moisture content was obtained at each exposure condition, the specimens were weighed, measured for thickness at a marked location, and measured for length using an optical gauge capable of reading to 0.0025 mm.

Six Pa and six Pe 50- by 204-mm tensile specimens were cut from each board. For a 50-mm length at midpoint, the Pa specimens were reduced to a width of 38 mm. Each of these specimens was conditioned to equilibrium at one of the six exposure conditions and tested according to ASTM D-1037 (ASTM 1989) to determine tensile MOE.

Statistical design.—Flakeboard data were separated into two groups: balanced (random, 30XA, and 70XA boards) and directional (30A, 30A-HD, and 70A boards). For the directional boards, the treatment structure considered two wood ages (mature and juvenile). For the balanced boards, the whole-plot treatment structure considered the two ages; and the split-plot treatment structure considered two alignments (Pa and Pe).

RESULTS AND DISCUSSION

Density measurements of the age-segregated sections of 50-mm-thick slices cut from the butt log of each tree showed that the specific gravity of the mature wood averaged slightly higher than that of the juvenile wood (0.491 and 0.484 SG, respectively). The standard deviation for four samples, one from each tree, was 0.035 for the mature wood and 0.038 for the juvenile wood. The fiber length of the macerated match-sized samples obtained from the latewood of selected growth rings of one tree increased in a typical manner with age (Fig. 2). Change in average slope of the curve was greatest at approximately 16 years of age. Additional measurements taken from the 4th, 8th, 12th, and 16th rings on the other three trees verified similar fiber characterization.

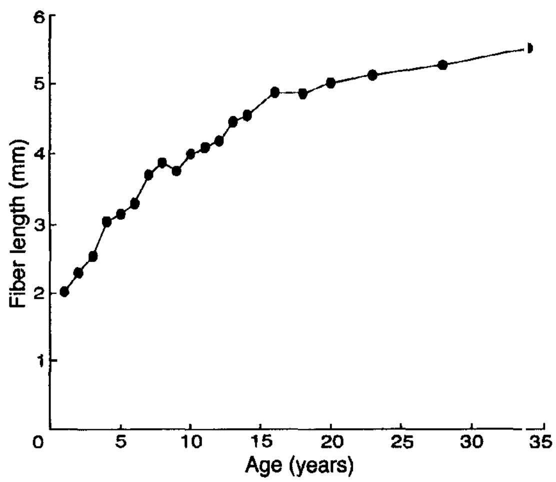

FIG. 2. Length of southern pine fiber by tree age.

In studying the effect of juvenile and mature wood on furnish variability and the resultant wood composite DS, we were also interested in (1) the "tree effect," i.e., the difference of average DS *level* affected by tree differences (mature and juvenile wood combined), and (2) the tree-to-tree variation, i.e., the variation in DS properties caused by variations in the actual *differences* between mature and juvenile wood from tree to tree.

Broad exploratory statistical analysis of the data showed that the effect of age on DS was influenced not only by the tree effect but also by tree-to-tree variation. This means that in studies of this nature we need to use a sufficient number of trees to best reflect real world normality.

TABLE 1. *Dimensional stability of veneer.*[a]

	Linear expansion (%)						Thickness swell[e] (%)			
	Longitudinal[b]		Transverse[c]		Water adsorption[d] (%)		Radial[f]		Tangential[g]	
Exposure	M	J	M_t	J_r	M	J	M	J	M	J
30 RH	0.20	0.33	0.89	0.90	4.5	4.5	1.9	0.8	1.4	1.6
65 RH	0.26	0.45	2.06	1.59	9.9	9.9	0.4	0.1	2.4	2.5
90 RH	0.48	0.70	3.77	2.74	14.9	15.1	1.2	0.6	4.0	2.8
VPS	0.25	0.57	6.89	4.76	137.1	143.1	4.6	2.8	9.3	7.7

[a] RH is relative humidity; VPS, vacuum-press-soak; M, mature wood; J, juvenile wood.
[b] Average for all longitudinal (radial and tangential) specimens (values used in prediction equations).
[c] Average values for mature-tangential (M_t) and juvenile-radial (J_r) specimens (values used in prediction equations).
[d] Average for all longitudinal specimens.
[e] Longitudinal specimens.
[f] Radial swelling of tangential-cut specimens.
[g] Tangential swelling of radial-cut specimens.

Veneer

Linear expansion.—The longitudinal linear expansion of juvenile veneer was greater than that of mature veneer for all exposure conditions (Table 1). Statistical analysis of these data, which incorporated measurements from both radial and tangential cuts, showed age significance (at the 0.01 level) for all exposure conditions (Table 2). The analysis also indicated a significant tree effect at all but one exposure level, but no significant difference resulting from the type of cut (radial or tangential).

