RELATIONSHIP OF STRESS WAVE- AND STATIC BENDING-DETERMINED PROPERTIES OF FOUR NORTHEASTERN HARDWOODS

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ABSTRACT

Stress wave modulus, velocity, and characteristic impedance of small, clear, straight-grained beams of sugar maple, yellow birch, white ash, and red oak were correlated with static bending MOE and MOR. Stress wave velocity increased in direct proportion to the square root of MOE for each species individually and for all four taken as a group. No meaningful relationship between wave velocity and specific gravity was found. Stress wave modulus was most strongly correlated with MOE, and characteristic impedance most strongly correlated with MOR for all species whether considered individually or as a group. Characteristic impedance, stress wave modulus, and MOE are nearly equally well correlated with MOR apparently because of their mutual relationship with specific gravity. No consistent differences in the relationships between stress wave- and static bending-determined properties were found for ring- versus diffuse-porous species.

Keywords: Nondestructive evaluation, stress wave, stress wave modulus, characteristic impedance, hardwood, mechnical properties.

INTRODUCTION

Various static elastic and strength properties of wood correlate with a dynamic elastic modulus based on the velocity at which longitudinal stress waves propagate through it. In his state-of-the-art review, Gerhards (1982) cited fifteen investigations in which meaningful correlations were found between the stress wave modulus (MSW) and the tensile, compressive, or flexural modulus (MOE) or strength (MOR) of lumber or veneer. He also summarized the effect various wood factors have on stress wave velocity (c), which ranges from 10,000 to 20,000 ft/sec parallel to the grain in defect-free wood at 9 to 15% moisture content (MC). Wave velocity 1) decreases as grain angle, wood temperature or moisture content increases; 2) is higher in latewood than in earlywood; 3) is decreased by the discontinuity and cross grain associated with knots; and 4) is lower in decayed wood, but 5) apparently unaffected in wood under stress. Elastic modulus values determined with stress waves are typically 10 to 20% higher than those determined with static tests. Gerhards concluded that for solid wood, the stress wave modulus is highly correlated with the static elastic modulus, but only moderately well correlated with static strength.

A related parameter, characteristic impedance (Z), has also shown promise in predicting the strength of wood. Equal to stress wave velocity times wood weight density (p_w), characteristic impedance is a measure of the resistance of the passage of sound waves parallel to the grain in wood. James (1964) found Z^2 to be more highly correlated with both static bending MOR and maximum crushing strength of Douglas-fir than MSW or density alone. Elvery and Nwokoye (1970) reported that for certain softwoods, Z was more highly correlated with maximum crushing strength than stress wave modulus.

Stress wave modulus and stress wave velocity and attenuation characteristics are also highly correlated with both static elastic and strength properties of particle- and flake-based wood composites (Pellerin and Morschauser 1973; Ross and Pellerin 1988).

The focus of most recent investigations has been towards realizing the potential of stress waves as a rapid, nondestructive means of stress grading softwood structural lumber. While a lumber grading system has yet to be commercialized, stress waves are presently being used to sort softwood veneers in commercial manufacture of parallel laminated veneer products (Logan 1987), and to assess the structural integrity of softwood carrying members in situ (Lanius et al. 1981).

Stress wave techniques have been applied to hardwoods only infrequently, but with results similar to those obtained for softwoods. Burmester (1965) reported good correlation between MSW and static bending MOE, with MSW exceeding MOE by 19 to 34%, for small, clear beams of beech and two tropical hardwoods. Correlation between wave velocity and MOR was "unsatisfactory." The velocity of stress waves in thin slices of aspen, red alder, yellow birch, sweetgum, and black cottonwood was well correlated with the tensile modulus of paper handsheets subsequently made from the macerated fibers of each (Yiannos and Taylor 1967). Stress wave velocity in one-inch cubes of yellow-poplar was found to decrease linearly with increasing moisture content within the hygroscopic range (Wen and Mohsenin 1970). A curvilinear relationship between velocity and moisture content outside the hygroscopic range was found by Gerhards (1975) using 8-foot sweetgum 2 by 4s. The ratio of MSW to flexural MOE decreased curvilinearly from 1.63 to 1.16 as lumber dried from 150 to 15% MC.

The effect of knots and grain angle with respect to instrument transducer alignment on stress wave velocity in hardwoods (Armstrong et al. 1990) and red oak veneer (Jung 1979) has been studied. Dean and Kaiserlik (1984) evaluated the potential of using stress waves to nondestructively screen hardwood specialty blanks. Linear and nonlinear regression models for predicting the static, rapid, and impact bending strengths of hickory, white ash, and sugar maple were based on stress wave transit time, MSW, MOE, and weight density. Static bending strengths were moderately well predicted by the models, while rapid and impact bending strengths were not. Regression constants, included variables, and accuracy of prediction varied widely among species and strength models.

The usefulness of characteristic impedance in predicting the static bending strength of hardwoods has not yet been studied. In this investigation relationships among stress wave velocity, characteristic impedance, stress wave modulus, and the static flexural moduli of elasticity and rupture of four eastern hardwoods were examined. The objective was to identify the stress wave parameters most highly correlated with static bending MOE and MOR. The results of this investigation may be useful in the nondestructive assessment of hardwood strength properties.

