USING ACOUSTIC ANALYSIS TO PRESORT WARP-PRONE PONDEROSA PINE 2 BY 4s BEFORE KILN-DRYING

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ABSTRACT

This study evaluated the potential of acoustic analysis as presorting criteria to identify warp-prone boards before kiln-drying. Dimension lumber, 38 by 89 mm (nominal 2 by 4 in.) and 2.44 m (8 ft) long, sawn from open-grown small-diameter ponderosa pine trees, was acoustically tested lengthwise at green condition. Three acoustic properties (acoustic speed, rate of wave attenuation, and acoustic modulus of elasticity (MOE)) were then determined through waveform analysis. Boards were then kiln-dried, and warp was measured immediately after drying and after equilibrating to about 13% equilibrium moisture content. Crook and bow measured after drying decreased as acoustic speed and acoustic MOE of green boards increased and rate of wave attenuation of green boards decreased. Twist was found to have no relationship with any acoustic properties of green 2 by 4s. The results also show a statistically significant correlation between acoustic properties of green 2 by 4s and the grade loss caused by exceeding warp limits. As the number of Structural Light Framing grade losses increased, the acoustic speed and acoustic MOE decreased significantly, whereas rate of wave attenuation increased significantly. However, no relationship was found between green board density and warp and grades lost.

Keywords: Green board, warp, presort, acoustic speed, rate of wave attenuation, acoustic modulus of elasticity.

INTRODUCTION

Lumber from small-diameter ponderosa pine trees is notoriously difficult to dry without warp. The value loss caused by warp through lumber downgrading and through waste of energy in kiln-drying is enormous. Past studies on sawing and kiln-drying ponderosa pine lumber have helped define the problem and have offered

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some approaches that help moderate the problem but do not completely solve it (Arganbright et al. 1978; Blake and Voorhies 1980; Maeglin and Boone 1983; Markstrom et al. 1984; Simpson and Green 2001). Heavy top weighting, altered sawing patterns, and higher drying temperatures have proven to be somewhat helpful.

Another approach to consider is to develop a method to identify and sort out warp-prone boards before kiln-drying and thus save some of the processing costs otherwise spent on boards that will lose some or all value because they do not meet grade warp limits. Warp in lumber (bow, crook, and twist) is often caused by differential longitudinal, radial, and tangential shrinkage when water is removed from the wood cell walls (Simpson 1991; Beard et al. 1993). Although no clear relationship between growth characteristics and warping has been identified, studies showed that specific gravity, juvenile wood content, compression wood content, grain angle, spiral angle, and heartwood–sapwood boundary contributed to warping during seasoning. For example, Beard et al. (1993) evaluated the influence of growth characteristics on warp occurring in southern pine 38- by 140-mm (nominal 2- by 6-in.) dimensional lumber and found that bow was significantly influenced by the presence of compression wood. Compression wood and wane also had a significant influence on the occurrence of crook. Wu and Smith (1998) studied the effects of various factors on warp in loblolly pine and concluded that pieces with larger knot area tended to develop greater amounts of crook. They also found that twist tended to increase as specific gravity decreased, juvenile wood content increased, and number of rings per inch decreased.

In contrast to warp in lumber, acoustic waves traveling lengthwise through lumber can also be affected by various growth characteristics. Elvery and Nwokoye (1970), Jung (1979), and Lee (1958) found that grain angle had a pronounced effect on stress wave speed in wood. Speed decreases as grain angle increases. More importantly, the rate of change in wave speed with grain angle is most pronounced in grain angles (up to about 15°) commonly associated with lower grades of lumber that are prone to warp. Gerhards (1982) studied the effects of knots on stress waves in lumber and found that wave speed was slowed through knots and the curved grain around knots. Gerhards also concluded that, in lumber with cross grain and knots, the stress wave does not propagate with a normal wave front as supposed by the long-slender-rod theory (Meyers 1994; Kolsky 1963) but has a wave front that leads in the direction of the grain and lags across the grain or through knots.

The most obvious cause of warp in lumber that contains juvenile wood is the difference in longitudinal shrinkage between juvenile and mature wood (Shelly et al. 1979). This difference is commonly attributed to the relatively large amount of compression wood associated with juvenile wood (Voorhies 1971; Gaby 1972; DuToit 1963) and the large microfibril angle common to wood laid down in the early stages of growth (Voorhies 1971).

The nature of acoustic wave propagation in wood suggests that the potential for this type of warp (bow, crook, and twist) could very likely be identified by acoustic speed lengthwise through lumber. It has been reported that wave propagation in lumber can be affected by the property variation across the width of lumber, which is a factor related to juvenile wood and compression wood contents, moisture gradient, and heartwood–sapwood boundary. As a wave travels through lumber in the longitudinal direction, the mature wood or drier wood in the lumber has a dominating effect on the propagation of the wave (Simpson 1998; Wang et al. 2000). Studies indicated that stress wave predicted lumber modulus of elasticity (MOE) often deviates from its static counterpart due to its tendency to seek out the high MOE zone for its path (Wang et al. 2002, 2004). It is therefore hypothesized that this nature of wave propagation can be used to identify lumber that contains a significant amount of juvenile wood, compression wood, and wood with large grain angle and knots, and hence would be much more likely to warp during kiln-drying.

The purpose of this study was to explore the potential of acoustic analysis as presorting criteria to identify warp-prone boards before kiln-drying. The specific objectives were to (1) determine if there are any relationships between acoustic properties (acoustic speed, rate of wave attenuation, and acoustic modulus of elasticity) of green ponderosa pine 2 by 4s and warp (crook, bow, and twist) developed during kiln-drying; and (2) determine if the acoustic properties differ significantly by grade level as determined by Structural Light Framing grading rules (WWPA 1998).

