MECHANICAL AND ANATOMICAL PROPERTIES IN INDIVIDUAL GROWTH RINGS OF PLANTATION-GROWN EASTERN COTTONWOOD AND LOBLOLLY PINE

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ABSTRACT

Growth in genetically improved trees under intensive management is so rapid that rotations may be as short as 20 to 30 years. At that age, the trees contain a high proportion of lower quality juvenile wood. Thus, the properties of juvenile wood need to be characterized to effectively use this resource.

This study determined relationships between age and mechanical and anatomical properties, the average properties of juvenile and mature wood, the age of demarcation between juvenile and mature wood, and the projected proportions of juvenile and mature wood at various ages in plantation cottonwood and loblolly pine. It also compared projected properties of plantation trees with those published for trees from natural forests.

All properties improved markedly with age, up to nearly a tenfold increase in modulus of elasticity of one loblolly pine tree from early juvenile wood to late mature wood. Average mechanical properties of juvenile wood ranged from 47% to 63% of those for mature wood in pine and from 62% to 79% in cottonwood. The age of demarcation between juvenile and mature wood varied by species and property, ranging from 13 to 20 years. At age 40, plantation trees sampled were projected to contain approximately 25% juvenile wood. The mechanical properties of the pine were projected to approximate those of trees from natural forests at 30 to 60 years, depending on property, while those for cottonwood will not achieve comparability.

Keywords: Plantation grown, anatomical properties, mechanical properties, juvenile wood, mature wood, loblolly pine, eastern cottonwood.

INTRODUCTION

To make timber production economical and to cope with rising demand for forest products, many forest managers must rely on genetically improved stock and intensive forest management practices. However, if we are to efficiently utilize this changing resource in structural applications, we may have to modify our processing, grading, and design procedures. Interest in the problems associated with faster growth and greater utilization is so extensive that the International

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Union of Forestry Research Organizations (IUFRO) Division 5 passed a resolution at its 1983 conference calling for research on the basic characteristics of wood from genetically controlled and intensively managed resources.

The study reported here was designed to evaluate the mechanical and anatomical properties of two widely planted, fast-growth species. Our research was aimed at determining basic wood characteristics for plantation-grown eastern cottonwood (*Populus deltoides* Bartr.) and loblolly pine (*Pinus taeda* L.). We selected these species because *Populus* and *Pinus* have probably received more attention worldwide than any other genera in genetics research and intensive forest management practices. More specifically, our objectives were to

* establish relationships between age and physical, anatomical, and mechanical properties;
* determine the age demarcation between juvenile and mature wood;
* compare average juvenile and mature wood properties;
* determine why the mechanical properties of juvenile wood are inferior to those of mature wood;
* estimate the proportion of juvenile wood in trees at various harvest rotation ages;
* and compare the mechanical properties of plantation material with published values for the species.

It is widely assumed that the properties of wood from fast-grown plantation trees are inferior to those from natural forests, primarily because the proportion of juvenile wood increases as rotation age is reduced. The pulp and paper industry learned to accommodate the shorter fibers and thinner cell walls of juvenile wood through improved technology and through blending juvenile wood with mature wood or wood of other species. But juvenile wood poses a more serious problem for performance of solid wood products.

Large fibril angles and the tendency for larger amounts of reaction wood in predominantly juvenile wood cause excessive longitudinal shrinkage and instability in service. This leads to difficulties in drying lumber without excessive distortion (Fig. 1) and is thought to be a major factor in the rising truss problem (separations between wall partitions and ceilings or floors that develop primarily in new construction as framing lumber dries during the first heating season) (Percival et al. 1982). Large fibril angles, short fibers with thin walls, and low percentages of latewood in the annual ring all contribute to low strength and stiffness in juvenile wood.

The latter are particularly important when wood is used for structural applications. In the United States and Canada, allowable design properties are currently derived universally for a species regardless of the source of the material (Douglas-fir excepted). It is questionable whether this "global" system for assigning design stresses is valid today, since solid wood products from rapid-growth plantation trees may be substantially inferior to those from old-growth stands.

METHODS

Abbreviated experimental methods are presented here to enable the reader to understand and interpret the report. Because of the broad interest in the properties

FIG. 1. Excessive distortion during drying of dimension lumber associated with juvenile wood and compression wood. (Photograph by William L. Galligan, Frank Lumber Co., Mill City, Oregon.)

of plantation trees, other researchers may be interested in applying our methods, particularly those pertaining to mechanical properties, to other species. A more detailed description of methods is available from the Forest Products Laboratory author.

Material.—Test material was one 6-foot butt bolt from each of six cottonwood and six loblolly pine trees. The pine came from a plantation in North Carolina; the cottonwood from a plantation in Wisconsin. Both plantations were about 30 years old. The cottonwood trees were progeny derived from a controlled cross of selected parents. Trees were chosen for straightness of bole and absence of discernible defects.

Specimen preparation.—A ⅛-inch-thick by 12 inches long piece centered on a radius was cut from each bolt (Fig. 2). The radius was selected giving preference to the wide portion of the growth rings and cut so that the rings were at right angles to the radius.

Specimens were serially ripped from the thin slabs with a small hobbyist tool set up as a table saw to minimize kerf loss. The kerf was centered on the interface of adjacent annual rings.