MATERIALS AND METHODS

Production-run turning blanks of sugar maple, yellow birch, white ash, and red oak obtained from a local furniture manufacturer were conditioned at 70 F and 66% RH until constant weight was achieved. Blanks were machined into 1-inch

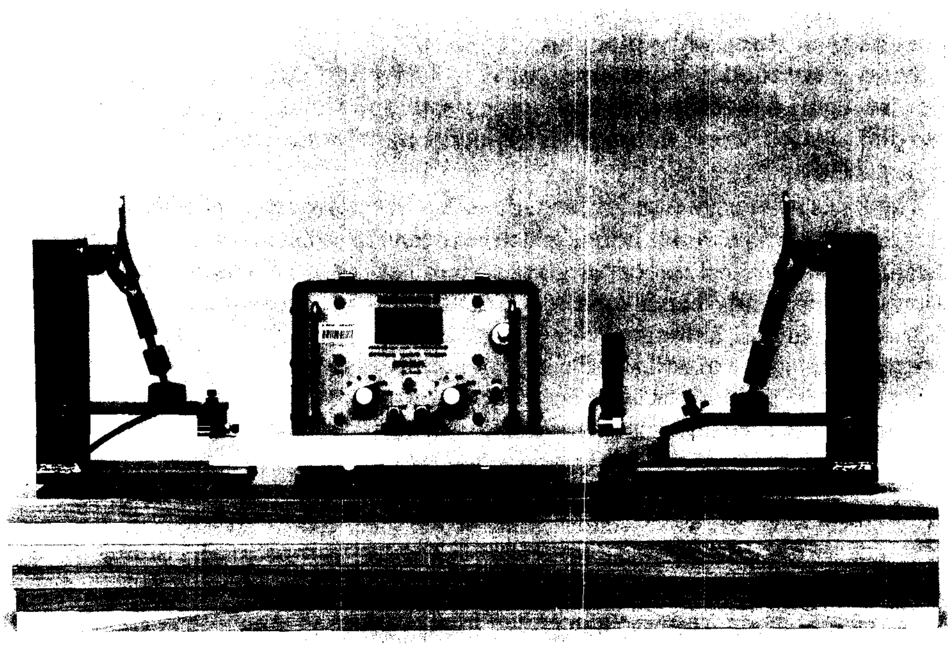


FIG. 1. Stress wave transit time apparatus. Pendulum impactor hangs inside right clamp.

by 1-inch by 16-inch straight-grained beams whose faces paralleled radial and tangential planes. A commercial device[1] was used to measure the time required for a longitudinal stress wave to propagate parallel to the grain over the central 14 inches of each beam (Fig. 1).

Instrument gain was fixed at the highest level unaffected by background vibration to maximize sensitivity. Transducers were clamped to each beam's pith-side tangential face at constant pressure. An independent clamp restraining one end of each beam was impacted with a pendulum released from a fixed height. The force exerted on the clamp induced a longitudinal stress wave in each beam one inch from the "start" transducer. With this test configuration a zero offset time correction, normally needed to account for noninstantaneous rise of the stress wave signal, was found unnecessary. Wave propagation times were measured to 0.1 microseconds.

The stress wave modulus (lb/in.^{2}) was computed as:

$$MSW = c^2 p_m \tag{1}$$

where c equals stress wave velocity (in./sec) and p_m is wood mass density (lb sec^2/in.^{4}). The latter is equal to wood weight density (weight of wood and moisture divided by volume of wood and moisture) in lb/in.^{3} divided by the gravitational constant (386 in./sec^2).

[1] Metriguard 239A Stress Wave Timer, Metriguard Inc., Pullman, WA.

Characteristic impedance[2] (lb/ft^2 sec), was computed as:

$$Z = cp_w. \tag{2}$$

Here c has units of ft/sec, and p_w equals wood weight density in lb/ft^3.

Static bending MOE and MOR were determined as per ASTM D-143 Secondary Methods (ASTM 1986). Deflection due to shear was unaccounted for in calculating MOE. Wood percent moisture content and specific gravity (sp gr) at test (based on oven-dry weight and weight of the displaced volume of water) were determined from two adjacent one-inch cubes taken near the zone of failure.

Relationships among stress wave velocity, characteristic impedance, stress wave modulus, and static bending moduli of elasticity and rupture were assumed to be of the form:

$$SB = a(SW)^b \tag{3}$$

where SB is static bending MOE or MOR, and SW represents c^2, Z, or MSW. Empirical constants a and b were evaluated for seven different relationships for each species, as well as for all species taken as a group, by performing simple linear regression on the linearized form of Eq. (3):

$$\ln SB = \ln a + b \ln SW. \tag{4}$$

Regression-derived values of ln SB were then calculated for each relationship by substituting observed values of SW into the appropriate regression expression. The differences between the antilogs of regression-derived values of SB and observed values of SB, i.e., $(SB_{reg} - SB_{obs})$ were then plotted versus SB_{obs}.

The strength of relationships between stress wave velocity, characteristic impedance, stress wave modulus, and static bending MOE and MOR was judged quantitatively on the basis of correlation coefficients derived from Eq. (4), and qualitatively by the degree to which the plotted differences between regression-derived and observed values of static bending MOE and MOR were clustered about zero over the range of observed values (Figs. 4–10).

