Analysis of acoustic velocity as a predictor of stiffness and strength in 5-inch-diameter pine dowels

R. Shmulsky*
R.D. Seale
R.D. Snow

Abstract

In an effort to optimize merchandizing and conversion of small-diameter trees, nondestructive assessment of mechanical properties may improve utilization and resultant product properties. This research tested the ability of acoustic velocity to predict bending stiffness and strength in 5-inch-diameter southern pine dowels. For nondestructive testing, a handheld receiver/computer was employed and used in conjunction with a 1.5-pound hammer (impactor). Acoustic velocity was measured in both green and dry dowels. Following drying and nondestructive testing, the dowels were destructively tested in bending under centerpoint loading. The best single-predictor correlation was observed between acoustic velocity (green) and stiffness (r^2 = 0.66), while correlation was poor for acoustic velocity (green) and strength (r^2 = 0.18). In each case, acoustic velocity (dry) was a less effective single predictor. Also in each case, the addition of the number of growth rings per inch as a predictor improved the regression model.

Meaningful efforts are ongoing at the regional and national levels to improve utilization options and markets for small-diameter trees. In addition to the vast quantities of such fiber in the western United States, a significant amount of such stems are available in the southeastern United States as plantation thinnings. Formerly, such woody fiber was channeled into pulp production; however, current global conditions limit continued domestic growth in that sector and there is therefore a surplus of these thinnings available for other markets.

Three potential value-added markets for small-diameter trees with high percentages of juvenile wood are lumber, structural composites, and structural round products. Lumber, both structural and appearance grade, can be claimed from plantation pine thinnings of sufficient diameter. Quality issues, especially related to warp, present challenges to production; however, processing technology is advancing such that greater proportions of higher value products are becoming possible. Significant markets for structural composites, both as panelized oriented strandboard (OSB) and plywood and as structural composite lumber (SCL) exist and expand annually. These products have much appeal in the sense that they turn low value small-diameter raw material into large-size dimensionally stable products that exhibit uniform performance. Growth and development of these markets is virtually certain because the raw materials are abundant and their utilization creates cost advantages in finished products.

There is also a potential market for relatively uncomminuted roundwood products. Small-diameter roundwood sections have a variety of benefits, including high product yield and good strength properties due to their straight and true grain from end to end and their fiber continuity about their knots (Wolfe and Murphy 2005). Products such as structural trusses and “rustic” or “log cabin” type construction are potential high-value outlets for these minimally converted round stems.

At the merchandizing stage of conversion, insight into the wood material’s ultimate performance is important with re-

The authors are, respectively, Associate Professor and Professor, Dept. of Forest Products, Mississippi State Univ., Mississippi State, MS (rshmulsky@cfr.msstate.edu; dseale@cfr.msstate.edu); and Graduate Research Assistant, Dept. of Forestry, College of Forest Resources, Forest and Wildlife Research Center, Mississippi State Univ. (rds45@msstate.edu). FWRC pub. no. FP349. This paper was received for publication in June 2005. Article No. 10071.
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Table 1. — Summary statistics for the measured properties.[a]

	V_G	V_D	R/in	MC_G	MC_D	SG_{17}	MOR	MOE
	------(ft/sec)------			------(%)------			(psi)	($\times 10^6$ psi)
Mean	10,024	13,764	5	75	17.2	0.45	9145	1.30
Median	10,236	14,239	4.8	72	16.5	0.44	8854	1.34
SD	1327	1630	1	16	3.4	0.048	1943	0.26
COV	13	12	23	21	20	11	21	20
N	69	69	69	5	69	17	64	64

[a]V_G and V_D = green and dry velocities, respectively; R/in = rings per inch; MC_G and MC_D = initial and final moisture percentages, respectively; SG_{17} = specific gravity at 17 percent MC for volume over ovendry weight; SD = standard deviation; COV = coefficient of variation in percent.

Table 2. — Prediction equations and r^2 values between the predictors (x): rings per inch (R/in), green velocity (V_G) as feet per second, dry velocity (V_D) as feet per second, and the response variable (y) MOE.