Bending specimens and tests.—Bending specimens were 2¼ inches long, ⅛ inch deep, and generally the width of one annual ring, less kerf. Two rings were combined into one specimen if the ring width was less than ⅛ inch (some rings in mature wood of pine). Specimens were loaded at the center of a 1¾-inch span (14:1 span depth ratio) at a rate of 0.02 inch per minute. The load head and beam supports were $^{3}/_{16}$-inch radius, and teflon was taped over the supports to reduce

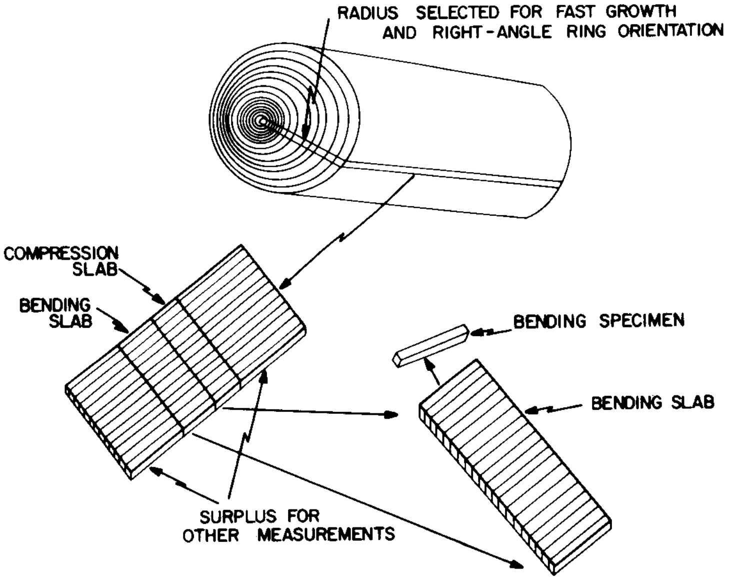

FIG. 2. Schematic of specimen preparation.

friction. Load and deformation were recorded. Duration of the tests was from 2 to 10 minutes.

Compression specimens and tests.—Compression specimens were 1¼ inches long, ⅛ inch deep, and the width of an annual ring (two rings if combined). Specimens were held lightly between steel cubes wrapped with rubber bands to assure axial loading. The load was applied through a spherical head at the rate of 0.005 inch per minute, and maximum load was recorded.

Fiber length measurements.—Radial specimens 30 μ thick were cut on a microtome from each annual ring and macerated. A slide was prepared from a thoroughly mixed solution of macerated fibers. The slide was viewed through a microscope-projector device whereby individual fiber lengths could be measured and automatically recorded for computer processing. A minimum of 100 cells per ring was measured and the average is reported.

Fibril angle measurements.—About 20 measurements of fibril angle were made at regular intervals across the width of radial microtome sections. The average is reported. In pine specimens, rapid drying induced checks in the S_2 cell-wall layer that, when stained with safranin, were readily visible through a microscope. Cottonwood sections were briefly immersed in iodine-potassium iodide and blotted dry; when nitric acid was added, the orientation of the iodine crystals (viewed microscopically) indicated the fibril angle (Senft and Bendtsen 1984).

Specific gravity and reaction wood measurements.—Specific gravity was determined by oven-drying the entire compression specimen. The percentage of reaction wood fibers was visually estimated under a microscope on microtomed cross sections, stained to accent reaction wood fibers.

RESULTS AND DISCUSSION

The property values and coefficients of variation for individual annual rings in Table 1 generally represent the average for six trees. For the mechanical properties and specific gravity of pine, values for age 11 and after are combined data and are reported for odd-numbered years only. These values represent either the observed value for a specimen containing two rings (because one or both rings were too narrow for evaluation) or the average of two individual observations. In all cases, the coefficients of variation are based on six observations.

Effects of age

All mechanical and anatomical properties evaluated in cottonwood and loblolly pine show pronounced trends with age (Figs. 3 and 4), with the exception of percentage of reaction wood fibers in both species and ring width in cottonwood. Generally, properties are minimum or near minimum in the earliest annual rings, show marked improvement for a number of years, and then exhibit stability or only gradual improvement thereafter. Fibril angle is maximum in the first-formed rings and decreases with age as does ring width for pine. Mechanical properties and specific gravity react to age differently than anatomical properties in that they tend to be unchanged for the first few years (about 3–4 years in pine and 6–7 years in cottonwood), whereas cell length and fibril angle tend to show improvement from year one.

These trends were reported by Bendtsen (1978) in a review of literature (Fig. 5). However, the magnitude of change in properties with respect to age observed here, particularly for mechanical properties, was not expected. For example, there is about a fivefold increase in the average modulus of elasticity (MOE) (300,000 to 1,600,000 psi) and about a threefold increase in the average modulus of rupture (MOR) (4,000 to 12,000 psi) from early juvenile wood to late mature wood in loblolly pine (Table 1, Fig. 4).

The degree of juvenility or change in properties with respect to age is much more pronounced in loblolly pine than in cottonwood. This is indicated by ratios of late mature wood to *early* juvenile wood (opposite ratio for fibril angle):

	Eastern cottonwood	Loblolly pine
Modulus of rupture	1.4	3.2
Modulus of elasticity	2.7	5.3
Compression strength	1.7	2.4
Specific gravity	1.1	1.4
Cell length	2.0	2.7
Fibril angle	1.5	3.0

These ratios were approximated from Figs. 3 and 4 by simply comparing the first few years of growth to those after a plateau was reached (or late in the life of the tree if there was no apparent plateau). The ratios are all considerably higher for pine than for cottonwood.

The greater degree of juvenility in the pine is further emphasized by comparing approximate mechanical property levels from Figs. 3 and 4. The bending strength and stiffness of early juvenile wood are similar in the two species: MOR is about 4,000 psi and MOE about 350,000 psi, yet in late mature wood these properties are at least twice as high in pine as in cottonwood, about 12,000 versus 5,000 psi for MOR and 1,600,000 versus 800,000 psi for MOE.