RESULTS AND DISCUSSION

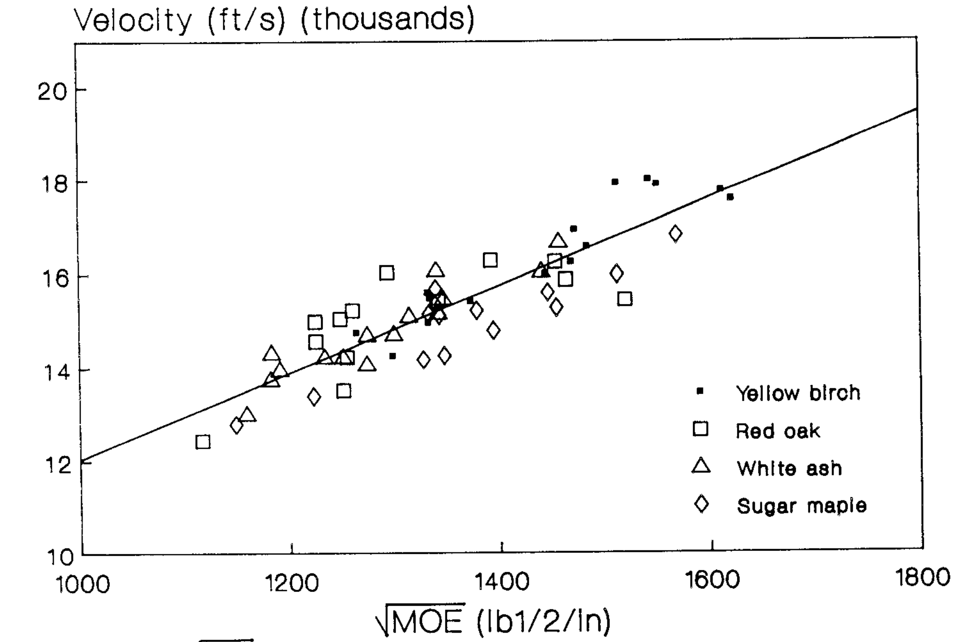
The mean observed mechanical and physical properties of the four hardwoods studied are summarized in Table 1. Specific gravity and static bending properties for each species compared favorably with recognized mean values (Forest Products Laboratory 1987).

The velocity at which longitudinal stress waves propagate through a material is directly proportional to the square root of its elastic modulus, and inversely proportional to the square root of its mass density:

$$c = \frac{\sqrt{MSW}}{\sqrt{p_m}} \tag{5}$$

For most solids wave velocity increases with increasing elastic modulus (Malecki 1969; Rinehart 1975). Such was the case for the hardwoods of this study. Good correlation between wave velocity and the square root of MOE was found for

[2] The SI unit for characteristic impedance is the rayl (kg/m^2 sec).



$c = 2819 + 9.2218\sqrt{MOE}$ $r = 0.89$

FIG. 2. Stress wave velocity as a function of square root of MOE.

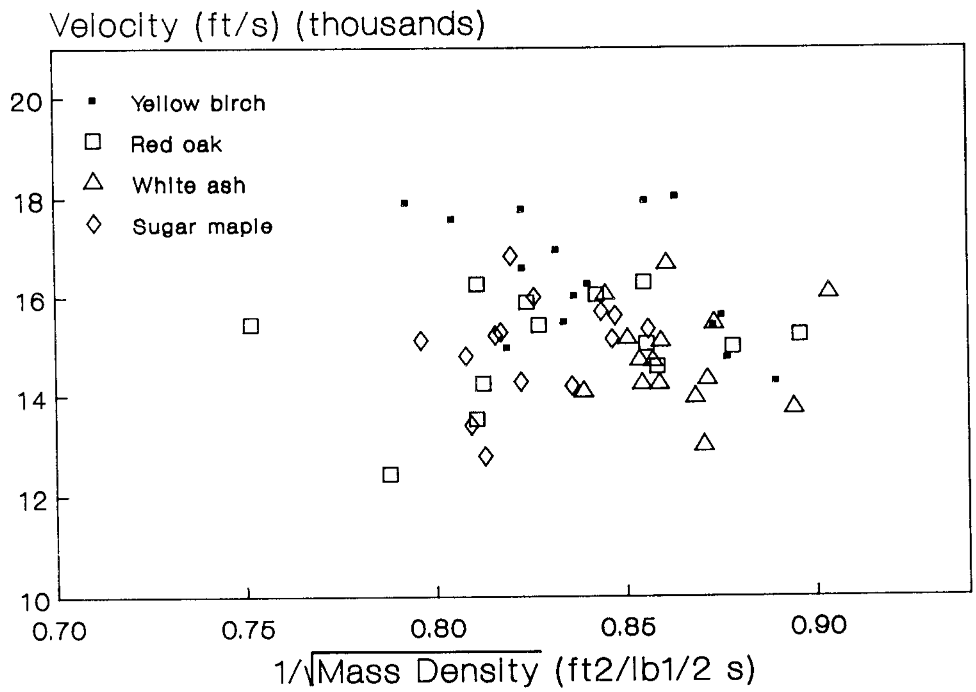


FIG. 3. Stress wave velocity and its lack of relationship with reciprocal of square root of mass density.