Independent variables	MOE	r^2
	(psi)	
R/in	y = 130,000 R/in + 693,000	0.30
V_G	y = 155 V_G − 252,00	0.66
V_D	y = 123 V_D − 391,000	0.63
$V_G \times R/in$	y = 135 V_G + 61,300 R/in − 338,000	0.72
$V_D \times R/in$	y = 109 V_D + 88,700 R/in − 606,000	0.76

spect to maximizing product mix value. At the processing stages of manufacturing, especially for composites, such insight is important because high-performance material can be directed into sectional areas that receive the most stress, within a given product. Examples of these areas are the extreme lamina of glulam and laminated veneer lumber and the flanges of I-joists. In the case of trusses, higher strength material is typically specified for the compression and tension chords, while lower performance material is directed to the webs.

Toward these ends, varying techniques of nondestructive testing have been proposed and developed. Traditionally, wood density has been used as a key predictor of mechanical properties (USDA 1999). Vibrational analysis and ultrasonic transmission properties have also been investigated. Experimental nondestructive analysis has been proven effective at assessing decay in standing trees (Wang et al. 2004), logs (Wang et al. 2001), and *in-situ* wood structures such as bridges (Ross et al. 1999). Other related work by Ross et al. (2005) on Douglas-fir peeler cores indicated that acoustic velocity correlated well to with modulus of elasticity (MOE). There, the product of the square of stress wave speed and wood density was termed stress wave MOE (MOE_{sw}). When compared to MOE_{sw}, elasticity of lumber sawn from their peeler cores and tested in static bending showed a correlation coefficient (r-value) of 0.68. The correlation coefficient for MOE in tension vs. MOE_{sw} was 0.84.

The fundamental concepts associated with nondestructive evaluation are well proven. A key task, however, has been refining technology to the point at which it is useful in commercial situations. The research detailed herein describes the how one type of nondestructive technology, acoustic wave propagation, performed at predicting the mechanical properties of small-diameter dowels and discusses some of the related implications and possibilities.

Methodology

A bundle consisting of 69 green loblolly pine posts (dowels), 8 feet long and 5 inches in diameter, was procured from a local mill. The dowels were of uniform section from end to end, that is, they had been processed through a doweling machine. This uniform section was specified because it greatly simplifies mechanical calculations as section modulus "z" = (pi r^3 / 4) is constant (Cheng 1997). Upon arrival at the laboratory, the green and untreated dowels were placed on the ground and numbered with indelible ink. Average number of growth rings per inch was measured. Acoustic velocity of each dowel was then measured. For acoustic velocity measurement, a commercially available handheld detection (receiver) instrument (Fiber-gen, a Carter Holt Harvey business) was used in conjunction with a 1.5-pound hammer (impactor). Input to the detection device included woody stem length only. Measurement required the following sequence: 1) press the detection sensor onto the end of the stem; 2) tap the same end of the stem with the hammer such that the device is excited while simultaneously the acoustic pulse is sent to the opposite end of the log and reflected back; 3) read the calculated acoustic velocity directly. Next a sample of five dowels was weighed such that an estimate of green moisture content (MC) could be calculated.

Dowels were then kiln-dried to approximately 17 percent MC as measured with a pin-type moisture meter. Kiln conditions were maintained at 180°F dry bulb and 140°F wet bulb throughout. Total drying time was approximately 4 days. Once dry, the acoustic velocity and MC of each dowel was measured. Dowels were then destructively tested to determine modulus of rupture (MOR) and MOE. The 8-foot-long dowels were tested by centerpoint loading across a clear span of 90 inches. Load was applied at 1.5 inches per minute until catastrophic failure occurred. Five dowels were not tested because their sections were not fully circular near midlength, i.e., significant wane was present. Following mechanical testing, specific gravity (SG) tests were conducted on a random sample of 17 dowels to ascertain the SG of the material.

Analysis

Summary statistics for the measured properties were calculated and are shown in **Table 1**. Next, correlations were developed using rings per inch (R/in), green velocity (V_G), dry velocity (V_D), and MOE as independent variables, and MOR and MOE as response variables. Both simple and multiple linear regression equations and r^2 values for these correlations are presented (**Tables 2** and **3**).

Results

Simple linear regression indicated that green acoustic velocity was the best single predictor of dowel stiffness (MOE), (r^2 = 0.66). Dry acoustic velocity ranked a close second (r^2 = 0.66), and rings per inch a distant third (r^2 = 0.30). With respect to maximum breaking stress (MOR), MOE was the best predictor; however, its correlation was mediocre at best (r^2 = 0.42). With respect to MOR, the other predictors, green velocity, dry velocity, and rings per inch, produced r^2 values of 0.18, 0.11, and 0.30, respectively.

