Stress-wave velocity of wood-based panels: Effect of moisture, product type, and material direction

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Abstract

The effect of moisture on longitudinal stress-wave velocity (SWV), bending stiffness. and bending strength of commercial oriented strandboard, plywood. particleboard. and southern pine lumber was evaluated. It was shown that the stress-wave verocity decreased in general with increases in panel moisture content (MC). At a given MC level. SWV varied with panel type and test directions. Regression equations relating SWV to MC and bending properties (modulus of elasticity [MOE] and modulus of rupture [MOR]) were established for various products. Both MOE and MOR at different MCs can be estimated by observing the speed of propagation of a longitudinal wave. This information is useful for developing moisture correction factors on the stress-wave related properties for wood-based panel products.

In the forest products industry. nondestructive evaluation (NDE) technology has been developed and is now used in structural product grading programs, which has resulted in engineered material with well-defined performance characteristics (Pellerin and Morschauser 1973, Ross 1984, Ross and Pellerin 1994). One NDE technique, which uses stress-wave propagation characteristics. has received considerable attention. Stress-wave-based NDE techniques have been investigated extensively during the past few decades and have shown promise for predicting the mechanical properties of wood in dry conditions (Pellerin and Ross 2002). Recent research has focused on determining whether stress-wave techniques could be used to evaluate the mechanical properties of green materials (such as trees, logs. green lumber and green veneer, etc.) and tu assess the structural condition of moisture-affected wood members in service (Ross and Pellerin 1991, 1994; Wang et al. 2001, 2002: Brashaw et al. 2004). For reliable application of the technique, the influences of various factors on measured results have to be considered.

Moisture is one of the many important variables that affect the magnitude of the stress-wave properties. In solid wood, stress-wave velocity (SWV) has been shown to decrease as moisture content (MC) of wood increases (Gerhards 1975, 1982). In air-dry conditions (9% to 15% MC). SWV has been reported to range from about 3000 to 6000 m/s in wood parallel to the grain. The velocity is affected by about 1 percent per percent of MC change in the hygroscopic range.

The influence of moisture on stress-wave properties (i.e., SWV. stress-wave modulus, etc.) for panel products is complicated by the fact that wood-based panels swell considerably during moisture up-taking. The swelling is often accompanied with internal bond failure and thus internal structure change (Wu and Suchsland 1997, Wu and Piao 1999). As a result, stress-wave properties of wood panels are expected to be considerably altered by moisture changes as compared to solid wood. Establishing correlations between stress-wave propertics and strength of panel products under swelling conditions may lead to a quick and reliable way to assess, for example, the safety margins of structural panels in applications.

The objectives of this study were to 1) assess effects of moisture on stress-wave velocity in wood-based panels as influenced by product type and test directions; and 2) establish predictive equations for bending modulus of elasticity (MOE) and modulus of rupture (MOR) based on measured stress-wave velocity.

Materials and methods

Five commercial oriented strandboards (OSBs) (two mixed hardwood sheathings. two southern pine sheathings. and one

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Table 1. — Basic properties of the materials used in the study.

Material type	Thickness	Specimen size
	(mm)	(mm by mm)
Solid wood (SW), southern pine	19	89 by 508
Plywood (PLW), southern pine	12	76 by 432
OSB - Mixed hardwood sheathing 1 (MHS1)	12	76 by 330
Mixed hardwood sheathing 2 (MHS2)	11	76 by 318
Southern pine sheathing 1 (SPS1)	12	76 by 330
Southern pine sheathing 2 (SPS2)	11	76 by 318
Southern pine flooring (SPF)	18	76 by 483
Particleboard (PB), southern pine	16	76 by 330

southern pine flooring), one southern pine construction plywood (3-ply). one southern pine interior particleboard, and 1- by 4-inch (19- by 89-mm) solid southern pine lumber were selected for the study. Sixty specimens were cut from each composite panel product along two principal directions. 30 along the parallel direction and 30 along the perpendicular direction. Thirty specimens were cut from southern pine lumber along the longitudinal direction. The sizes of the specimens are shown in **Table 1.** The specimens of each product type were randomly divided into six groups with five specimens in each group. They were labeled according to board type. group number, and replications. Separate groups of specimens were initially dried at 60°C to reach a constant weight (dry condition), and then conditioned in a climate-controlled conditioning chamber at 55, 75, 85, and 94 percent relative humidity (RH) and 25°C for obtaining four corresponding target equilibrium MCs of 8, 12, 17, and 25 percent. During conditioning at a given RH level, two samples were selected from each group. and the sample weight was monitored until reaching constant weight. Time to reach equilibrium MC varied for each RH step. For comparison, a 24-hour water soaking test was also conducted. Specimen weight and sizes before and after conditioning were measured. Specimen thickness swelling (TS) was calculated based on the thickness change before and after conditioning.

