MECHANICAL PROPERTIES OF LUMBER FROM PARTIALLY CAD-DEFICIENT LOBLOLLY PINE (*PINUS TAEDA*)

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Abstract. Fast-growing loblolly pine produced by the North Carolina State University–Industry Cooperative Tree Improvement Program is a natural carrier of a rare gene, *cad-n1*, an allele code for deficiency in cinnamyl alcohol dehydrogenase (CAD), an enzyme that catalyzes the last step in the biosynthesis of lignin precursors. Wood from totally CAD-deficient loblolly pine trees is known to have low mechanical properties, but not much is known about the mechanical performance of wood from partially CAD-deficient trees. The effect associated with this genetic modification of loblolly pine was evaluated by comparing the mechanical properties in bending, compression parallel and perpendicular to the grain, tension perpendicular to the grain, and shear parallel to the grain of small clear specimens of wood from partially CAD-deficient with those from wild-type loblolly pine trees. Results indicate that there is no significant difference between the two genotypes for all mechanical properties measured.

Keywords: Mechanical properties, loblolly pine, cinnamyl alcohol dehydrogenase, partially CAD-deficient, *Pinus taeda,* mutant.

INTRODUCTION

The southern region of the United States extending from east Texas to Virginia produces approximately 60% of the nation's lumber (Wear and Greis 2002). The majority of the tree species are marketed as southern pine (or southern yellow pine), and its lumber is commonly used for residential, nonresidential, and industrial construction in the US and other countries. Design properties of southern pine lumber, as being overseen by the Southern Pine Inspection Bureau under the approval by the American Lumber Standard Committee, are among the highest for softwoods. Loblolly pine (*Pinus taeda* L) is one of the major lumber species marketed as southern pine, the others being shortleaf, longleaf, and slash pine. Most of this lumber is genetically improved loblolly pine from intensively managed plantations. This species has been the subject of extensive genetic improvement by the North Carolina State University–Industry Cooperative Tree Improvement Pro-

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gram for almost 50 yr. One of the best performing first-generation parents of genetically improved loblolly pine is Plus-tree 7-56. Because of its extremely fast growth, progeny of this tree are widely planted in the south. This line is also the only known natural carrier of a mutant gene, the *cad-n1* allele, which codes for deficiency in cinnamyl alcohol dehydrogenase (CAD). In the biosynthesis of softwood lignin, the CAD enzyme is required during the reduction of coniferaldehyde to coniferyl alcohol (MacKay et al 1995). The incidence of the *cad-n1* allele is manipulated in breeding work to produce two types of mutant trees: totally CAD-deficient (homozygous for the *cad-n1* allele) and partially CAD-deficient (heterozygous for the *cad-n1* allele).

Extensive chemical analyses (Ralph et al 1997; MacKay et al 1997, 1999, 2001; Lapierre et al 2000) of totally CAD-deficient loblolly pine have revealed that its lignins contain a low level of coniferyl alcohol but high levels of coniferaldehyde, vanillin, dihydroconiferyl alcohol, and p-coumaryl alcohol. Additionally, totally CAD-deficient pine has slightly reduced lignin content and contains fewer β-O-4 linkages and more 5-5 linkages. As part of a pulping study, Dimmel et al (2001) looked at milled-wood lignin molecular weight and observed that isolated lignin from totally CAD-deficient wood had approximately 35% lower molecular weight than lignin from normal trees. These results indicate that the shortage of normal lignin in totally CAD-deficient pine is compensated by using nontraditional wall phenolics to construct unusual lignins that yield wood that is brownish in color (MacKay et al 1997) and is easily delignified (MacKay et al 1999; Dimmel et al 2001).