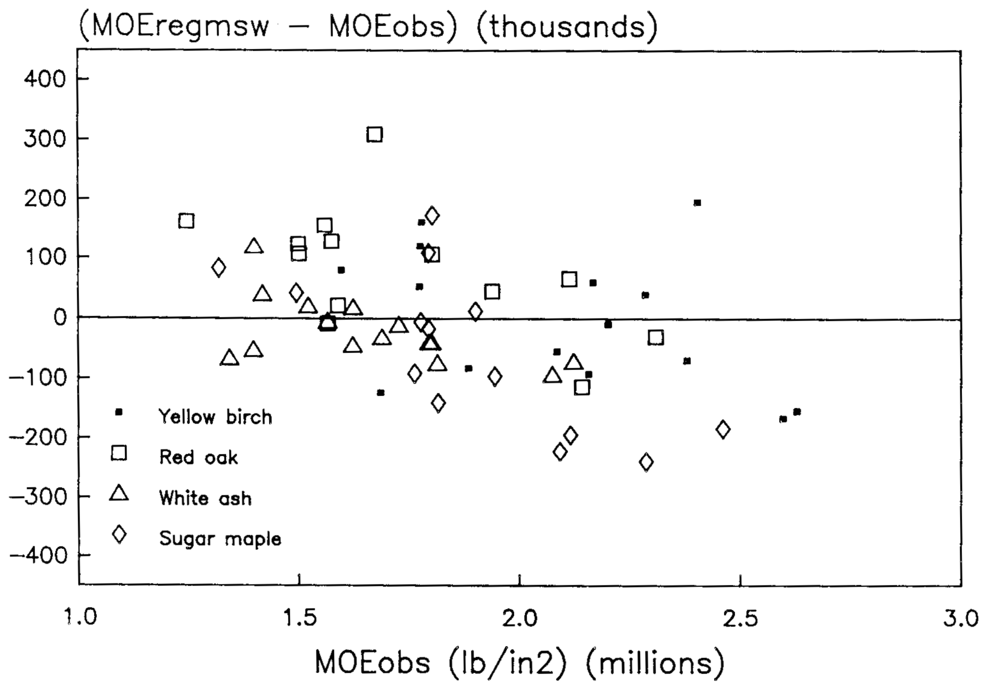


FIG. 4. Residual difference between regression-derived MOE obtained from ln-ln correlation with MSW and observed MOE over the range of observed MOE.

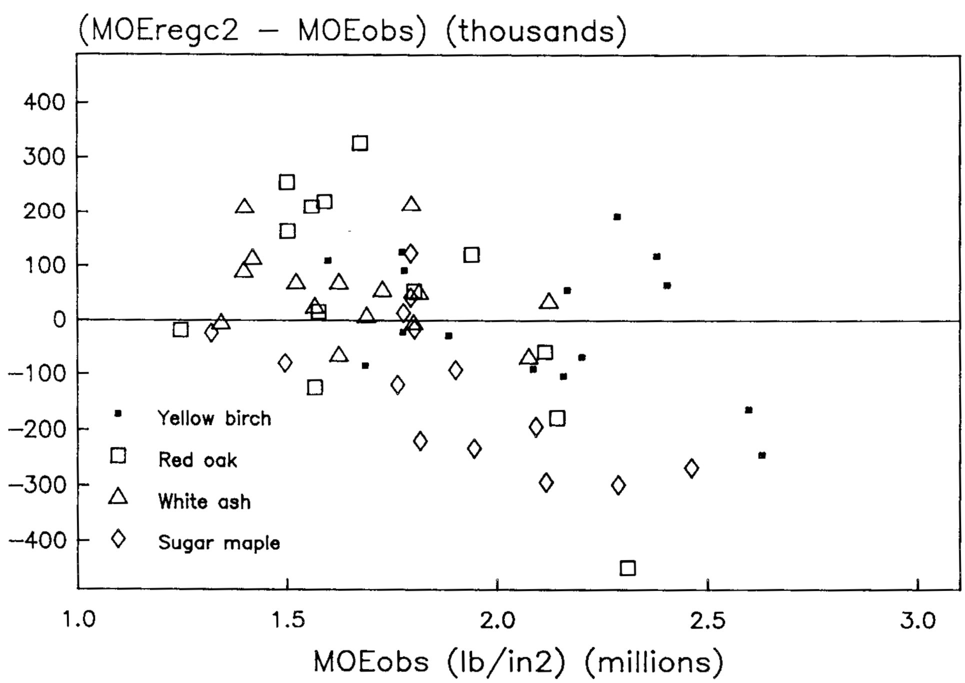


FIG. 5. Residual difference between regression-derived MOE obtained from ln-ln correlation with c^2 and observed MOE over the range of observed MOE.