A Metriguard 239A stress-wave timer **(Fig. 1)** was used to measure the time required for a longitudinal stress-wave to propagate along the long dimension of each specimen after conditioning. The zero offset time ofthe machine was established to be 11.5 µs using the method recommended by the timer manufacturer. Stress-wave velocity was calculated from measured propagation time (after subtracting the zero offset time) and specimen length. Flatwise static bending tests were then performed on all specimens based on ASTM D 1037-96a (ASTM 1998) to determine bending MOE and MOR. Tests were conducted in a three-point bending mode over an effective span of 24 times the specimen nominal thickness. Finally. all specimens were ovendried to determine their MC on the ovendry basis.

A nonlinear regression analysis based on a backward selection procedure (SAS 1996) was performed to establish relationships between SWV (m/s) and MC (%):

$$\mathrm{SWV} = a + b\,\mathrm{MC} + c\,\mathrm{MC}^2 + \mathrm{d}\,\mathrm{MC}^3 + \mathrm{e}\,\mathrm{MC}^4 \qquad [1]$$

where *a, b, c, d* and *e* are regression coefficients. The backward selection procedure removed insignificant terms (at the 5% confidence level) from the model. Finally, relationships between bending properties (MOE/MOR) and SWV at various levels of MC were established using a linear model.

Figure 1. — Stress-warre testing equipment.

Results and discussion

Testing data on specimen specific gravity (SG), MC, TS, static bending MOE and MOR, and SWV in the longitudinal direction for southern pine lumber and in both parallel and perpendicular directions for OSB, plywood, and particleboard are summarized in **Table 2.**

Moisture-related thickness swelling

All materials swelled in the thickness direction due to MC increases **(Table 2).** The magnitudes of the swelling are comparable for solid wood and plywood **(Fig. 2),** indicating a similar swelling behavior of the two products. The swelling of OSB and particleboard followed a similar trend as the solid wood at MC levels below about 10 percent. Further MC increase. however. led to significant thickness swelling in both OSB and particleboard. This large TS of OSB and particleboard at higher MC levels was a result of the combined effect of the compression stress release from the pressing operation and differential swelling potential due to inherent in-plane density variation. The latter results in normal swelling stresses between high and low density areas in the plane of the panel. These stresses are often large enough to break the adhesive bonds, reading to significant thickness swelling.

Stress-wave velocity

Among the products tested, southern pine lumber had the largest SWV at a given MC level. The SWV decreased as wood MC increased, as expected from the known effect of moisture on the stiffness of wood **(Table 2** and **Fig. 3).** At the 0.6 percent MC level, the velocity averaged about 5900 m/s. The speed reduced to about 4900 m/s at the 23 percent MC level. There was about a 17 percent reduction in SWV for the 22.4 percentage unit increase in wood MC. These data are compared to a 15 percent reduction for a 27 percentage unit MC increase in pine (Burmester 1965) and a 13 percent reduction for a 25 percentage unit MC increase in Douglas-fir (James 1961).

Figure 4 shows the plot of SWV in southern pine lumber as a function of MC in the hygoscopic range. Also shown in **Figure 4** are the velocity data of Douglas-fir (James 1961). yellow-poplar (Wen and Mohsenin 1970), and pine (Burmester 1965). The velocity data for southern pine from this study show a similar trend as the data for Douglas-fir and yel-

Table 2. — Summary of rest data on specimens.[a]