Table 3. — Prediction equations and r^2 *values between the predictors* (x)*: rings per inch (R/in), green velocity* (V_G) *as feet per second, dry velocity* (V_D) *as feet per second, and MOE and the response variable* (y) *MOR.*

Independent variables	MOR	r^2
	(psi)	
R/in	$y = 973$ R/in + 4,620	0.30
V_G	$y = 0.601\ V_G + 3{,}140$	0.18
V_D	$y = 0.387\ V_D + 3{,}830$	0.11
MOE	$y = 0.0048$ MOE + 2870	0.42
$V_G \times R/in$	$y = 0.341\ V_G + 799$ R/in + 2020	0.35
$V_D \times R/in$	$y = 0.245\ V_D + 879$ R/in + 1700	0.34
$V_G \times MOE$	$y = -0.441\ V_G + 0.00672$ MOE + 4830	0.45
$V_D \times MOE$	$y = -0.5590\ V_D + 0.00769$ MOE + 6840	0.51
$R/in \times MOE$	$y = 490$ R/in + 0.00371 MOE + 2050	0.47
$V_G \times R/in \times MOE$	$y = -0.400\ V_G + 463$ R/in + 0.00548 MOE + 3870	0.50
$V_D \times R/in \times MOE$	$y = -0.461\ V_D + 304$ R/in + 0.00649 MOE + 5630	0.53

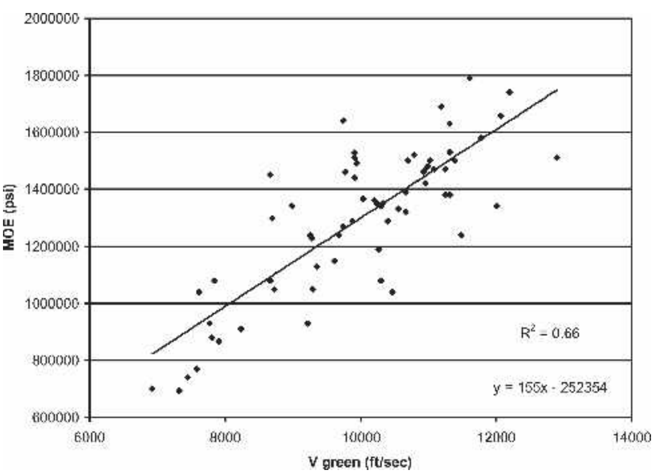

Figure 1. — Plot of acoustic velocity (green) vs. MOE.

Multiple linear regression indicated that models could be improved by utilizing combined predictors. For MOE, the two-predictor combination of dry velocity and rings per inch showed the highest correlation ($r^2 = 0.76$). For MOR, the two-predictor combination of dry velocity and MOE showed the highest correlation ($r^2 = 0.51$), and the highest three-predictor combination was that of dry velocity, rings per inch, and MOE ($r^2 = 0.53$).

Good agreement was noted between the population MC as measured with a pin-type meter after drying and the sample MC measured with an oven and scale as part of the SG sampling after mechanical testing. The values averaged 17.2 and 16.6 percent, respectively.

Discussion

In general, the acoustic velocity was a better predictor of stiffness than of ultimate stress. It is surmised that this relationship occurs because stiffness is considered a global quality, from end to end, as is acoustic velocity. Ultimate stress (MOR), however, is highly contingent upon the nature of defects that are localized at the point of maximum stress. As such, it is shown that acoustic velocity can be a meaningful and commercially viable tool for merchandizing and segregating small-diameter timber with respect to ultimate stiffness. It is recognized that such merchandizing and production decisions can occur at any time from initial harvesting through stem comminution and reconstitution.

In the case of this research, a sample of green MC showed a mean value of 75 percent and a SD of 16 percent. Despite this relatively wide range, green acoustic velocity was the best predictor of stiffness. **Figure 1** shows the fit of the model against the data. This information suggests that individual measures of stem MC values or rings per inch are not requisite for producing a meaningful MOE prediction model.

Because the acoustic detection instrument is handheld and is used at the same end of the stem as the impactor, its commercial application is relatively easy. With this technology, one individual can quickly and easily acquire a large amount of information regarding wood quality, namely as stiffness, and further processing can be optimized based on these results.

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