TABLE 1. *Average properties and their coefficient of variation by age for plantation-grown eastern cottonwood and loblolly pine.*[1]

	Specific gravity		Modulus of rupture		Modulus of elasticity		Maximum crushing strength		Cell length		Fibril angle		Ring width		Tension wood	
Age	Average	COV[2]	Average	COV[2]	Average	COV[2]	Average	COV[2]	Average	COV[2]	Average	COV[2]	Average	COV[2]	Average	COV[2]
Yr		*Pct*	*Psi*	*Pct*	*10⁶ psi*	*Pct*	*Psi*	*Pct*	*mm*	*Pct*	*Degrees*	*Pct*	*In.*	*Pct*	.... *Pct*	
							COTTONWOOD									
1	0.344	9.93	2,610	—	0.139	—	1,270	11.1	0.525	3.71	22.3	17.0	0.175	72.6	17.5	20.2
2	0.371	5.42	4,670	17.4	0.376	12.0	1,660	9.72	0.631	5.80	22.2	20.1	0.209	20.4	15.0	69.9
3	0.366	8.56	4,050	23.7	0.346	30.7	1,610	12.7	0.694	2.46	21.3	20.0	0.241	29.1	10.0	94.9
4	0.344	7.82	3,600	26.2	0.302	26.9	1,500	16.3	0.751	5.70	22.2	19.0	0.274	27.8	4.17	90.3
5	0.346	7.57	3,700	20.9	0.324	22.5	1,500	15.0	0.793	4.74	21.8	16.0	0.262	27.6	4.17	118.0
6	0.340	7.66	3,700	19.7	0.336	19.1	1,490	16.1	0.851	5.16	20.8	21.3	0.256	41.0	1.67	155.0
7	0.335	7.58	3,550	16.0	0.338	25.2	1,460	14.0	0.898	2.89	20.5	21.0	0.318	31.1	3.33	155.0
8	0.347	8.97	4,020	26.7	0.388	42.1	1,530	19.2	0.919	5.29	19.8	18.2	0.363	33.7	8.33	159.0
9	0.332	6.92	3,710	17.7	0.389	22.6	1,570	17.3	0.974	6.07	19.0	11.0	0.389	19.1	10.8	164.0
10	0.359	5.15	3,900	21.3	0.410	23.7	1,690	17.2	0.975	4.32	18.8	19.7	0.353	18.1	20.0	156.0
11	0.344	5.27	4,070	19.9	0.452	30.9	1,660	17.1	1.01	4.04	18.3	12.8	0.425	15.7	9.7	152.0
12	0.357	5.58	4,250	19.6	0.485	37.7	1,700	14.5	1.03	5.23	17.8	21.1	0.365	27.6	14.2	165.0
13	0.340	6.41	3,730	18.0	0.424	22.3	1,740	16.0	1.05	4.35	17.7	13.2	0.372	27.5	13.3	153.0
14	0.340	9.45	3,630	22.8	0.402	29.5	1,720	18.8	1.08	7.55	17.0	16.6	0.377	31.4	22.5	147.0
15	0.351	7.32	4,260	22.5	0.516	31.6	1,820	20.7	1.06	6.54	17.0	16.2	0.382	36.4	15.0	167.0
16	0.357	7.09	4,480	21.2	0.600	33.7	1,900	17.6	1.09	6.61	18.5	21.8	0.351	17.6	10.0	200.0
17	0.365	8.52	4,900	22.5	0.659	28.0	2,110	20.3	1.14	4.78	16.7	18.1	0.310	10.9	11.7	225.0
18	0.377	7.05	5,420	18.2	0.698	30.7	2,330	16.5	1.12	7.02	17.5	15.2	0.321	25.5	8.33	159.0
19	0.382	5.28	5,420	16.3	0.793	28.1	2,427	13.2	1.17	4.81	16.0	22.4	0.243	35.1	1.67	245.0
20	0.380	6.85	5,370	19.0	0.798	25.8	2,350	14.1	1.16	1.54	13.5	19.2	0.255	33.2	2.50	167.0
21	0.391	6.04	4,790	21.3	0.708	32.1	2,380	14.9	1.16	3.46	13.7	18.3	0.294	27.9	0.833	245.0
22	0.376	4.61	4,280	26.4	0.627	27.1	2,240	16.7	1.20	4.58	13.8	27.2	0.229	46.7	3.33	245.0
23	0.385	7.65	5,270	23.0	0.808	25.7	2,390	17.6	1.19	4.02	14.3	25.2	0.209	35.1	3.33	245.0
24	0.396	7.08	5,580	19.4	0.855	27.3	2,500	10.8	1.18	3.61	12.7	12.9	0.238	45.0	12.5	245.0
25	0.375	6.84	4,960	20.1	0.752	24.7	2,360	8.58	1.22	3.23	12.7	17.1	0.239	28.6	13.3	245.0
26	0.348	7.18	4,860	24.5	0.737	41.6	2,250	12.6	1.18	5.29	14.0	10.1	0.323	36.4	—	—