Product type	Parallel direction						Perpendicular direction					
	SG	MC	TS	MOE	MOR	SWV	SG	MC	TS	MOE	MOR	SWV
		---- (%) ----		(GPa)	(MPa)	(m/s)		---- (%) ----		(GPa)	(MPa)	(m/s)
SW	0.56	0.6	1.2	16.01 (2.65)	127.50 (19.21)	5898.2 (246.9)	--	--	--	--	--	--
	0.54	10.9	2.4	13.78 (1.88)	92.15 (10.79)	5641.8 (293.5)	--	--	--	--	--	--
	0.61	14.2	6.7	12.62 (2.26)	89.33 (12.13)	5068.8 (534.3)	--	--	--	--	--	--
	0.59	19.7	9.1	11.62 (1.73)	71.66 (8.50)	4896.7 (132.7)	--	--	--	--	--	--
	0.50	23.6	9.4	11.10 (0.34)	57.14 (2.59)	4950.0 (48.6)	--	--	--	--	--	--
	0.52	50.9	9.4	8.28 (1.27)	43.73 (2.24)	4235.9 (243.3)	--	--	--	--	--	--
PLW	0.55	0.5	0.2	9.30 (1.06)	56.11 (12.6)	4804.9 (434.8)	0.53	0.5	0.2	1.18 (0.12)	9.61 (1.25)	2832.5 (130.8)
	0.56	9.4	2.7	9.26 (0.35)	66.96 (9.22)	4833.2 (229.9)	0.56	9.2	2.2	1.51 (0.22)	23.0 (0.73)	3300.2 (604.7)
	0.56	12.9	4.3	9.05 (0.62)	67.90 (8.50)	4134.9 (386.9)	0.56	13.1	3.0	1.43 (0.25)	20.6 (4.98)	3050.4 (227.3)
	0.57	19.6	8.2	6.34 (0.66)	41.58 (2.40)	4321.1 (300.6)	0.56	19.8	5.5	1.32 (0.1 7)	18.40 (2.58)	2792.4 (47.4)
	0.58	22.2	7.9	7.28 (0.54)	41.41 (4.83)	4049.8 (311.3)	0.54	23.4	5.8	1.27 (0.35)	18.11 (5.14)	2733.8 (321.6)
	0.58	52.9	11.1	4.91 (0.69)	28.73 (2.21)	3796.5 (321.9)	0.55	52.8	8.9	0.78 (0.11)	10.79 (2.01)	2335.1 (226.1)
OSB	0.68	0.69	0.4	5.35 (0.52)	29.24 (5.60)	3084.6 (72.0)	0.65	0.8	1.1	1.85 (0.12)	13.44 (2.53)	2533.9 (146.1)
(MHS1)	0.69	8.65	5.1	5.51 (0.25)	38.49 (2.72)	3072.8 (92.0)	0.66	8.6	6.8	1.98 (0.34)	17.53 (1.57)	2574.4 (221.8)
	0.69	12.1	10.1	4.03 (0.55)	28.19 (3.74)	3066.9 (94.0)	0.67	11.8	8.1	1.44 (0.38)	12.33 (3.98)	2470.8 (108.1)
	0.64	16.9	12.5	3.25 (0.36)	22.53 (4.13)	2821.3 (178.9)	0.66	17.4	13.8	1.09 (0.15)	10.14 (2.27)	2311.2 (80.6)
	0.66	25.6	25.6	3.31 (0.48)	19.64 (3.56)	2431.2 (32.6)	0.63	25.4	20.8	1.25 (0.12)	10.24 (0.87)	2083.4 (77.0)
	0.67	78.1	28.9	1.53 (0.08)	11.54 (1.26)	2198.9 (69.7)	0.63	79.8	23.3	0.67 (0.20)	5.31 (1.25)	1771.2 (124.1)
PB	0.79	0.5	0.9	3.97(0.15)	13.97 (0.91)	2241.1 (23.9)	0.76	0.4	1.0	2.53(0.16)	7.37 (0.55)	1850.5 (40.5)
	0.78	8.2	4.1	3.17 (0.50)	13.25 (3.29)	2184.8 (78.5)	0.76	8.4	4.3	2.48(0.56)	9.81 (3.16)	2010.2 (167.6)
	0.80	11.3	8.5	2.69 (0.48)	11.43 (3.28)	2046.4 (134.5)	0.77	11.6	8.6	1.95 (0.21)	7.76 (0.80)	1794.5 (43.3)
	0.77	16.9	17.4	1.29 (0.26)	5.34 (1.51)	1690.8 (105.4)	0.76	17.9	18.3	0.91 (0.08)	3.17 (0.32)	1468.4 (52.2)
	0.77	21.7	25.2	2.48 (0.98)	7.77 (2.14)	1449.9 (43.9)	0.75	20.2	22.1	1.14 (0.11)	1.52 (0.87)	1308.9 (68.9)
	0.78	36 3	131	0.97 (0.30)	4.79 (1.66)	1607.0 (163.5)	0.76	36.1	14.1	0.85 (0.11)	3.53 (0.66)	1436.5 (55.9)

[a] SW = solid wood: PLW = plywood; PB = particleboard. Values in parentheses are standard deviations based on five specimens.