The relatively low longitudinal linear expansion measured at the VPS exposure for both the mature and juvenile wood specimens was probably a result of warp and/or the "Poisson effect"—diminished longitudinal expansion caused by large thickness swell in the transverse direction. As explained previously, no statistical analysis was conducted on the veneer tested transversely to the grain because of the dissimilar nature of the mature and juvenile samples. Reduced linear expansion in juvenile-radial compared to mature-tangential veneer transverse to the grain is attributed in part to anatomical differences in cellulose fibril angles and in part to the reinforcement provided by ray cells in the radially cut juvenile veneer.

Water adsorption.—Mature and juvenile veneer water adsorption values, averaged for all the longitudinally cut specimens, are given in Table 1. In-depth analysis showed that statistical differences in water adsorption could not be attributed to wood age or tree (Table 2). Type of cut was significant (15.3% water adsorption for tangential specimens versus 14.7% for radial) only at the 90 RH exposure.

Thickness swell.—Veneer thickness swell data are presented in Table 1. Radial thickness swell of 4.6% and tangential thickness swell of 9.3%, measured for the mature veneer at the VPS exposure, can be compared to respective values of 4.8 and 7.4% given in the *Wood Handbook* (Forest Products Laboratory 1987) for shrinkage of loblolly pine.

TABLE 2. *Statistical significance of tests on veneer.*[a]

	Linear expansion			Water adsorption			Thickness swell		
Exposure	Tree	Age	Cut	Tree	Age	Cut	Tree	Age	Cut
30 RH	**	**							
65 RH	**	**					**		***
90 RH	*	**				**			***
VPS		**						*	***

[a] Longitudinal specimens. The boxhead "tree" refers to the tree effect. Boxing indicates significant tree-to-tree variation; in the case of veneer, tree-to-tree variation includes interaction of tree with all treatments.
* $P = 0.05$, ** $P = 0.01$, *** $P = 0.001$. Blank cells indicate no significance at the 0.05 level.

TABLE 3. *Tensile modulus of elasticity of veneer.*

	Tensile MOE ($\times 10^3$ MPa)					
	Longitudinal				Transverse	
	Tangential		Radial		Tangential	Radial
Exposure	M	J	M	J	M	J
30 RH	9.77	5.90	10.96	6.15	0.31	0.37
65 RH	7.12	7.34	7.66	4.44	0.23	0.32
90 RH	6.42	3.58	8.04	5.21	0.19	0.23
VPS	4.80	4.71	7.88	2.92	0.09	0.10

TABLE 4. *Dimensional stability of plywood.*

	DS property (percent)					
	Linear expansion[a]		Water adsorption		Thickness swel	
Exposure	M	J	M	J	M	J
30 RH	0.16	0.15	4.7	4.8	0.7	0.[illegible]
65 RH	0.25	0.34	9.2	9.2	2.6	1.[illegible]
90 RH	0.26	0.45	16.0	16.3	6.8	5.[illegible]
VPS	0.27	0.52	79.2	91.8	12.0	10.[illegible]

[a] Specimens tested parallel to face-layer grain.

Some discrepancies were noted in the low moisture radial thickness swelling measurements of both mature and juvenile wood. However, in the majority of cases, radial thickness swelling was less than tangential thickness swelling, and juvenile veneer swelled less than mature veneer. Analysis showed that type of cut was highly significant in three of the four exposures (Table 2). However, age was significant (0.05 level) only for the VPS exposure.

Tensile properties.—Tensile modulus values are given in Table 3. Because the tensile specimens were loaded to destruction, only one specimen from each tree/cut/testing direction combination was exposed to each RH condition. This reduction in replications accentuated variations within the data set. With three exceptions, longitudinal juvenile veneer modulus averaged between 51 and 65% of the value for the mature wood. The direction of cut was not important in determining modulus in the longitudinal direction. However, the radially oriented ray cells were responsible for the higher tensile values of the juvenile-radial veneer compared to the mature-tangential veneer tested in the transverse direction.

Plywood

Linear expansion.—Linear expansion of plywood made from juvenile-tangential veneer was greater than that of plywood made from mature-tangential veneer at all exposure conditions except 30 RH (Table 4, Fig. 3). Values shown are averages of 32 samples with no distinction for trees. In-depth analysis reflected those results obtained for veneer and indicated that differences attributed to age were statistically significant at the 0.05 level (Table 5). Surprisingly, no statistical difference could be attributed to tree effect. However, tree-to-tree variation (boxed area in table) was significant at the 90 RH exposure.