TABLE 1. *Continued.*

Age	Specific gravity		Modulus of rupture		Modulus of elasticity		Maximum crushing strength		Cell length		Fibril angle		Ring width		Tension wood	
	Average	COV[2]	Average	COV[2]	Average	COV[2]	Average	COV[2]	Average	COV[2]	Average	COV[2]	Average	COV[2]	Average	COV[2]
Yr		*Pct*	*Psi*	*Pct*	*10⁶ psi*	*Pct*	*Psi*	*Pct*	*mm*	*Pct*	*Degrees*	*Pct*	*In.*	*Pct*	*Pct*	
								PINE								
1	0.412	8.21	4,200	19.2	0.289	26.2	2,020	23.2	1.57	5.52	36.5	10.5	0.394	30.2	36.7	42.0
2	0.384	7.09	4,240	18.6	0.294	29.2	1,880	17.2	1.73	13.2	39.0	15.6	0.508	19.4	33.3	76.3
3	0.400	7.34	3,800	11.0	0.293	27.4	1,620	12.2	1.95	11.8	39.3	18.8	0.360	15.1	31.7	106.0
4	0.400	10.2	4,400	14.9	0.349	39.8	1,730	15.9	2.14	17.8	37.0	19.6	0.367	34.4	32.5	99.6
5	0.436	8.92	5,470	18.4	0.498	41.0	2,160	16.4	2.37	16.2	31.0	21.5	0.348	20.8	29.2	122.0
6	0.423	14.6	5,490	16.7	0.514	38.1	2,100	20.3	2.53	15.1	33.7	20.4	0.312	45.3	32.5	106.0
7	0.467	10.8	6,470	13.8	0.642	40.3	2,550	18.5	2.68	14.4	33.2	15.7	0.260	44.2	28.3	102.0
8	0.502	17.0	6,848	21.7	0.710	45.7	2,960	18.4	2.82	19.1	29.5	15.9	0.223	38.6	30.8	120.0
9	0.514	8.95	8,160	23.0	0.904	21.6	3,190	16.2	3.03	15.5	24.5	24.3	0.181	21.2	36.7	65.5
10	0.531	9.04	9,820	11.8	1.12	32.7	3,430	8.04	3.16	16.3	27.3	20.8	0.164	33.8	31.7	96.6
11	0.575	8.39	10,690	10.1	1.309	23.2	3,760	7.26	3.23	11.6	25.3	18.1	0.145	22.1	30.8	108.0
12									3.48	15.9	21.0	20.2	0.138	14.8	32.5	85.8
13	0.600	9.26	11,790	16.1	1.534	22.8	4,060	5.11	3.39	18.9	21.8	36.0	0.132	17.2	33.3	105.0
14									3.46	17.2	22.2	22.9	0.132	25.3	28.3	80.2
15	0.582	6.53	11,570	12.4	1.541	13.6	4,140	6.31	3.51	16.3	22.0	32.9	0.138	26.9	25.0	82.0
16									3.69	10.0	22.2	41.9	0.099	51.4	32.5	83.0
17	0.576	6.78	11,570	13.5	1.545	5.75	4,110	9.28	3.75	7.80	23.3	20.0	0.117	36.0	30.0	94.9
18									3.89	9.91	19.3	15.6	0.118	27.8	20.0	128.0
19	0.560	9.50	11,450	14.3	1.495	15.0	3,940	11.5	3.68	6.76	21.2	41.1	0.138	35.2	20.0	125.0
20									3.61	5.71	22.8	38.2	0.154	22.3	17.5	89.9
21	0.555	11.4	10,680	12.1	1,313	20.5	4,140	9.80	3.66	8.82	17.0	48.1	0.143	27.6	25.8	90.3
22									3.71	8.11	18.5	22.9	0.136	28.0	18.3	70.4
23	0.574	6.97	12,400	18.8	1.606	23.9	4,570	13.0	3.92	8.69	17.5	19.4	0.114	45.6	15.0	135.0
24									3.96	6.61	16.7	16.0	0.110	37.1	22.5	104.0
25	0.577	6.13	12,070	11.1	1.590	18.6	4,450	7.99	3.94	8.00	19.0	17.9	0.128	43.3	32.5	103.0
26									3.78	8.78	18.0	15.3	0.134	50.0	30.8	86.7
27	0.553	6.99	11,370	8.29	1.538	17.7	4,230	8.39	3.95	5.73	14.5	32.9	0.114	35.1	24.2	96.5
28									4.03	6.64	12.3	20.9	0.106	19.8	26.7	93.9

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[1] Most values in the table generally represent the average for six trees and thus, six observations. For cell length and fibril angle the value for one tree represents the average of many observations. For the mechanical properties of pine after 12 years, each value represents 2 years because in some trees a single specimen encompassed 2 years' growth.

[2] COV = Coefficient of variation.

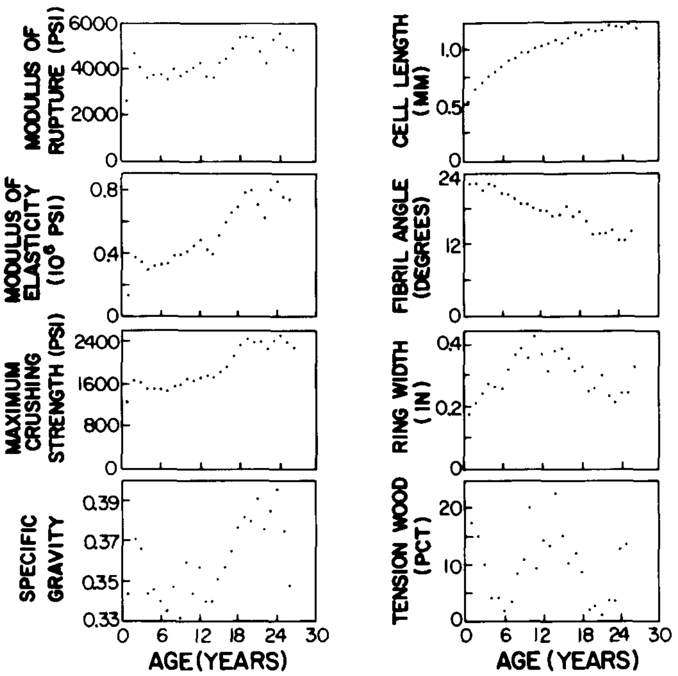

FIG. 3. The change in properties with age in cottonwood.