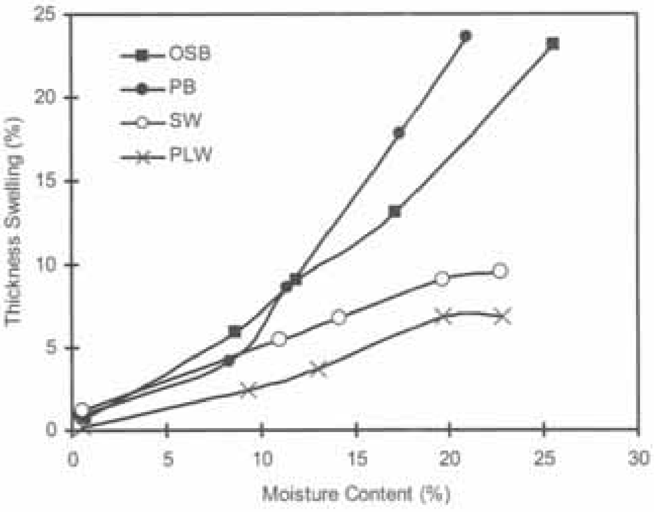

Figure 2. — Thickness swelling as a function of MC for southern pine lumber, plywood, OSB, and particleboard. PB = particleboard; SW = solid wood; PLW = plywood.

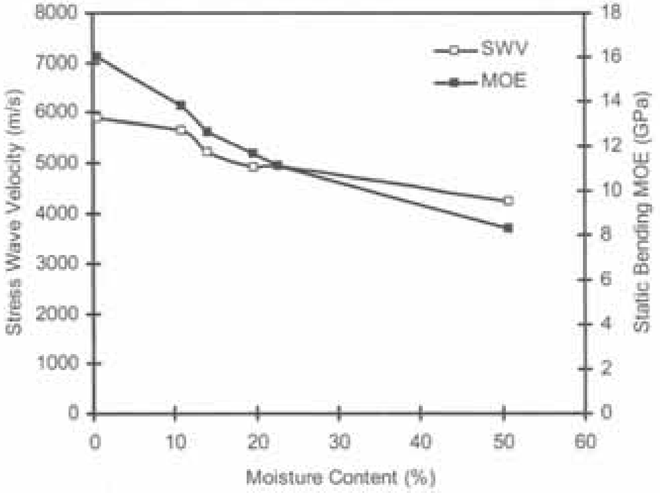

Figure 3. — Stress-wave velocity and static bending MOE as a function of MC in southern pine lumber along the longitudinal direction.

low-poplar. The speed values from pine by Burmester (1965) are obviously larger than the rest of the data at each given MC level. A linear model was established with the combined data from Douglas-fir, yellow-poplar. and southern pine. The model has the following form:

$$\text{SWV (m/s)} = 5783 - 36.3\text{MC} \qquad r^2 = 0.83 \qquad [2]$$

Equation [2] seems adequate to describe the SWV-MC relationship for solid wood within the hygroscopic range. As shown. for every percent of MC increase, SWV decreased about 36 m/s.

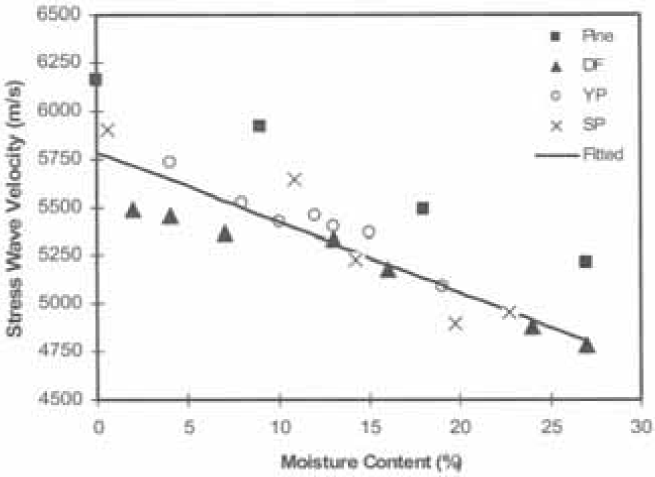

Figure 4. — A comparison of stress-wave velocity as a function of MC for several solid wood species along the longitudinal direction. DF = Douglas-fir; YP = yellow-poplar; SP = southern pine.