Linear expansion predicted for balanced

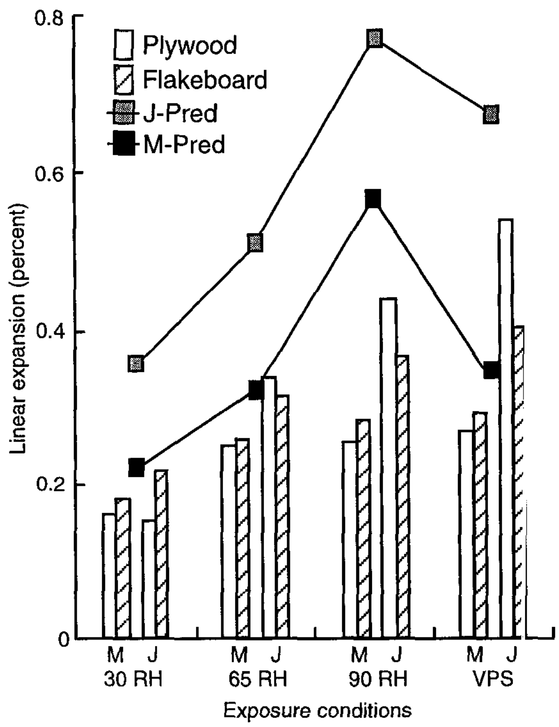

FIG. 3. Linear expansion of plywood and balanced flakeboard constructed with mature (M) and juvenile (J) wood. Values for flakeboard are averages of Pa and Pe specimens from all balanced (random, three-layer 30% cross-aligned (30XA), and 70% cross-aligned (70XA)) flakeboard. Values predicted from linear expansion and tensile modulus of veneer are shown as line graphs.

TABLE 5. *Statistical significance of tests on plywood.*

	Linear expansion		Water adsorption		Thickness swell	
Exposure	Tree	Age	Tree	Age	Tree	Age
30 RH						
65 RH		*				**
90 RH		*				*
VPS		*				

TABLE 6. *Dimensional stability of balanced flakeboard.*[a]

	DS property (percent)					
	Linear expansion		Water adsorption		Thickness swell	
Exposure	M	J	M	J	M	J
30 RH	0.19	0.22	4.6	3.8	1.3	1.0
65 RH	0.26	0.32	9.1	8.4	5.2	3.9
90 RH	0.28	0.37	16.1	15.4	13.5	11.6
VPS	0.30	0.44	102.6	95.1	21.3	18.5

[a] Values represent average of both Pa and Pe specimens from all balanced (random, 30XA, and 70XA) boards.

panels using Heebink's equation is compared to linear expansion of plywood and average linear expansion of all balanced flakeboard in Fig. 3. The predicted values using veneer-derived tension and linear expansion data (Tables 1 and 3) were higher than measured values. In this respect, results were similar to those obtained by Heebink et al. (1964).

Water adsorption.—No difference in plywood water adsorption was attributed to age or tree. Therefore, the greater linear expansion experienced by juvenile wood plywood, as compared to mature wood plywood, can be directly attributed to a difference in wood anatomy.

Thickness swell.—The same changes in fiber fibril angle that increase the hydro-dimensional movement of fiber in the longitudinal direction decrease the movement in thickness. This characteristic is reflected by the reduced thickness swell of plywood made from juvenile wood (Table 4). Significant differences were attributed to age in the 65 RH and 90 RH exposures (Table 5).

Press thickness loss, calculated using radial veneer and plywood thickness swell data (VPS exposure),

$$\text{Plywood Press Loss} = 1 - \frac{1 + (\text{veneer thickness swell}(\%/100))}{1 + (\text{plywood thickness swell}(\%/100))}$$

was 6.6% for both mature and juvenile plywood. This value correlates reasonably well with the nonrecoverable thickness swell (3.8 and 5.5%, respectively) measured at VPS-OD (data not shown).

Flakeboard

Linear expansion.—Three-layer balanced boards: Linear expansion of balanced flakeboard was similar to that of plywood (Fig. 3). However, at the higher moisture exposures, juvenile wood had less impact on flakeboard than on plywood. For balanced flakeboard constructed of juvenile wood, average linear expansion was in all cases greater than that of flakeboard made from mature wood. When the juvenile flakeboard was fully saturated, linear expansion was 0.4% compared to 0.3% for mature flakeboard. The flakeboard linear expansion values given in Table 6 and used in Fig. 3 are averages for the combined Pa and Pe data of all the balanced flakeboard (random, 30XA, and 70XA) grouped together. All percentages are based on an increase from the OD state. Using these data, linear expansion from 30 to 90 RH can be calculated as 0.10% for the mature wood and 0.15% for the juvenile wood.