The change in specific gravity with age is not nearly so pronounced, amounting to only about a 10% increase from early juvenile to late mature wood in cottonwood and about 40% in pine (ratios above). These increases are not sufficient to account for the increases observed in mechanical properties for either species. The large change in mechanical properties with age apparently reflects the composite effect of increasing specific gravity, cell length, and fibril angle. This will be discussed in more detail in a later section.

In this study, growth rate (ring width) in loblolly pine declines steadily until about age 12 and then remains relatively constant, while growth rate in cottonwood peaks in the middle years. However, it is not likely that these growth rates are characteristic of plantation material in general.

The percentage of compression wood fibers in pine was about 35% in early years and showed a slight decreasing trend with age. The percentage of tension wood fibers in cottonwood was lower, more erratic from year to year, and without a general trend with age. Because of the sporadic occurrences of reaction wood and the general difficulty in making positive identification and measurement, we found reaction wood an unimportant variable in this study.

As an example, the MOE in one loblolly pine tree increased from about 200,000 to over 1,800,000 psi from early juvenile to late mature wood, a ninefold increase. The same tree also showed a considerably larger increase than the average in other mechanical properties and specific gravity.

Juvenile wood/mature wood demarcation

Because of the gradual change in properties with age, the age at which a tree stops producing juvenile wood and begins producing mature wood is not well

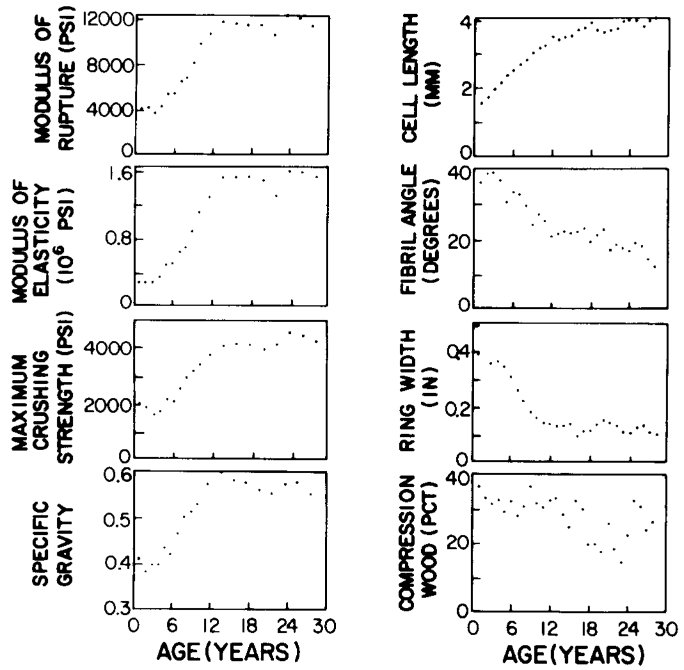

FIG. 4. The change in properties with age in pine.

defined. Rather, the wood formed each year gradually assumes the character of mature wood. In fact, this progression from juvenile to mature wood differs among properties and species.

However, researchers, forest managers, and wood processors would benefit from establishment of a definite demarcation point: Researchers should be able to compare juvenile and mature wood properties; forest managers should be able to make decisions on tree spacing, fertilization, thinning, and harvest rotation based on proportions of juvenile and mature wood in the tree; and wood processors should know which drying, machining, finishing, and other wood processing procedures to select, based on juvenile wood proportions. In the latter instance, pulp blends and design stresses for structural lumber may need to be modified when juvenile wood is present.

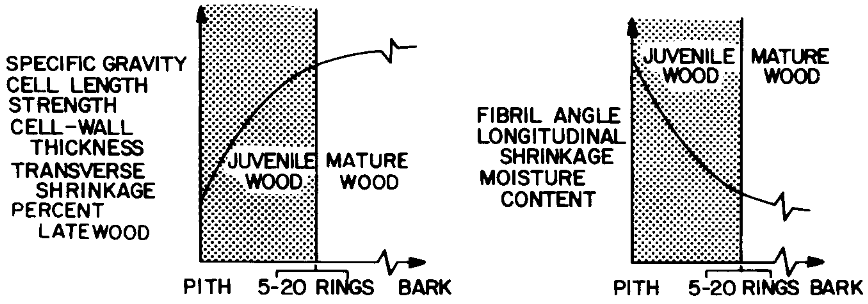

FIG. 5. Schematic representation of the gradual improvement in properties with age (Bendtsen 1978).

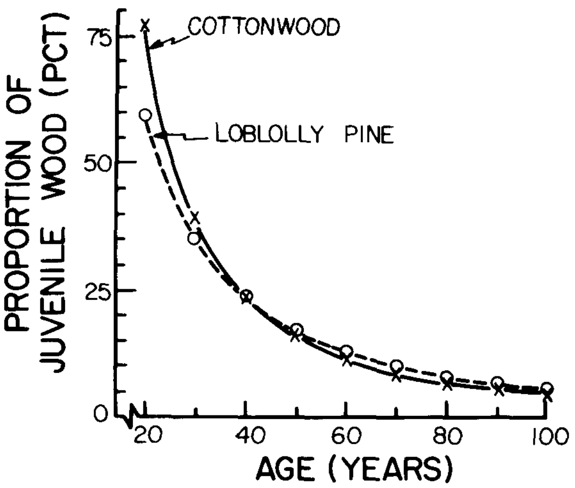

FIG. 6. Projected proportion of juvenile wood at the 6-foot height in cottonwood and loblolly pine at ages 20 to 100 years.