Only limited studies on the chemical composition of partially CAD-deficient pines are available. Capanema et al (2005), using near infrared spectroscopy, observed no significant difference in the amount of lignin, α-cellulose, and hemicellulose contents of partially CAD-deficient and wild-type pines (homozygous for normal CAD allele). Using quantitative nuclear magnetic resonance spectroscopy, they also reported a similar amount of milled-wood lignin content in the juvenile wood but slightly higher milled-wood lignin content in the mature wood of partially CAD-deficient compared with wild-type loblolly pine. The same study also reported that the structure of the kraft lignin isolated from pulping was similar for partially CAD-deficient and wild-type pine.

Because of the altered chemical structure of lignin in totally CAD-deficient pine, it was suggested that the plant material has the potential to produce wood well suited for milder pulping conditions, thereby consuming lower amounts of chemicals, requiring less energy, and generating less waste (MacKay et al 1999). However, Dimmel et al (2002) pointed out that totally CAD-deficient loblolly pine is not the ideal wood raw material for pulp and paper manufacture because of poor pulp yields and tree growth. In contrast, partially CAD-deficient loblolly pine trees showed increased growth rate at an early age (Wu et al 1999) and in later years (Dimmel et al 2002) compared with wild-type pine. Dimmel et al (2002) proceeded to evaluate the properties of partially CAD-deficient pine and reported that pulping and bleaching differences were not observed in those trees and in wild-type pine. Jameel (2006) performed studies on the pulping characteristics and paper properties of the same loblolly pine samples used in this study. He found no significant difference in the pulping rate, pulp yield, bleachability, refining energy, and tear-tensile relationship between the partially CAD-deficient and wild-type loblolly pine. Capanema et al (2005) showed similar results in terms of pulping rate of 10-yr-old pine.

This study was performed to extend the evaluation of partially CAD-deficient loblolly pine to applications other than pulp and paper. Considering that 75% of the income to the landowner is from sawn timber, whereas only 12% is from pulpwood (Lupold 2003), there is an increasing interest in and a need for more research effort on the genetic modification of wood characteristics for solid wood and structural wood-based composites. Because lignin serves as an adhesive in wood, there is a concern that lignin modification in CAD-deficient pine might result in wood with reduced mechanical performance. Hence, wood from mature partially CAD-deficient and wild-type trees was evaluated for mechanical properties in bending, compression parallel and perpendicular to the grain, tension perpendicular to the grain, and shear parallel to the grain. Mechanical properties are the primary criteria for material selection leading to structural application.

MATERIALS AND METHODS

Eighteen trees from a 28-yr-old loblolly pine stand were harvested from five replicated plots at the North Carolina State University–Industry Cooperative Tree Improvement Program experimental plantation in Rockingham, NC (latitude: 34.939, longitude: −79.774, elevation: 87 m, annual average precipitation: 1.25 m). The 18 trees were half-sibs, having the same mother (Plus-tree 7-56). Nine of the trees were partially CAD-deficient, whereas the remaining nine were wild-type. The number of trees selected for this study (nine per genotype) is less than the 10 trees per genotype that is specified in ASTM D5536-94 (ASTM 2006d). The 2.4-m-long butt log of each tree was used for testing of mechanical properties, whereas the rest of the tree was set aside for other studies. Each of the logs was sawn into 45-mm-thick boards (Fig 1) that were kiln-dried to 12% MC.

Small clear specimens for the different tests were cut from the dried boards using the cruciform secondary method described in ASTM D5536-94 (ASTM 2006d). As shown in Fig 1, this involves cutting samples along two diameters that form a cruciform. Along the longitudinal direction, samples were randomly chosen, keeping them free from pith, knots, checks, wane, and other defects. We used the coefficients of variation for clearwood strength values for loblolly pine given in ASTM D2555-96 (ASTM 2006b) to calculate the minimum number of samples required for each test as described in ASTM D2915-94 (ASTM 2006c).