Results of statistical analysis on each board type showed that age had a significant effect on linear expansion for both the 30XA and 70XA boards (Fig. 4, Table 7). A significant tree effect occurred in these three-layer boards in half the cases. In most cases, linear expansion was slightly greater than that in the random boards (Fig. 4). Although significant tree-to-tree variation did occur in all the random boards, as shown by the boxed areas in Table 7, neither the tree nor age singularly affected the linear expansion of these boards. The reason for this is not clear. Perhaps from a linear expansion perspective, the three-layer cross-aligned boards, unlike the random boards,

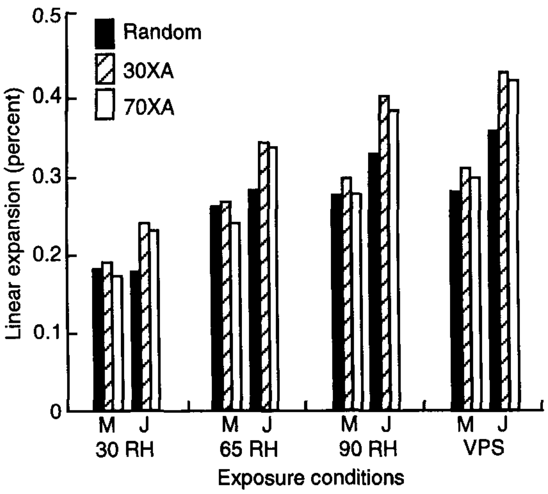

FIG. 4. Average linear expansion of random, 30XA, and 70XA flakeboard constructed with mature and juvenile wood.

were not truly balanced and the mechanisms that affect linear expansion were accentuated.

When panel direction was considered in addition to panel type, the linear movement in the cross-aligned panels was slightly greater parallel (Pa) than perpendicular (Pe) to the face alignment (Fig. 5). This characteristic was more prominent in the juvenile boards, but it diminished in both juvenile and mature boards as moisture exposure conditions became more severe. Linear expansion in the Pe direction is primarily a function of the Pe directional swelling of the face layer. We attribute the reduction in Pe linear expansion to a reduction in water adsorption of the higher density face layers.

Linear expansion.—Single-layer directional boards: Linear expansion of directional aligned flakeboard is shown in Fig. 6. Because of the inherent difference in microfibril structure, one might expect the juvenile wood flakeboard to have somewhat higher linear expansion values in the Pa direction and somewhat lower values in the Pe direction than the mature wood flakeboard. However, the data, averaged in Table 8, show that in most cases this was not true for the Pe specimens. Statistically, age was only significant for one ex-

TABLE 7. *Statistical significance of balanced flakeboard tests.*

	Linear expansion						Water adsorption						Thickness swell					
	30XA		70XA		Random		30XA		70XA		Random		30XA		70XA		Random	
Exposure	Tree	Age	Tree	Age	Tree	Age	Tree	Age	Tree	Age	Tree	Age	Tree	Age	Tree	Age	Tree	Age
30 RH	*	*						**		**						*		
65 RH	*	**		**				*		**		**		*		**		**
90 RH		*	*	*				*		**				*		**		
VPS		*	*	*						*			*	**			*	**

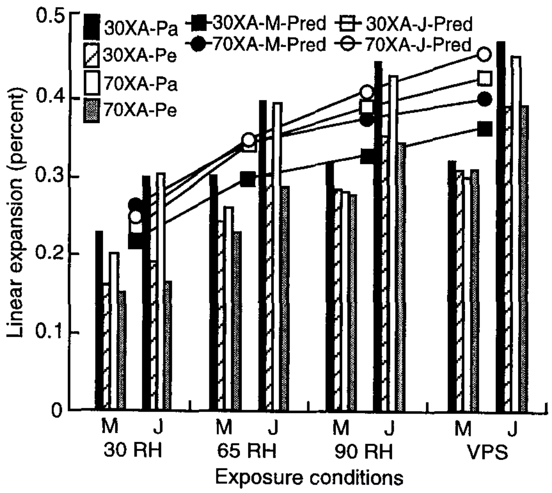

FIG. 5. Average linear expansion of test specimens cut parallel (Pa) and perpendicular (Pe) to face layer of three-layer aligned balanced flakeboard. Values predicted from linear expansion and tensile modulus of aligned directional flakeboard are shown as line graphs.

posure level of the high density boards (Table 9).

As expected, Pe linear expansion of the directional boards increased with increasing flake alignment and board density. However, the highest average Pe linear expansion (1.7%), which occurred in the 70A juvenile boards tested at the VPS exposure (Table 8), was considerably less than the highest average linear expansion (4.76%) for juvenile veneer tested transverse to the grain (Table 1).