Although the improvement in properties with age is gradual, there is a point when the rate of improvement distinctly decreases. Thus, we sought an objective method to determine the age when the change is "significant"; this age could be interpreted as the point of demarcation between juvenile and mature wood.

We applied three methods to both the individual tree and average values of MOR, MOE, compression strength, specific gravity, cell length, and fibril angle for each species in an attempt to determine this "age of significance." Because of the large variability in values from tree to tree or year to year, none of the three methods produced demarcation points that appeared to be consistent juvenile-mature wood boundaries. Thus, we resorted to visual interpretation of the data and the data plots to determine the demarcation point (Table 1, Figs. 3 and 4), yet we feel the methods we tried are worth considering here:

Segmented regression analysis.—A segmented regression was fit to the age-property data with two linear segments. The regression segments were chosen to minimize the total residual sum of squares under the constraint that the intersection point of the two regressions is to be between the two consecutive ages that split the data set. The intersection point is taken as the point of demarcation between juvenile and mature wood (Hudson 1966).

TABLE 2. *Weighted average juvenile and mature wood properties.*

Type of wood	Modulus of rupture	Modulus of elasticity	Compression strength	Specific gravity	Cell length	Fibril angle
	Psi	*10^6 psi*	*Psi*		*mm*	*Degrees*
			COTTONWOOD			
Juvenile	4,070	0.470	1,730	0.344	1.02	18.4
Mature	5,170	0.761	2,360	0.375	1.17	14.1
			LOBLOLLY PINE			
Juvenile	6,850	0.706	2,660	0.475	2.64	31.1
Mature	11,500	1.510	4,210	0.565	3.74	18.9

TABLE 3. *Projected weighted average properties of juvenile and mature wood combined at ages 20 to 100 years.*

Years	Modulus of rupture	Modulus of elasticity	Compression strength	Specific gravity	Cell length	Fibril angle
	Psi	*10^6 psi*	*Psi*		*mm*	*Degrees*
			COTTONWOOD			
20	4,320	0.536	1,870	0.351	1.05	17.4
30	4,740	0.648	2,120	0.363	1.11	15.8
40	4,910	0.693	2,220	0.367	1.14	15.1
50	5,000	0.716	2,260	0.370	1.15	14.8
60	5,050	0.728	2,290	0.371	1.16	14.6
70	5,080	0.737	2,310	0.372	1.16	14.5
80	5,100	0.742	2,320	0.373	1.16	14.4
90	5,110	0.746	2,330	0.373	1.17	14.3
100	5,120	0.749	2,340	0.373	1.17	14.3
			PINE			
20	8,760	1.036	3,290	0.512	3.09	26.1
30	9,850	1.225	3,660	0.533	3.35	23.2
40	10,400	1.320	3,840	0.544	3.48	21.8
50	10,710	1.374	3,950	0.550	3.55	21.0
60	10,910	1.408	4,010	0.554	3.60	20.5
70	11,040	1.431	4,060	0.556	3.63	20.1
80	11,130	1.447	4,090	0.558	3.65	19.9
90	11,200	1.458	4,110	0.559	3.67	19.7
100	11,250	1.467	4,130	0.560	3.68	19.6

Discriminate analysis.—In this method, sometimes referred to as "classification," we assumed that values of 6 years of age or less are representative of juvenile wood, and that values of 20 years of age and greater are representative of mature wood. The cutoff years were chosen to be safely within the juvenile and mature wood and equally distant from an age "judged" to be the demarcation point. Each year is then successively "labeled" mature or juvenile wood, depending upon whether it is closer to the mean (after normalizing for standard deviation) of the mature or juvenile wood property values. The demarcation between mature and juvenile wood is assumed to fall between the two clusters after all ages have been so assigned. Usually, more than two clusters arose from this labeling scheme, so a unique demarcation point could only be obtained subjectively.

Analysis of slope.—Here we assumed that a property is constant once the mature stage is reached. The point at age t is "labeled" juvenile if, when a linear regression is fit to the data for ages greater than or equal to t, the slope is significantly different than zero ($P \leq 0.05$), and mature if the slope is not different from zero.

Subjective analysis.—The demarcation between juvenile and mature wood is generally better defined in pine than cottonwood, and better defined in mechanical properties and specific gravity than in cell length and fibril angle. The mechanical properties and specific gravity also appear to mature earlier than cell length and fibril angle.

For loblolly pine, we judged the MOR, MOE, compression strength, and specific gravity to have reached maturity by age 13 years; after age 12 these values were relatively constant. For cell length and fibril angle, there was a change of slope at

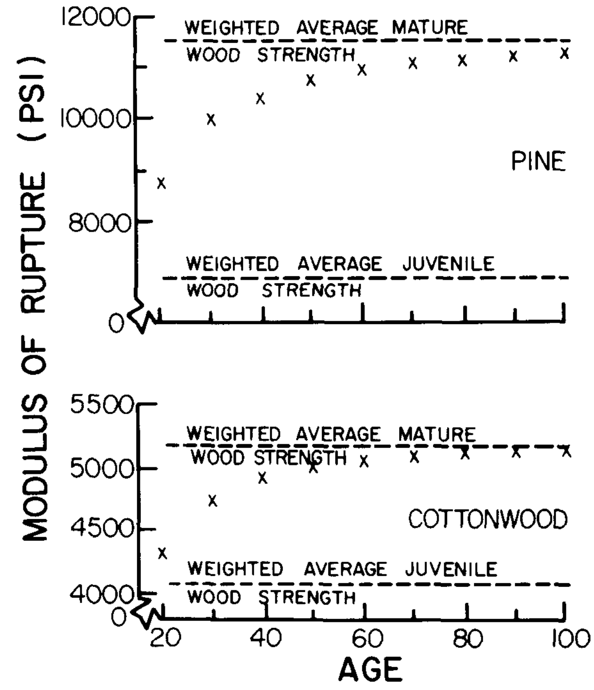

FIG. 7. Projected weighted average for MOR of juvenile and mature wood combined at ages 20 to 100 years.