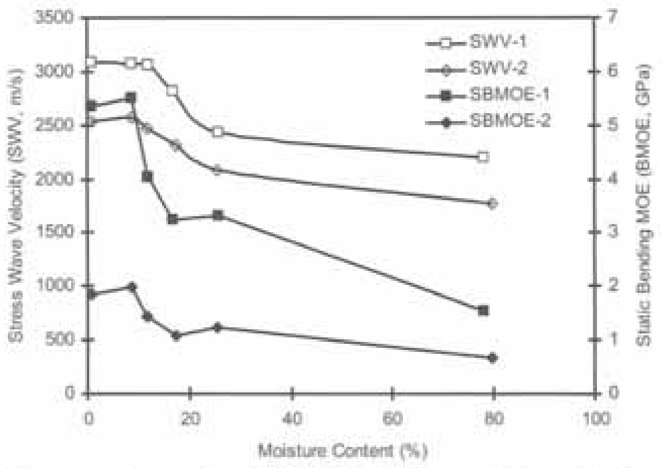

Figure 5. — Stress-wave velocity and static bending MOE as a function of MC for OSB (mixed hardwood for sheathing).

The SWV data at the soaked condition **(Table 2)** showed that for an additional 27 percent MC increase, mainly free water, 12 percent more reduction in SWV occurred. Therefore, the reduction rate in SWV per percent of MC change above the fiber saturation point was much smaller than the corresponding value in the hygroscopic range.

For the panel products including plywood, OSB, and particleboard, MC increases from about 0.5 to 9 percent did not lead to a significant decrease in SWV **(Table 2** and **Fig. 5).** Instead, most of the data showed an increase in the SWV value at a higher MC level. The MOE and MOR data had a similar trend. The MOE and MOR values remained about the same or increased with MC increase from 0.5 to 9 percent. Thus. for wood-based panels, there was a maximum in MOE values at an MC level between 0 percent (completely dry) and 9 percent. The similar trend in both SWV-MC and bending MOE-MC curves as shown in **Figure 5** indicates that stress-wave velocity can be used to determine the MC point at which MOE is at a maximum. Further increases in MC beyond the 9 percent level led to significant SWV decreases in the panel products. This is a result of a significant internal structure change

Table 3. — Results of regression analysis on SWV-MC relationship. Model: SWV (m/s) = a + b MC + c MC^2 + d MC^3 + e MC^4.

Product type[a]	Regression constants					
	a	*b*	*c*	*d*	*e*	r^2
Parallel direction						
SW	5974.4	−52.75	0	0.007	0	0.71
PLW	4679.8	−18.75	0	0	0	0.38
OSB - MHS1	3057.2	38.54	-4.44	0.091	-0.00054	0.94
MHS2	3048.4	25 03	−2.95	0.054	-0.00029	0.95
SPS1	3098.6	0	−1.99	0.055	−000043	0.94
SPS2	3052.6	0	−1.60	0.034	−0.00020	0.89
SPF	2929.3	0	−1.32	0.034	−0.00020	0.83
PB	2226.8	55.83	−10.49	0.386	−0.00418	086
Perpendicular direction						
PLW	2780.2	120.99	−10.14	0.249	−0.00196	0.49
OSB - MHS1	2569.9	0	−0.97	0.011	0	0.81
MHS2	2427.5	−13.89	0	0	0	0.93
SPS1	2630.4	0	−1.76	0.043	−0.00029	0.91
SPS2	2461.2	0	−1.03	0.012	0	0.71
SPF	2329.6	42.38	-4.31	0.097	−0.00066	0.72
PB	1805.6	131.02	—17.96	0.666	−0.00770	0.89

[a] SW = solid wood; PLW = plywood, PB = particleboard.