Linear expansion.—Predictions: Linear expansion of a three-layer balanced board was in the same range as that experienced in the Pa direction of a single-layer directional board having the same degree of alignment. Predictions of linear expansion in balanced boards according to Heebink's equation (using the tension and linear expansion data derived from the directional flakeboard, rather than veneer)

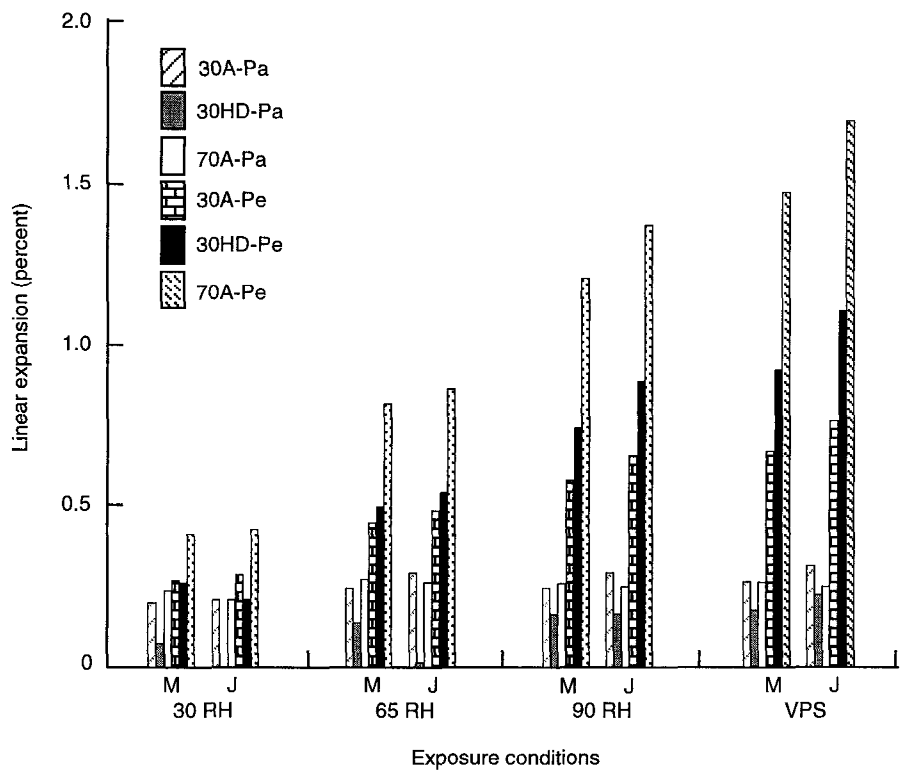

FIG. 6. Linear expansion of 30% and 70% single-layer directional flakeboard constructed with mature and juvenile wood.

TABLE 8. *Linear expansion of directional flakeboard.*

Exposure	Linear expansion (percent)											
	30A				70A				30A-HD			
	Pa		Pe		Pa		Pe		Pa		Pe	
	M	J	M	J	M	J	M	J	M	J	M	J
30 RH	0.20	0.21	0.27	0.29	0.24	0.21	0.42	0.43	0.08	0.00	0.26	0.22
65 RH	0.25	0.30	0.45	0.49	0.27	0.26	0.81	0.86	0.14	0.09	0.50	0.54
90 RH	0.25	0.30	0.58	0.65	0.26	0.25	1.20	1.38	0.17	0.16	0.74	0.89
VPS	0.26	0.31	0.66	0.76	0.24	0.26	1.47	1.70	0.18	0.23	0.92	1.10

were very close to actual measured values (Fig. 5). Tension data for these calculations are given in Table 10.

Water adsorption.—Three-layer balanced boards: Water adsorption averaged slightly less in all exposure conditions for flakeboard made from juvenile wood compared to flakeboard made from mature wood (Table 6). When the three-layer flakeboard data were analyzed by board type, statistically significant differences in water adsorption could be attributed to age for the 30XA and 70XA boards at most exposures, but at only the 65 RH exposure for the random boards (Table 7).

Water adsorption.—Single-layer directional boards: Similar to the data for balanced boards, water adsorption averaged slightly less at all exposure conditions for directional flakeboard made from juvenile wood than for directional flakeboard made from mature wood (Table 11). Wood age was significant at all exposures for the 30A boards, but only a few exposures for the 70A and 30A-HD boards (Table 9). In all cases, high density flakeboard adsorbed less water than the 0.64 SG boards (Table 11). This was true for both mature and juvenile boards. The large reduction in water adsorption of the high density flakeboard (as compared to 0.64 SG boards) exposed to OD-VPS conditions resulted from the reduction in void space and was expected (Geimer 1982). Moisture content at this condition was considered to be above the fiber saturation point in all the boards.