about age 12 to 13 years also; but these properties continued to improve rather significantly, for cell length until about age 18 and for fibril angle until the trees were cut. Thus, for the pine the juvenile-mature wood demarcation point for mechanical properties and specific gravity was between 12 and 13 years of age, for cell length about 18 years, and for fibril angle it had not yet been reached at age 30.

For cottonwood, the demarcation point for mechanical properties and specific gravity was about 17 to 18 years. Cell length and fibril angle appeared to stabilize about a year or two later.

Proportions of juvenile wood at various ages

A question frequently asked is how much juvenile wood is in a tree. The answer, of course, depends upon age. We calculated the proportions of juvenile wood that can be expected in loblolly pine and cottonwood at harvest ages ranging from 20 to 100 years under several assumptions: (1) The last year of juvenile wood is 12 in pine and 17 in cottonwood, as determined earlier; (2) the radius of juvenile wood is 3.3 inches in pine and 5.4 inches in cottonwood, as determined from the sample trees at 12 and 17 years; and (3) the projected radial growth rate is 0.125 inch per year in pine and 0.25 in cottonwood (the average growth rate for years 13 and later in pine and 17 and later in cottonwood).

These calculations represent the proportions of juvenile wood at the sample height in the trees, about 6 feet above ground. In whole trees the proportion of juvenile wood will be greater because it increases with tree height and because growth rate may be expected to decline somewhat unless silvicultural treatments (thinning, fertilization, etc.) are applied.

At 20 years, the proportion of juvenile wood in pine is about 60% and in cottonwood about 80% (Fig. 6). The difference reflects the fact that cottonwood matures 5 years later than pine. At 40 years, the juvenile wood proportion has decreased to about 24% in both species. From 40 to 100 years, the proportions of juvenile wood in pine and cottonwood are about the same, decreasing to about 5% at 100 years. From the standpoint of juvenile wood proportion, there is little benefit in delaying harvest beyond 60 years.

Average juvenile and mature wood properties and predicted overall average at various ages

Average juvenile and mature wood properties were calculated by weighting the values for each age according to the corresponding areas of annual increments of growth (Table 2). The weighted averages are assumed to better represent the properties of the two wood types than would straight averages of yearly values. In pine, the average mechanical properties of mature wood are nearly twice those for juvenile wood; average cell length and fibril angle show about a 40% improvement from juvenile to mature wood, and specific gravity about a 20% improvement (Table 2). In cottonwood, the differences in mechanical properties between mature and juvenile wood are much less.

Using the same assumptions used in developing juvenile wood proportions (Fig. 6), the combined weighted average properties of mature and juvenile wood (i.e., average tree properties) were estimated for ages ranging from 20 to 100 years (Table 3).

For MOR, most of the improvement in the projected average occurred by age 40–50 years in both species, with little to be gained by delaying harvest beyond 60 years (Fig. 7). A similar observation holds for all other properties (Table 3). These observations are as expected, based on the juvenile/mature wood proportions at various ages (Fig. 6).

Source of variation in mechanical properties with age

Regression analysis was used to identify the potential source of improvement in mechanical properties with age. Scatter diagrams of mechanical properties versus specific gravity, cell length, and fibril angle typically were linear except at low values of the variables (high values of fibril angle). These low values corresponded to the early years of growth where no change was observed in mechanical properties. When data for the first 3 years in pine and 6 in cottonwood were deleted, scatter diagrams appeared linear; thus, the data for these early years were omitted in the regression analysis.

With the above data omitted, the correlation between mechanical properties and specific gravity, cell length, and fibril angle ranged from 0.50 for cell length versus MOR in cottonwood to 0.80 (absolute value) for specific gravity versus compression strength in pine (Table 4). None of the independent variables (specific gravity, cell length, or fibril angle) had consistently higher correlations with mechanical properties. The correlations were always higher for pine than cottonwood and tended to be higher for compression strength than MOE or MOR.

Using regressions to predict mechanical properties (MOR, MOE, and compres-

TABLE 4. *Correlation coefficients (r) for mechanical versus anatomical properties.*

Mechanical property	Anatomical property		
	Specific gravity	Cell length	Fibril angle
	COTTONWOOD		
Modulus of rupture	0.64	0.50	0.62
Modulus of elasticity	0.60	0.66	0.62
Compression strength	0.78	0.73	0.79
	PINE		
Modulus of rupture	0.74	0.75	0.67
Modulus of elasticity	0.65	0.79	0.71
Compression strength	0.80	0.75	0.70

sion strength) from specific gravity, cell length, and fibril angle, the best one-variable model had multiple correlation coefficients squared (R^2) ranging from 0.41 to 0.64 (Table 5) (note: for one-variable models $R^2 = r^2$). For the best two-variable model, (R^2) ranged from 0.52 to 0.86 (Table 5). Specific gravity and cell length were always the best two-variable combination for pine. For cottonwood, specific gravity was always included in the best two-variable models, while fibril angle was included for two of three mechanical properties. Little improvement in R^2 was gained by adding a third variable and, in two of six cases, the coefficient of the third variable was not significantly different from zero ($P = 0.05$).