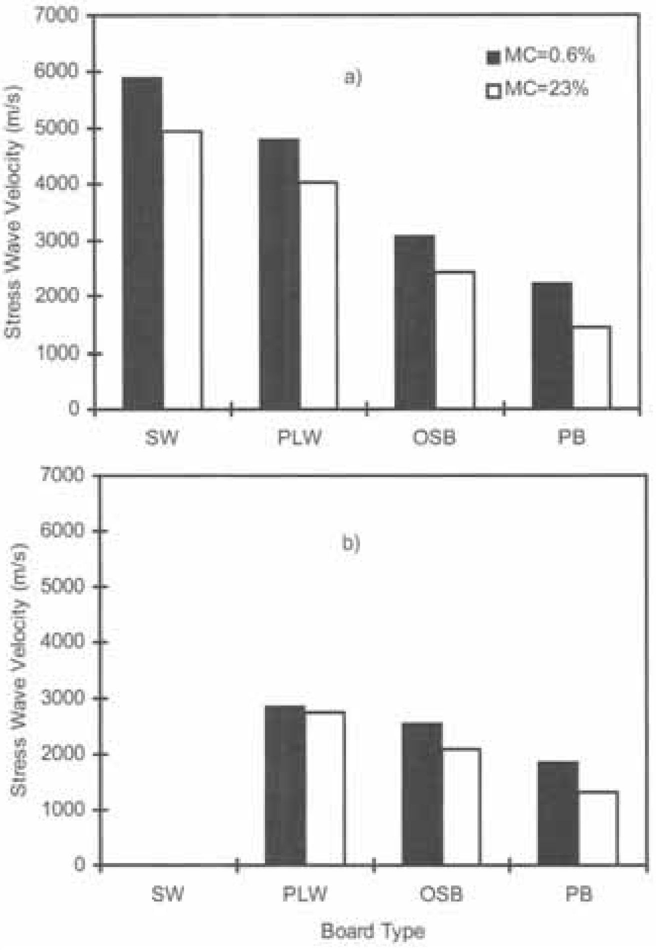

Figure 6. — A comparison of stress-wave velocity in solid wood (southern pine), plywood, OSB, and particleboard: a) parallel direction; and b) perpendicular direction. SW = solid wood; PLW = plywood; PB = particleboard.

as reflected by large TS (Fig. 2) and loss in MOE arid MOR as shown in **Table 2.** In general, the SWV-MC relationship was nonlinear for most. panel products as shown in **Figure 5** for OSB. **Table 3** lists results of regression analysis. The nonlinear polynomial fits the SWV-MC data very well as reflected by the high correlation coefficient from the analysis.

A direct comparison of SWV values of the various materials tested is shown in **Figure 6.** In the parallel direction (longitudinal direction for solid wood), SWV values decreased from solid wood (southern pine). to plywood, to OSB, to particleboard. This reduction in SWV was due to cross-lamination and/or existence of internal voids in the panel products. Stress waves travel at a lower speed in the cross-grain direction than the along-the-grain direction. The velocity of stress-wave propagating perpendicular to the grain was shown as approximately 30 to 50 percent of the velocities parallel to the grain (Gerhards 1982). In addition, when gaps or voids were encountered inside the panel, the wave was diverted and the transit time increased.

Table 4. — Regression results on relationship between bending MOE (GPa), MOR (MPa) and SWV (m/s). Model: MOE or MOR = a + b SWV.

Product type.[a]	Range of MC change	Parallel direction			Perpendicular direction		
		a	*b*	r^2	*a*	*b*	r^2
	(%)						
Bending MOE-SWV relationship							
SW	0.6 to 51	−4.810	0.00330	0.77	--	--	--
PLW	0.5 to 53	−1.389	0.0021	0.35	-0.169	0.00050	0.40
OSB - MHS1	0.6 to 78	−5.586	0.00339	0.76	-1.604	0.00131	0.66
MHS2	0.8 to 82	−2.001	0.00217	0.61	−1.129	0.00112	0.66
SPS1	0.5 tu 57	−8.125	0.00436	0.76	−2.222	0.00164	0.83
SPS2	0.9 to 76	−4641	0.00299	0.80	−2.124	0.00171	0.70
SPF	0.6 to 54	−6.852	0.00390	0.60	−2.760	0.00197	0.81
PB	0.5 to 36	−2.421	0.00259	0.50	−2.650	0.00226	0.84
Bending MOR-SWV relationship							
SW	0.6 to 51	−101.33	0.0036	0.56	--	--	--
PLW	0.5 to 53	− 793	0.0131	0.18	−8.07	0.0868	0.34
OSB - MHS1	0.6 to 78	-32.46	0.0206	0.66	—11.88	0.0102	0.54
MHS2	0.8 to 82	−8.71	0.0109	0.49	-7.39	0.0082	0.64
SPS1	0.5 to 57	−42.17	0.0234	0.83	—11.45	0.0101	0.64
SFS2	0.9 to 76	−30.26	0.0196	0.81	—11.15	0.0113	0.75
SPF	0.6 to 54	-40.12	0.0233	0.58	−17.41	0.0135	0.82
PB	0.5 to 30	-11.42	0.0111	0.68	−9.21	0.0093	0.79