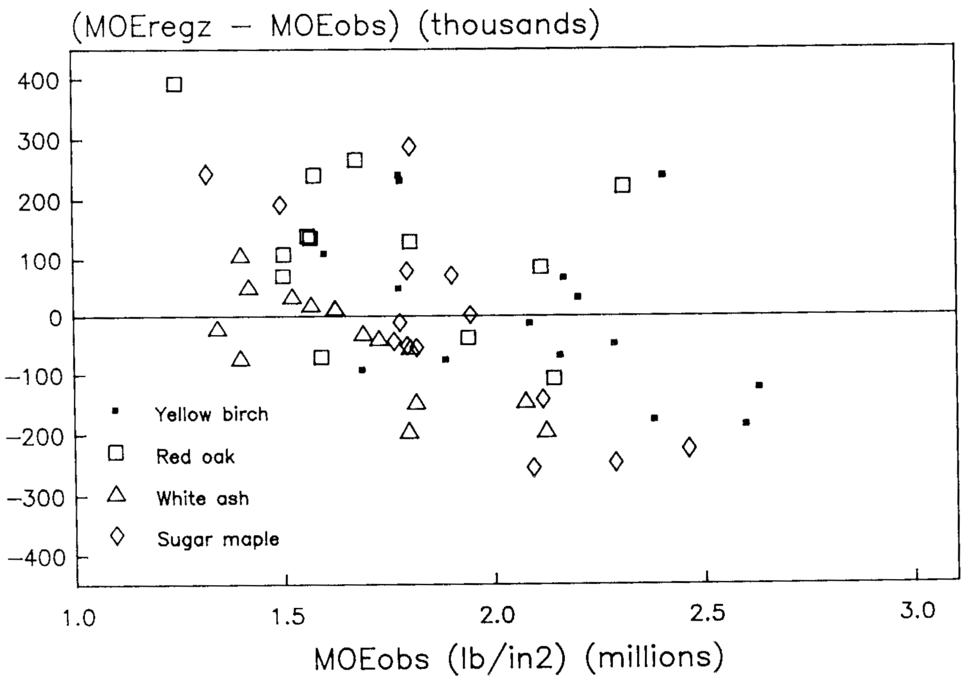


FIG. 6. Residual difference between regression-derived MOE obtained from ln-ln correlation with Z and observed MOE over the range of observed MOE.

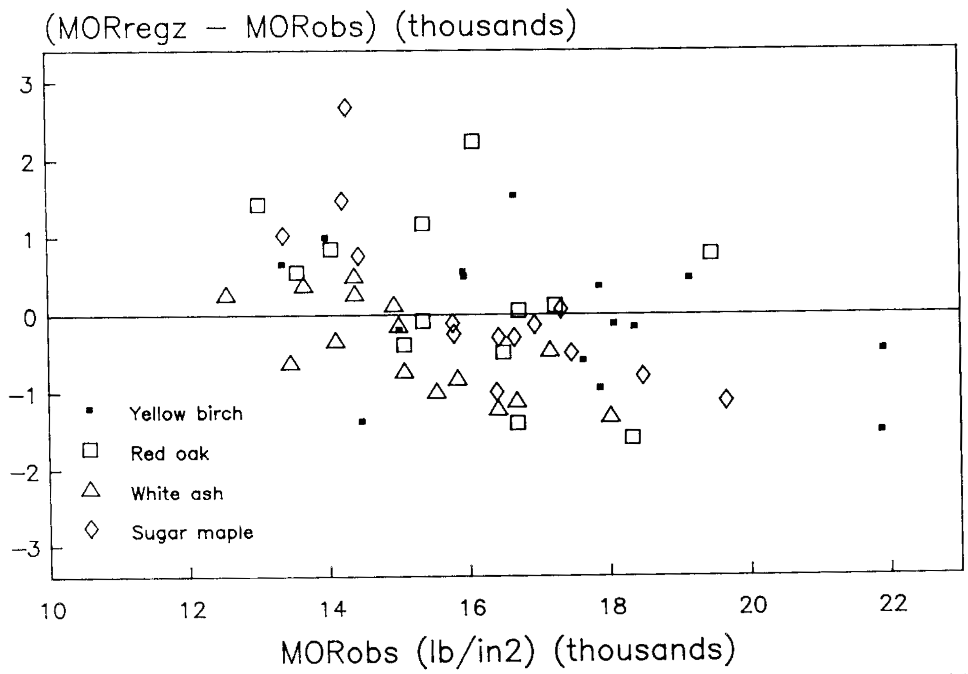


FIG. 7. Residual difference between regression-derived MOR obtained from ln-ln correlation with Z and observed MOR over the range of observed MOR.

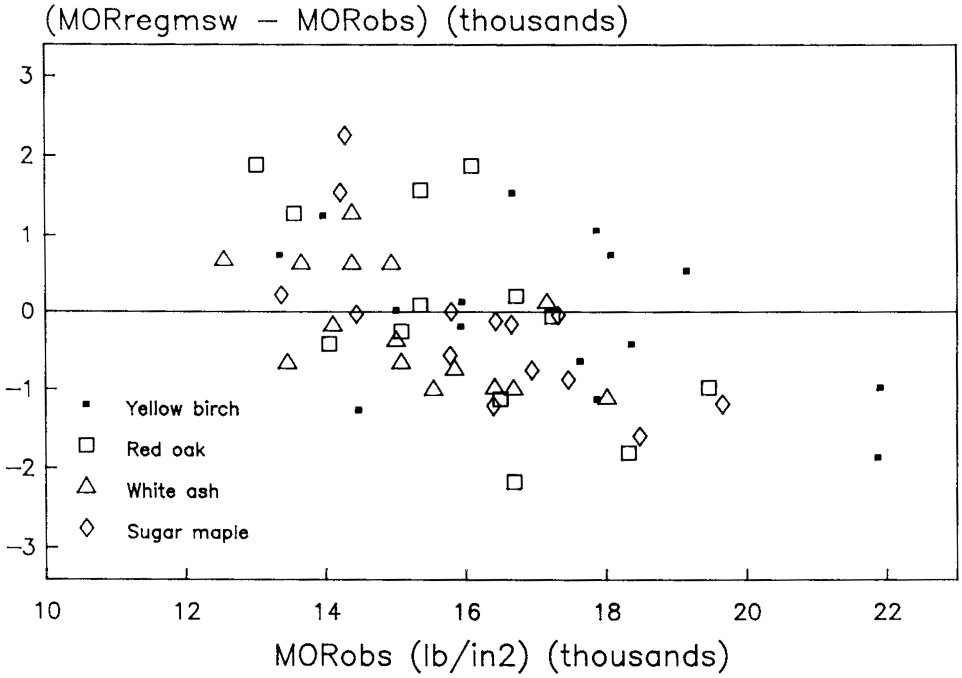


FIG. 8. Residual difference between regression-derived MOR obtained from ln-ln correlation with MSW and observed MOR over the range of observed MOR.