The reduced water adsorption of juvenile flakeboard, compared to mature flakeboard, is opposite to that found in lumber or veneer products. This trait reversal is attributed to a difference in flake packing and to the increased compression needed in the construction of flakeboard made with lower density juvenile wood. Reduced water adsorption at those exposures other than VPS tends to diminish DS differences caused by microstructural arrangement of cell wall fibril components.

Thickness swell.—Thickness swell by definition implies that this property is measured in one direction only, i.e., perpendicular to the plane of the board. Since flakes are positioned with radial or tangential surfaces perpendicular to the board surface and since these dimensions have reduced movement in juvenile wood because of the fibril arrangement, it follows that thickness swell should be reduced in flakeboard constructed with juvenile wood. Reinforcing this trend is the reduction in thickness swell caused by reduced water adsorption in flakeboard constructed with juvenile wood. However, the majority of thickness swell in flakeboard has been attributed to expansion of the compressed cell. This "springback" component of thickness swell is more severe in flakeboard constructed with low specific gravity juvenile wood and will tend to offset the above-mentioned advantage of juvenile wood. Our study showed that average thickness swell was lower in both balanced and directional boards made of juvenile wood (Tables 6 and 11). Surprisingly, this relationship held true even at VPS exposures, indicating that reduction of thickness swell resulting from fibril arrangement was greater than the increase in thickness swell caused by added cell com-

TABLE 9. *Statistical significance of directional flakeboard tests.*

	Linear expansion												Water adsorption						Thickness swell					
	30XA				70XA				30A-HD				30XA		70XA		30A-HD		30XA		70XA		30A-HD	
	Tree		Age		Tree		Age		Tree		Age													
Exposure	Pa	Pe	Pa	Pe	Pa	Pe	Pa	Pe	Pa	Pe	Pa	Pe	Tree	Age	Tree	Age	Tree	Age	Tree	Age	Tree	Age	Tree	Age
30 RH											*			**						**		*		
65 RH														**		*		*		**		**		
90 RH														**				*		*				
VPS													*	**										

pression. Thickness swell of 0.85 SG boards relative to 0.64 SG boards followed expected trends, being predominantly influenced by reduced moisture content at exposure levels below VPS and by the increased amount of wood at VPS exposures (Geimer 1982).

REMARKS

In the broad type of exploratory research described in this report, testing replication is often sacrificed to investigate the relative importance of many interacting variables. We have shown statistically that wood age is a factor in determining the dimensional stability of three-layer cross-aligned balanced flakeboard. However, statistical verification of the same relationship in directional boards which are the fabrication units of balanced boards, was prevented by the higher variability found in directional boards. Future in-depth studies of specific variables will profit by increased sample replication.

The results indicate that differences in the dimensional stability properties of flakeboard made from juvenile and mature wood vary with RH exposure levels. Nonlinear changes in length were noted for individual flakeboard specimens. In particular, specimens could actually shrink in length when exposed to higher RH levels. This anomaly was verified by cycling selected samples several times through the various exposure levels prior to VPS exposure.

CONCLUSIONS

Veneer specimens cut from loblolly pine trees were used to verify that juvenile wood increases linear expansion in the longitudinal direction and decreases linear expansion in the transverse direction. Tree effect (relative level of linear expansion experienced by both juvenile and mature wood in the same tree) and tree-to-tree variation (relative difference between linear expansion of juvenile and mature wood from tree to tree) were considered in the experimental design. Statistical analysis showed that both of these factors affected the

TABLE 10. *Tensile modulus of elasticity of directional flakeboard.*

	Tensile MOE (×10³ MPa)											
	30A				70A				30A-HD			
	Pa		Pe		Pa		Pe		Pa		Pe	
Exposure	M	J	M	J	M	J	M	J	M	J	M	J
30 RH	10.21	11.51	3.12	3.68	14.74	14.18	1.53	1.98	19.26	18.23	6.31	7.58
65 RH	10.15	12.39	3.45	4.01	13.79	14.14	1.97	2.33	18.96	19.82	6.46	6.98
90 RH	9.31	9.70	2.86	3.45	10.99	12.26	1.55	2.02	17.32	17.06	6.33	6.59
VPS	5.69	7.17	1.86	2.43	8.22	8.32	1.05	1.45	9.18	10.47	3.52	3.98

linear expansion of plywood made from the veneers.

Average linear expansion of balanced flakeboard (cross-aligned and randomly distributed) constructed with juvenile wood was higher than that of balanced flakeboard constructed with mature wood. Statistical analysis showed that wood age directly affected linear expansion of cross-aligned boards but not that of random boards. However, tree-to-tree variation was a strong factor influencing the linear expansion of random boards.