[a] SW = solid wood; PLW = plywood; PB = particleboard

SWV values along the perpendicular direction were considerably smaller than the corresponding values in the parallel direction for plywood and OSB, indicating the anisotropic properties of the products. For particleboard, the difference was smaller, indicating more uniform properties between the two principal directions. The fact that SWV decreased considerably from the parallel to the perpendicular direction for the panel products indicates that specimen face layer played a larger role in controlling the traveling speed of a longitudinal wave inside a large specimen. This trend became more noticeable as the anisotropy between face and core layers increased from particlehoard, to OSB. to plywood.

Static bending MOE and MOR in relation to SWV

Regression results on the relationships between bending MOE. MOR, and SWV are summarized in **Table 4,** which shows the MC range at which measurements were made for each product. **Figure 7** shows a combined plot of bending MOE and MOR as a function of SWV over the MC range in the parallel direction for various products tested. Both MOE and MOR decreased proportionally with decreases in SWV.

Figure 7 and **Table 4** show linear MOE-SWV and MOR-SWV relationships over the MC range tested. Thus, a simple linear SWV-based model can be used to predict MOE and MOR at different levels of MC based on nondestructive measurements of stress-wave time. Since SWV reflects internal structure change as a result of MC change (e.g., internal glue bond failure due to TS at high MC levels), SWV-based prediction models for MOE and MOR are more reliable for wood-based panels compared to MC-based models that are normally used for solid wood.

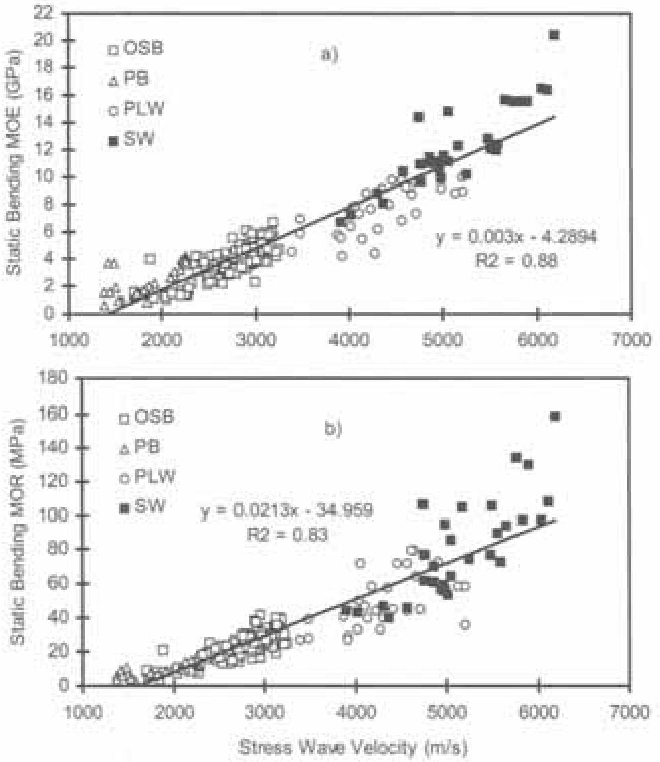

Figure 7. — Relationships of static bending MOE and MOR with stress-wave velocity in the parallel direction for various products. PB=particleboard; PLW=plywood; SW=solidwood.

Conclusions

The effects of moisture on SWV in various wood-based products were investigated in this study. The SWV decreased in general with increases in panel MC. At a given MC level, SWV varied with panel type and test directions. Regression equations relating SWV to MC and bending properties (MOE and MOR) were established for solid southern pine lumber, plywood, OSB, and particleboard. The relationships deduced from regression analysis between MOE, MOR and stress-wave velocity make it possible to predict the strength properties based on nondestructive measurements of stress-wave time. The technique and test results can help engineers estimate current strength and safety margins of wood-based panel products in field use.

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