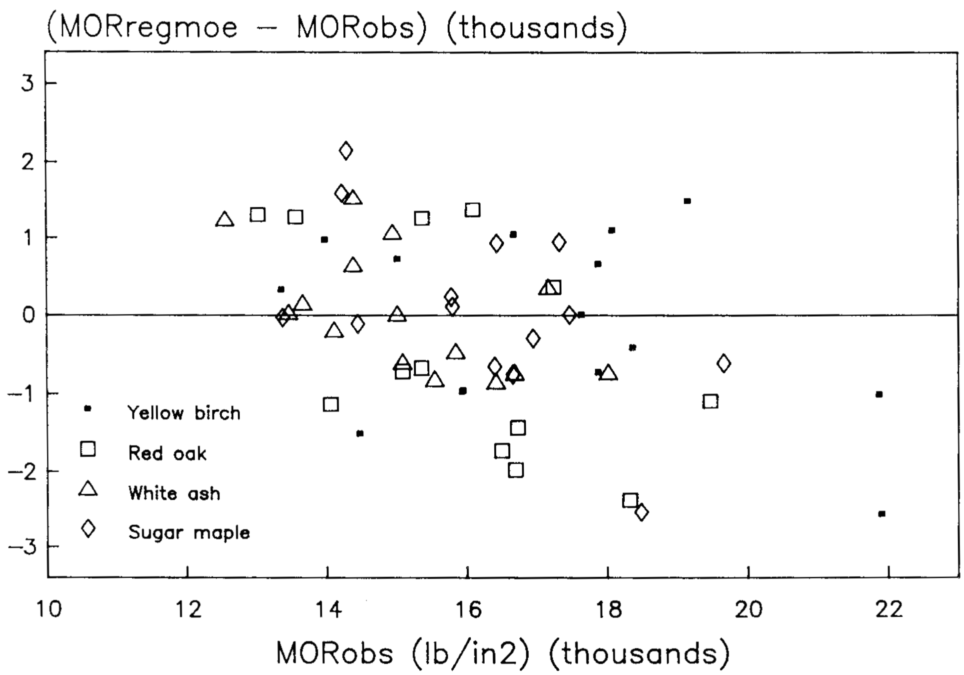


FIG. 9. Residual difference between regression-derived MOR obtained from ln-ln correlation with MOE and observed MOR over the range of observed MOR.

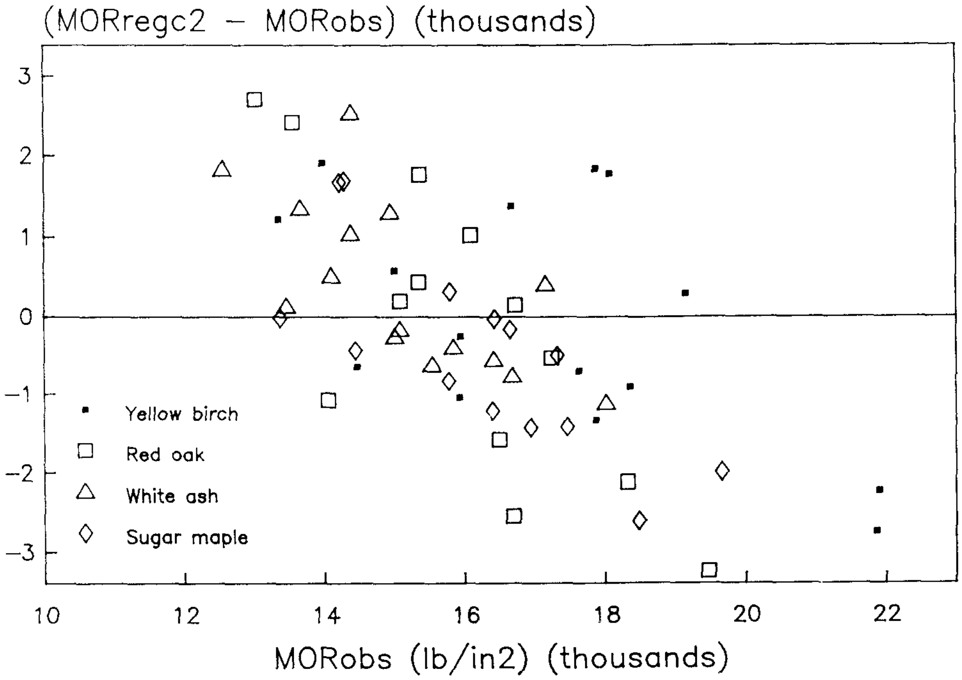


FIG. 10. Residual difference between regression-derived MOR obtained from ln-ln correlation with c^2 and observed MOR over the range of observed MOR.

each species individually, and for all four species taken as a group, despite the limited range of specific gravity represented (0.53–0.80) (Fig. 2). The highest mean wave velocity and MOE were measured in birch; both were significantly different from those of the other species (Table 1).

Also for most solids wave velocity decreases with increasing mass density (Malecki 1969; Rinehart 1975). This generalization, however, does not hold true for wood for two reasons. (N.B. In light of the convertibility of mass density, weight density, and specific gravity, the more familiar term specific gravity will be used here for convenience.) First, in the case of a porous material such as wood, specific gravity reflects the amount of actual cell-wall substance present in a given volume. Though the specific gravity of cell-wall substance is constant at about 1.5 for all woods, the volume occupied by cell lumina, pits, intercellular spaces, and cell-wall microvoids varies tremendously. Because voids affect only volume, the specific gravity of domestic woods ranges from about 0.3 (large void volume) to 0.8 (small void volume). Since the route by which stress waves propagate in wood is through its cell-wall substance, no meaningful correlation between stress wave velocity and wood specific gravity (or in this case mass density) would be expected, nor was found (Fig. 3).