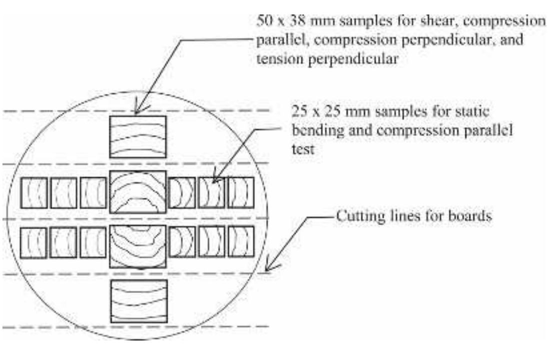

Figure 1. The cruciform secondary method of cutting clear wood samples from a log.

Static bending and compression parallel to the grain tests were made on 25- × 25- × 410-mm and 25- × 25- × 100-mm secondary method specimens, respectively. Test specimens for shear parallel to the grain, compression perpendicular to the grain, and tension perpendicular to the grain were smaller than standard sizes, particularly in thickness. The shear parallel to the grain tests were made on 38- × 50- × 63-mm specimens instead of the standard 50- × 50- × 63-mm specimens. For tension perpendicular to the grain, the sample dimensions were reduced from the standard 50 × 64 × 50 mm to 38 × 64 × 50 mm, resulting in a tension area of 38 × 25 mm compared with the standard area of 50 × 25 mm. The compression perpendicular to the grain tests were made on 38- × 50- × 150-mm specimens instead of the 50- × 50- × 150-mm specimens, resulting in a bearing area of 38 × 50 mm compared with the standard bearing area of 50 × 50 mm. After being cut to final dimensions, all test specimens were conditioned to 21°C and 65% RH in a conditioning chamber for at least 4 wk before testing.

For all the mechanical tests, specifications described in ASTM D143-94 (ASTM 2006a) such as the speed of testing, growth ring orientation, load, and bearing block were followed except for specimen dimensions as described previously. In several studies of nonstandard sizes, there had been no reported significant effect of size on the measured properties. In a study of size effect on shear test, Lang and Kovacs (2001) found that varying the shearing length and width from 20 to 55 mm had no significant effect on shear strength. For compression perpendicular to the grain, Kunesh (1968) found no significant difference in fiber stress at proportional limit for a thickness of 50 mm when the bearing area was varied from 0.645×10^{-3} m^2 to 10.323×10^{-3} m^2. The bearing area for the current study was 1.935×10^{-3} m^2. Based on these earlier studies, it is assumed that the test results here are comparable to those using ASTM standard sizes.

Tests were conducted at the Hodges Wood Products Laboratory using a universal testing machine and linear variable displacement transducers. After the mechanical tests, the MC and specific gravity of the samples were measured using an oven-drying method (ASTM 2006a). The specimens that were used for MC determination were then saturated with water and their green volumes measured using the water displacement method (ASTM 2006e) to allow for the calculation of the green specific gravity.

The significance of the genotype effect on the different mechanical properties was tested using a linear model for the two-way analysis of variance:

$$y = \mu + g + p + (g \times p) + e \qquad (1)$$

where y is the mechanical property of interest, μ is the overall mean, g is the genotype effect, p is the plot effect, $(g \times p)$ is the effect of interaction between the genotype and plot, and e is the residual term. The within-log effect (subsampling resulting from the cruciform method) is incorporated in the error term whose variance is assumed to be normally and independently distributed.

RESULTS AND DISCUSSION

As suggested from the published wood chemistry, there was no significant difference between the genotypes for any measured mechanical property (Table 1). This result indicates that partially CAD-deficient loblolly pine wood should perform as well as wild-type loblolly pine. The analyses of variance also show that the interaction between the genotype and plot was not significant, whereas the plot main effect was significant only for shear strength parallel to the grain and compressive strength parallel to the grain.