In the case of single-layer directionally aligned flakeboard, the effect of wood age on linear expansion varied with degree of alignment, test direction, board specific gravity, and exposure condition. With one exception, differences in linear expansion could not be significantly related to wood age in any of the directional boards. Analysis did show that variability was high and that prediction reliability could be improved with increased sample replication.

Both water adsorption and thickness swell were reduced in all types of flakeboard made from juvenile wood. These relations were statistically significant in many cases.

Using tensile MOE and linear expansion data derived from the directional flakeboard, linear expansion of balanced flakeboard could be predicted with reasonable accuracy.

ACKNOWLEDGMENT

The authors wish to acknowledge the late Joseph Saucier, Former Project Leader, Utilization of Southern Timber, USDA Forest Service, Athens, Georgia, for supplying the trees and for his interest in and patience during this study.

REFERENCES

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM). 1972. Standard methods of testing veneer, plywood, and other glued veneer construction. ASTM D805-72. ASTM, Philadelphia, PA.

———. 1989. Standard methods of evaluating properties of wood-based fiber and particle panel materials. ASTM D1037. ASTM, Philadelphia, PA.

BENDTSEN, B. A. 1978. Properties of wood from improved and intensively managed trees. Forest Prod. J. 28(10):61–72.

———. 1986. Mechanical and anatomical properties in individual growth rings of plantation-grown eastern cottonwood and loblolly pine. Wood Fiber Sci. 18(1):23–28.

TABLE 11. *Water adsorption and thickness swell of directional flakeboard.*[a]

	Water adsorption				Thickness swell			
	0.64 SG		0.85 SG		0.64 SG		0.85 SG	
Exposure	M	J	M	J	M	J	M	J
30 RH	4.6	4.5	3.9	3.4	1.5	1.2	1.2	1.5
65 RH	9.1	8.6	8.1	7.5	5.4	4.0	3.6	2.3
90 RH	16.4	15.7	14.4	13.5	14.7	12.4	13.1	11.3
VPS	107.8	101.0	66.6	57.2	22.3	19.4	24.9	21.6

[a] Values represent average of both Pa and Pe specimens.

BOYD, J. D. 1968. Effect of plantation conditions on wood properties and utilization. Pages 789–822 *in* Proc. FAO World Symposium on Manmade Forests and Their Industrial Importance.

DIMITRI, L., C. V. BISMARCK, P. BOTTCHER, AND J. C. SCHULZE. 1981. Production and use of poplar small-wood for particleboard manufacture. Holzzucht 35(1/2): 1–7.

ERICKSON, H. D., AND T. ARIMA. 1974. Douglas-fir wood quality studies. Part II. Effects of age and stimulated growth on fibril angle and chemical constituents. Wood Sci. Technol. 8:255–265.

FOREST PRODUCTS LABORATORY. 1987. Wood handbook: Wood as an engineering material. USDA, Forest Serv. Forest Prod. Lab., Madison, WI.

GEIMER, R. L. 1976. Flake alignment in particleboard as affected by machine variables and particle geometry. Research Paper FPL 275. USDA, Forest Serv., Forest Prod. Lab., Madison, WI.

———. 1982. Dimensional stability of flakeboards as affected by board specific gravity and flake alignment. Forest Prod. J. 32(8):44–52.

———. 1986. Properties of structural flakeboard manufactured from 7-year-old intensively cultured poplar, tamarack, and pine. Forest Prod. J. 36(4):42–46.

———, AND J. B. CRIST. 1980. Structural flakeboard from short-rotation intensively cultured hybrid populus clones. Forest Prod. J. 30(6):42–48.

GOGGANS, J. F. 1961. The interplay of environment and heredity as factors controlling wood properties in conifers with special emphasis on their effects on specific gravity. Tech. Rep. No. 11, School of Forestry, North Carolina State University, Raleigh, NC.

HALLOCK, H. 1968. Observations on forms of juvenile core in loblolly pine. Res. Note FPL-0188. USDA, Forest Serv., Forest Prod. Lab., Madison, WI.

HEEBINK, B. G., E. W. KUENZI, AND A. C. MAKI. 1964. Linear movement of plywood and flakeboards related to the longitudinal movement of wood. Research Note FPL-073. USDA, Forest Serv., Forest Prod. Lab., Madison, WI.

ISEBRANDS, J. G., AND D. W. BENDTSEN. 1972. Incidence and structure of gelatinous fibers within rapid-growing eastern cottonwood. Wood Fiber 4(2):61–71.

———, AND C. M. HUNT. 1975. Growth and wood properties of rapid grown Japanese larch. Wood Fiber 7(2): 119–128.