Secondly, the static elastic modulus and specific gravity of native woods tend to increase at a constant ratio of about 3×10^6 for hardwoods and 3.5×10^6 for softwoods (Forest Products Laboratory 1987). Since the range of values for MOE/sp gr is relatively narrow, the variability of stress wave velocity in wood likewise would be expected to be narrow (Table 1). One effect of this trend is that wave

TABLE 1. *Mechanical and physical properties of four eastern hardwoods.*†

	Stress wave			Static bending			
	Velocity (ft/sec)	MSW (lb/in.^{2})	Z (lb/ft^2 sec)	MOE (lb/in.^{2})	MOR (lb/in.^{2})	mc (%)	Specific gravity
Sugar maple	14,990	2,300,000	707,950	1,883,900	16,200	11.9	0.66
n = 14	1,030	298,790	49,100	293,460	1,750	0.64	0.04
	12,790–16,820	1,719,800–2,922,200	622,670–804,560	1,320,100–2,461,800	13,380–19,660	10.4–12.7	0.57–0.72
Yellow birch	16,370#	2,657,800*	746,030	2,094,100#	17,200	11.3	0.64
n = 15	1,280	521,570	94,310	331,050	2,560	0.39	0.04
	14,270–18,020	1,787,200–3,546,100	580,240–917,090	1,597,900–2,629,100	13,350–21,900	10.8–12.1	0.58–0.71
White ash	14,770	2,040,000	637,150*	1,662,100	15,150	12.1	0.61*
n = 15	990	285,900	49,630	236,100	1,490	0.21	0.03
	13,000–16,680	1,550,700–2,605,700	552,190–723,640	1,344,200–2,124,000	12,560–18,020	11.8–12.5	0.57–0.67
Red oak	15,000	2,282,000	701,880	1,732,000	15,960	10.7	0.66
n = 13	1,120	363,120	75,990	308,710	1,830	0.48	0.07
	12,440–16,280	1,728,000–2,926,000	624,830–879,050	1,247,200–2,310,200	13,030–19,470	10.0–11.6	0.53–0.80

† For each species, the mean is given in the first row, standard deviation in the second, and range in the third; n is the number of replications.
\# Significantly different at $\alpha = 0.01$ using Duncan's Multiple Range Test.
* Significantly different at $\alpha = 0.05$ using Duncan's Multiple Range Test.

TABLE 2. *Correlation of stress wave- and static bending-determined properties using the linear model ln SB = ln a + b ln SW.*†

	SW	MOE			MOR		
		ln a	b	*r*	ln a	b	*r*
Sugar maple	MSW	−1.6641	1.0998	0.92	0.1139	0.6540	0.80
n = 14	c^2	−5.2976	1.0264	0.91	−0.9367	0.5527	0.72
	Z	−11.5533	1.9298	0.84	−7.3742	1.2670	0.81
	MOE	—	—	—	2.1641	0.5212	0.77
Yellow birch	MSW	3.5567	0.7436	0.94	−0.1797	0.6716	0.92
n = 15	c^2	−3.9291	0.9521	0.94	−5.3094	0.7759	0.82
	Z	−0.3879	1.1054	0.92	−4.8149	1.0772	0.93
	MOE	—	—	—	−2.5723	0.8468	0.91
White ash	MSW	0.3184	0.9640	0.97	1.0050	0.5934	0.85
n = 15	c^2	−4.3514	0.9724	0.93	−0.2098	0.5121	0.70
	Z	−7.9826	1.6687	0.94	−5.7926	1.1536	0.92
	MOE	—	—	—	1.1133	0.5944	0.85
Red oak	MSW	−0.9392	1.0452	0.95	2.4029	0.4969	0.68
n = 13	c^2	−2.1874	0.8601	0.76	5.4914	0.2174	0.29
	Z	−5.2119	1.4538	0.87	−2.4758	0.9027	0.82
	MOE	—	—	—	3.2975	0.4442	0.67
All species	MSW	1.0372	0.9136	0.93	1.2146	0.5783	0.85
n = 57	c^2	−4.1006	0.9610	0.89	−0.2679	0.5164	0.69
	Z	−4.3847	1.3976	0.87	−3.5857	0.9864	0.88
	MOE	—	—	—	1.4543	0.5708	0.82

† Units: MOE, MOR, MSW (lb/in.^{2}); Z (lb/ft^2 sec); c (ft/sec).

velocity in a low specific gravity softwood may be as great as, or greater than, in a high specific gravity hardwood at the same moisture content. McDonald (1979), for example, reported a wave velocity of 19,200 ft/sec for dry Western redcedar (sp gr 0.32), while the highest value measured in this study was 18,020 ft/sec for birch (sp gr 0.62).

Relationship of stress wave velocity, characteristic impedance, stress wave modulus, and static bending MOE

Stress wave modulus was found to be the stress wave property most highly correlated with MOE for each of the four hardwoods individually, as well as when considered as a group (Table 2). Observed values of MSW for maple, birch, ash, and oak were on average 22, 27, 23, and 32% higher than observed values of MOE, respectively. The results corroborate those obtained by Burmester (1965) for European beech and two tropical hardwoods, and are in keeping with the generalization that elastic modulus values measured with dynamic methods are higher than those determined with static tests.