Overall, the maturation of specific gravity, cell length, and fibril angle contribute about equally to the improvement in mechanical properties as cottonwood and loblolly pine progress through the juvenile stage to maturity. In combination, they explain better than 80% of the improvement in the three mechanical properties in pine, and in compression strength in cottonwood. The lower degree of association among variables in cottonwood is probably because the change in properties from juvenile to mature wood is less pronounced.

Mechanical properties of sample trees compared with those of trees from natural forests

According to the U.S. Department of Agriculture, Forest Service (1974), the average values (green moisture condition) of the three mechanical properties tested here for eastern cottonwood and loblolly pine grown under natural conditions are:

	Eastern cottonwood	Loblolly pine
MOR (psi)	7,210	9,940
MOE (10^6 psi)	1.01	1.4
Compression strength (psi)	2,280	3,510

The values for MOR have been increased by a depth factor of 1.36 (American Society for Testing and Materials 1983) to adjust the result from standard specimen of a 2-inch depth to the ⅞-inch depth used here. The accuracy of this adjustment for depths of less than 1 inch is untested (Bohannan 1966), but we do not believe the potential error is sufficient to change our conclusions.

TABLE 5. *Multiple correlation coefficient squared (R^2) for the best one- and two-variable models and for three-variable models.*

	Independent variables in models and associated R^2[1]		
Dependent variable	Best one-variable model	Best two-variable model	Three-variable model
		COTTONWOOD	
Modulus of rupture	SG; $R^2 = 0.41$	SG, FA; $R^2 = 0.53$	SG, FA, CL; $R^2 = 0.53$[2]
Modulus of elasticity	CL; $R^2 = 0.43$	CL, SG; $R^2 = 0.52$	CL, SG, FA; $R^2 = 0.56$
Compression strength	FA; $R^2 = 0.62$	FA, SG; $R^2 = 0.78$	FA, SG, CL; $R^2 = 0.81$
		PINE	
Modulus of rupture	CL; $R^2 = 0.56$	CL, SG; $R^2 = 0.81$	CL, SG, FA; $R^2 = 0.82$
Modulus of elasticity	CL; $R^2 = 0.62$	CL, SG; $R^2 = 0.78$	CL, SG, FA; $R^2 = 0.80$
Compression strength	SG; $R^2 = 0.64$	SG, CL; $R^2 = 0.86$	SG, CL, FA; $R^2 = 0.86$[2]

[1] SG = specific gravity, CL = cell length, FA = fibril angle.
[2] Addition of third variable cells not significant ($P > 0.05$).

The "standard" values (above) of MOR and compression strength for pine compare closely with the projected values at about 30 years of age, while that for MOE compares closely at about 60 years (Table 3). The standard and projected values for compression strength in cottonwood reach comparability at about age 40, but the projected MOE and MOR are substantially inferior at all ages. Although it is probable that these projections apply to plantations of different site classes, the application of different management practices could well affect their accuracy.

SUMMARY AND DISCUSSION

MOR and MOE in bending, compression strength parallel to grain, specific gravity, cell length, fibril angle, and the percentage of reaction wood fibers were measured in individual annual rings of plantation-grown eastern cottonwood and loblolly pine. Material was taken from the 5- to 6-foot height in the tree.

All properties show marked improvement with age as the trees progressed through juvenile wood to maturity. The juvenile to mature wood transition is more pronounced in pine than in cottonwood and more pronounced in mechanical properties and specific gravity than cell length and fibril angle. In pine, MOE shows a fivefold average increase from early juvenile wood to maturity, with one tree showing nearly a tenfold increase.

The age at which sample trees begin to produce fully mature wood is not well defined; the demarcation between juvenile and mature wood varies among species and properties. In pine, mechanical properties and specific gravity are mature beginning at about age 13, while cell length matures at about age 18. Fibril angle continues to improve (lower angle) through age 30. In cottonwood, mechanical properties and specific gravity reach maturity at about 17 to 18 years, while cell length and fibril angle mature a year or two later.

At age 20, the pine samples contain an estimated 60% juvenile wood, and the cottonwood samples 80%. Based on the growth rate in mature wood zones, we estimate that juvenile wood proportions will be about 25% at age 40 in both species. By year 60, the juvenile wood proportion will be down to about 10%, with only an additional 5% reduction in the following 40 years. Values for mechanical properties will reach 87% to 95% of mature wood values (depending upon species and property) by age 40.

For pine, average strength properties are projected to equal those of natural forest trees at age 30; MOE will equal that of natural trees at age 60. For cottonwood, compression strength will reach comparability at about age 40, while other mechanical properties are projected to be substantially inferior at all ages.

These projections could vary considerably from site to site and plantation to plantation. Their applicability will depend on growth rates during juvenile and mature wood production. However, we do not believe that the age at which trees begin to produce mature wood is a function of growth rate. Thus, the forest manager can use the reported juvenile-mature wood demarcation points to assess the effect of forest management practices (such as the suppression of growth during juvenile wood production, irrigation, fertilization and thinning, and harvest age) on the proportions of juvenile wood in the harvest and the overall average properties.

The increase in specific gravity and the gradual maturation of cell length and fibril angle contribute about equally to improvements in mechanical properties from juvenile wood to mature wood in both pine and cottonwood. Linear regression analysis indicates that individually these variables explain about 25% to 60% of the improvement in mechanical properties, while in combinations they explain about 40% to 85%. The differences in percentages are largely due to differences between mechanical properties rather than species, with highest correlations observed for compression strength.

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