Because specific gravity is directly correlated with many mechanical properties (Forest Products Laboratory 1999), it is instructive to investigate the variation in the specific gravity be-

Table 1. *Mechanical properties and specific gravity (based on oven-dry mass and green volume) of partially CAD-deficient and wild-type loblolly pine and the F test for significance of genotype effect.*

	Partially CAD-deficient		Wild-type		
Property	N[a]	Mean (CV[b]) (MPa)	N[a]	Mean (CV[b]) (MPa)	F test of significance
Static bending					
Modulus of rupture	41	84.8 (0.19)	46	85.7 (0.24)	0.72[c]
Modulus of elasticity	41	7356 (0.37)	46	7178 (0.42)	0.99[c]
Compression parallel to the grain					
Maximum crushing strength	52	41.0 (0.24)	54	40.6 (0.24)	0.75[c]
Modulus of elasticity	52	8680 (0.47)	54	8500 (0.46)	0.83[c]
Shear parallel to the grain					
Maximum strength	51	10.6 (0.13)	54	10.8 (0.14)	0.28[c]
Compression perpendicular to the grain					
Stress at proportional limit	47	6.6 (0.18)	54	6.6 (0.16)	0.70[c]
Stress at 1-mm deformation	47	11.5 (0.18)	54	11.4 (0.15)	0.80[c]
Tension perpendicular to the grain					
Maximum strength	48	4.7 (0.22)	54	4.6 (0.24)	0.20[c]
Specific gravity	112	0.48 (0.12)	127	0.48 (0.12)	0.76[c]

[a] Number of samples.
[b] Coefficient of variation.
[c] Not significant at $\alpha = 0.05$.

Table 2. *Mechanical and physical properties of partially CAD-deficient and wild-type loblolly pine compared with those reported in ASTM D2555-96 for the loblolly pine population (ASTM 2006b).*

Property	Partially CAD-deficient	Wild-type	ASTM D2555-96 Mean	SD[a]	LL[b]	UL[c]
Static bending						
Modulus of rupture (MPa)	84.8	85.7	88.1	14.5	59.7	116.5
Modulus of elasticity (MPa)	7356	7178	12400	2830	6820	17930
Compression parallel to the grain						
Maximum crushing strength (MPa)	41.0	40.6	49.2	8.6	32.4	65.9
Shear						
Maximum strength (MPa)	10.6	10.8	9.6	1.2	7.1	12.0
Compression perpendicular to the grain						
Stress at proportional limit (MPa)	6.6	6.6	5.5	1.5	2.5	8.5
Tension perpendicular to the grain						
Maximum strength (MPa)	4.6	4.6	3.2	0.4	2.4	4.0
Specific gravity	0.49	0.48	0.47	0.05	0.37	0.57

[a] Standard deviation.
[b] 95% confidence interval lower limit.
[c] 95% confidence interval upper limit.

tween the two loblolly pine genotypes. The lack of significant difference in the specific gravity between partially CAD-deficient pine and wild-type pine (Table 1) strengthens the earlier findings that partial CAD deficiency had no effect on the mechanical properties. Similar results were obtained by Dimmel et al (2002) in a study of the density of 4-yr-old plants, which led them to suggest that partially CAD-deficient pine trees will likely be a good source of wood for lumber uses.

ASTM D2555-96 provides tabulated values for different mechanical properties of loblolly pine. The values for mechanical properties of wild-type and partially CAD-deficient pine were both within the 95% confidence interval of the values shown in ASTM D2555-96 for loblolly pine when adjusted to 12% MC (Table 2), except for maximum strength in tension perpendicular to the grain in which the values obtained for partially CAD-deficient and wild-type pine were above the upper limit.

CONCLUSIONS

This study showed no significant differences in static bending, compression parallel and perpendicular to the grain, tension perpendicular to the grain, or shear parallel to the grain in small clear specimens of 28-yr-old partially CAD-deficient vs wild-type loblolly pine. It follows that partial CAD deficiency does not significantly alter the mechanical properties of loblolly pine; therefore, there is no penalty for its use where "normal" loblolly pine lumber has end-use applications.

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