The wide range of differences between MSW and MOE reported by various investigators and tabulated by Gerhards (1982) are apparently relative rather than absolute, and due in large part to differing experimental techniques. With the instrumentation of this study, for example, stress wave propagation time over the fixed distance between "start" and "stop" transducers was found to vary with transducer sensitivity. Normally, sensitivity is maximized by adjusting the gain of each transducer channel to the highest level at which it is unaffected by extraneous vibration. With both channels are set at the same gain, sensitivity is maximized at the highest setting, and the shortest wave transit times are measured. If both channels are reset to an identical, but lower, gain setting, sensitivity is reduced, and longer transit times result. Shorter transit time translates to higher wave velocity and higher MSW, while longer transit time means lower velocity and lower MSW. For a fixed distance on a given specimen, then, stress wave transit time, velocity, and MSW are affected by transducer sensitivity. Galligan and Courteau (1965), for example, tailored their technique for measuring stress wave transit time so that it yielded a MSW virtually equal to MOE. Though the percent difference between the values of MSW and MOE varies with experimental technique, correlation between the two nevertheless remains consistently strong.

Wave velocity squared and characteristic impedance were less well correlated with MOE than was MSW. The possibility of species/structure effects on wave velocity and impedance was considered, as c^2 was better correlated with MOE for maple and birch which are diffuse-porous, while Z was more strongly correlated with MOE for ring-porous ash and oak. The large differences in specific gravity and modulus of earlywood and latewood in ring-porous hardwoods that are essentially absent in diffuse-porous hardwoods might form the basis for such effects. In light of the small differences between correlation coefficients, and the absence of this trend when c^2 and Z were correlated with MOR (see below), evidence for such effects was inconclusive.

The small differences between correlation coefficients indicate that a similarly strong relationship exists between MOE and MSW, c^2, and Z. Stress wave modulus is clearly most strongly related to MOE, as the residual differences between regression-derived values for MOE obtained from correlation with MSW and observed values of MOE ($MOE_{regmsw} - MOE_{obs}$) were more tightly clustered about zero over the range of observed MOE (Fig. 4) than corresponding residual differences for MOE correlated with either wave velocity squared (Fig. 5) or impedance (Fig. 6).

Relationship of stress wave velocity, characteristic impedance, stress wave modulus, static bending MOE, and static bending MOR

The stress wave property most highly correlated with MOR for each of the four hardwoods individually, as well as when considered as a group, was characteristic impedance, with stress wave modulus next most highly correlated with MOR (Table 2). The results mirror those of Elvery and Nwokoye (1970), who found that impedance was more highly correlated with maximum crushing strength of certain softwoods than MSW. Similarly, James (1964) reported that Z^2 was more highly correlated with maximum crushing strength of Douglas-fir than MSW. After considering MOE, MSW, c, and weight density, Dean and Kaiserlik (1984) concluded that MSW was most highly correlated with MOR for hickory, ash, and sugar maple. They reported a correlation coefficient of $r = 0.69$ between MSW and MOR for ash, compared to $r = 0.85$ found in the present study.

Static bending MOE was nearly as well correlated with MOR as was MSW, while wave velocity squared was weakly correlated with MOR. No species/structure effects were suggested, as the rank ordering of the strength of the relationship between each property and MOR based on correlation coefficients was consistent whether the woods were considered separately, as diffuse- and ring-porous, or as a group.

Characteristic impedance is clearly most strongly related to MOR, as the residual differences between regression-derived values for MOR obtained from correlation with Z and observed values of MOR ($MOR_{regz} - MOR_{obs}$) were more tightly clustered about zero over the range of observed MOR (Fig. 7) than corresponding residual differences for MOR correlated with either MSW (Fig. 8), MOE (Fig. 9) or wave velocity squared (Fig. 10).

Characteristic impedance, stress wave modulus, and static bending MOE are nearly equally well correlated with static bending MOR. This arises because each increases in proportion to increasing wood specific gravity, the single most important determinant of the bending strength of clear, straight-grained wood. Wave velocity squared was the least well correlated with bending strength because no meaningful relationship exists between it and wood specific gravity. Characteristic impedance and stress wave modulus are likely the most highly correlated with MOR because two factors related to bending strength—specific gravity and wave velocity—are combined in each. Wave velocity and strength are indirectly related through their mutual relationship with MOE: both c and MOR increase with increasing MOE.

SUMMARY

Relationships among stress wave velocity, stress wave modulus, characteristic impedance, and the static flexural moduli of elasticity and rupture of four eastern hardwoods were examined. While wave velocity was found to increase in direct proportion to the square root of MOE for each species considered separately and for all four taken as a group ($r = 0.89$), no meaningful relationship existed between wave velocity and wood specific gravity. Stress wave modulus was most strongly correlated with MOE for all species whether considered individually or as a group ($r = 0.93$). Wave velocity squared ($r = 0.89$) and characteristic impedance ($r = 0.87$) were only slightly less well correlated with MOE. Characteristic impedance was most strongly correlated with MOR for all species whether considered individually or as a group ($r = 0.88$). Both MSW ($r = 0.85$) and MOE ($r = 0.82$) were only slightly less well correlated with MOR. Wave velocity squared was weakly correlated with MOR ($r = 0.69$). Characteristic impedance, MSW, and MOE are apparently well correlated with MOR because of their mutual relationship with specific gravity. No consistent differences in the relationships between stress wave- and static bending-determined properties were found for ring- versus diffuse-porous species.

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