———, AND R. A. PARHAM. 1974. Tension wood anatomy of short-rotation *Populus* spp. before and after kraft pulping. Wood Science 6(3):256–265.

JO, J. M., B. J. CHUNG, Y. D. LEE, D. H. KANG, D. J. CHUNG, AND S. G. CHUNG. 1981. Developing multiple utilization of larch wood. Forest Research Institute, No. 28. Seoul, Korea.

KRAHMER, R. L. 1986. Fundamental anatomy of juvenile and mature wood. Pages 12–16 *in* Proc., Juvenile Wood: What does it mean to forest management and forest products? Forest Products Research Society, Madison, WI.

LEHMANN, W. F., AND R. L. GEIMER. 1974. Properties of structural particleboard from Douglas-fir forest residues. Forest Prod. J. 24(10):17–25.

MALONEY, T. M., J. W. TALBOTT, E. M. HUFFAKER, J. B. SAUNDERS, AND M. T. LENTZ. 1981. Dimensional stability of COM-PLY and other composition board panels. Pages 21–46 *in* T. M. Maloney, ed. Proc. Fifteenth International Particleboard Symposium, Washington State University, Pullman, WA.

MEYLAN, B. A. 1968. Cause of high longitudinal shrinkage in wood. Forest Prod. J. 18(4):75.

NATIONAL PARTICLEBOARD ASSOCIATION. 1989. American national standard ANSI/A 208.1–1989. Gaithersburg, MD.

OLSON, R. A., N. V. POLETIKA, AND H. W. HICOCK. 1947. Strength properties of plantation-grown coniferous woods. Connecticut Agricultural Experiment Station Bulletin 511.

PANSHIN, A. J., AND C. DE ZEEUW. 1980. Textbook of wood technology. McGraw Hill Book Co., New York, NY.

PEARSON, R. G., AND R. C. GILMORE. 1971. Characterization of the strength of juvenile wood of loblolly pine. Forest Prod. J. 21(1):23–30.

———, AND ———. 1980. Effect of fast growth rate on the mechanical properties of loblolly pine. Forest Prod. J. 30(5):47–54.

PUGEL, A. D., E. W. PRICE, AND C. Y. HSE. 1990a. Composites from southern pine juvenile wood. Part I. Panel fabrication and initial properties. Forest Prod. J. 40(1): 29–33.

———, ———, AND ———. 1990b. Composites from southern pine juvenile wood. Part II. Durability and dimensional stability. Forest Prod. J. 40(3):57–61.

RENDLE, B. J., AND E. W. J. PHILLIPS. 1957. The effect of rate of growth (ring width) on the density of softwoods. *in* Proceedings, Seventh British Commonwealth Forest Conference, Forest Products Research Laboratory, Princes Risborough, Bucks, England.

SENFT, J. F., A. B. BENDTSEN, AND W. L. GALLIGAN. 1985. Weak wood: Fast-grown trees make problem lumber. J. Forestry 83(8):477–484.

SHIOKURA, T. 1982. Extent and differentiation of the juvenile wood zone in coniferous tree trunks. Mokuzai Gakkaishi 28(2):85–90.

SMITH, R. W., AND D. G. BRIGGS. 1986. Juvenile wood: Has it come of age? Pages 1–11 *in* Proc., Juvenile Wood: What does it mean to forest management and forest products? Forest Products Research Society, Madison, WI.

STEFANIAK, J. 1981. Use of juvenile wood in production of particleboard: Properties of particleboard produced from pine branch wood. Prace Komisji Technol. Drewna 10:95–116.

———. 1985. Suitability of pine juvenile wood for particleboard production: Properties of particleboard from topwood. Prace Komisji Technol. Drewna 11:111–131.

TALBOTT, J. W., T. M. MALONEY, E. M. HUFFCHER, R. J. HOYLE, AND R. W. MEYER. 1979. Analysis and design of COM-PLY panels for dimensional stability as determined by interaction between the particleboard core and veneer facing components. *In* Proc., 13th International Particleboard Symposium, Washington State University, Pullman, WA.

WASNIEWSKI, J. L. 1989. Evaluation of juvenile wood and its effect on Douglas fir structural composite panels. *In* Proc. 23rd Particleboard and Composite Materials Symposium, Washington State University, Pullman, WA.

ZOBEL, B. J., AND R. BLAIR. 1976. Wood and pulp properties of juvenile wood and topwood of the southern pines. *In* Proc., 8th Cellulose Conference, May 19–23, Syracuse, NY.

———, R. C. KELLISON, AND D. G. KIRK. 1972. Wood properties of young loblolly and slash pines. Pages 1–22 *in* Proc., Symposium on the effect of growth acceleration on the properties of wood, Nov. 10–11, Madison, WI.