METHODOLOGY

This study was conducted as a substudy of a larger effort to determine the effectiveness of high temperature kiln-drying on ponderosa pine 38- by 89-mm (nominal 2- by 4-in. (2 by 4)) boards sawn from small-diameter trees (Simpson 2004). The trees averaged 229 mm (9 in.) in diameter and were from an open-grown, 30- to 35-year-old stand in Idaho. The 2.44-m (8-ft) long 2 by 4s were sawn and later kiln-dried by several levels of drying temperature, which is described in Simpson (2004). It was not possible to obtain all the test specimens for this study from material that had been kiln-dried at the same temperature. Thus, it is possible that drying temperature is a confounding factor in the results. The 2 by 4s were graded green as Structural Light Framing lumber (WWPA 1998). A total of 1,216 2 by 4s were included in the drying study (Simpson 2004), and a subset of 531 2 by 4s was used in this presorting study.

On each of the 531 2 by 4s, longitudinal acoustic speed, wave attenuation rate, and green density were measured before kiln-drying. Acoustic measurements were made using a computer equipped with a data acquisition system and an acoustic wave analysis program, coupled with an accelerometer (Columbia Research Laboratories, Inc., Woodlyn, Pennsylvania) attached to the end of a board. A detailed testing procedure can be found in Wang et al. 2001.

After drying and cooling, the 2 by 4s were measured for crook, bow, and twist using a wedge gauge and flat reference table. The boards were then planed, stickered, and equilibrated to approximately 13% moisture content in an environment of 24°C (75°F) and 70% relative humidity. Warp of each board was measured again after equilibration.

Acoustic waveform analysis

Acoustic speed, rate of wave attenuation, and acoustic MOE were considered as predictor parameters of potential board warp. Acoustic speed and wave attenuation relate to energy storage and energy dissipation of a material and can be determined by analyzing the waveform observed in a time-domain signal.

The waveform observed in acoustic testing of a board consisted of a series of equally spaced pulses whose magnitude decreases exponentially with time (Fig. 1). The speed C at which an acoustic wave moves through a board was determined by coupling measurements of the time between pulses (peak to peak) Δt and the length L of the board using the following equation:

$$C = \frac{2L}{\Delta t} \quad (1)$$

The general equation defining the exponential attenuation of an acoustic wave through a board is

$$A_n = A_0 e^{-\alpha n} \quad (2)$$

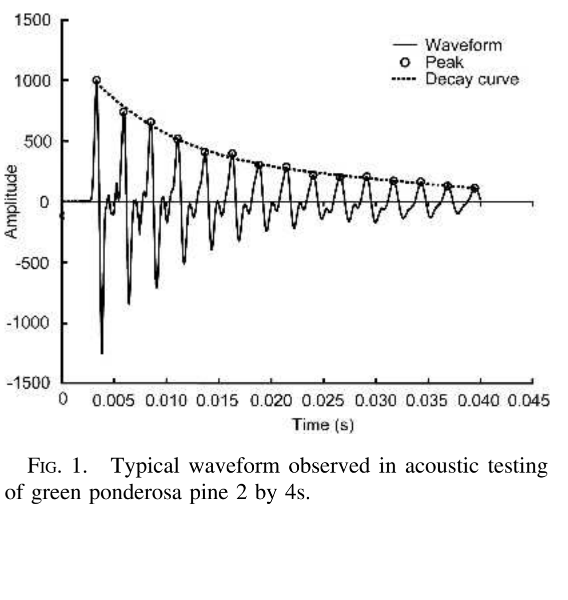

FIG. 1. Typical waveform observed in acoustic testing of green ponderosa pine 2 by 4s.

where A_0 and A_n are the amplitudes of two pulses n cycles apart, α is the rate of wave attenuation.

The rate of wave attenuation in Eq. (2) can be solved for by taking the logarithm of both sides of the equation, which gives

$$\alpha = \frac{1}{n} \ln\left(\frac{A_0}{A_n}\right) \qquad (3)$$

This analysis method is an estimate that can be improved by using additional pulses to give an average result. Using the time value between several pulses and dividing by the number of cycles gives an accurate value for C. In addition, using a high value of n in Eq. (3) gives an accurate value of wave attenuation rate. During acoustic measurements, we used a computer program to determine the average peak to peak time Δt and the rate of wave attenuation (logarithmic decrement) α from the acoustic waveform observed in testing each 2 by 4.

Acoustic MOE is a dynamic measure of a material's stiffness and is often used as an estimate of the static MOE of a board. Acoustic MOE of a board can be calculated from the following one-dimensional wave equation:

$$\text{MOE} = C^2\rho \qquad (4)$$

where ρ is density of the board.

Data analysis

The general approaches of data analysis were to examine the relationships between acoustic properties of green 2 by 4s and the warp developed during kiln-drying and determine if any acoustic measures differ significantly by different levels of grade loss caused by warp.

First, the crook, bow, and twist data of 2 by 4s measured after drying were directly used to establish the relationships between warp and the acoustic measures. Considering relatively large variations of both acoustic and warp data, all boards were first segregated into groups based on the value of acoustic speed, rate of wave attenuation, and acoustic modulus of elasticity, respectively. The relationships between each acoustic measure and the warp were then examined in terms of group averages.

From the perspective of mill processing, the warp developed during kiln-drying will eventually be evaluated in terms of grade loss. Therefore, it is necessary to determine if each of the 2 by 4s maintained the green grade after drying on the basis of meeting the grade's warp limit or was downgraded one, two, three, or more grades because of exceeding the grade's warp limit. These warp limits for 2.44-m (8-ft) long 2 by 4s are shown in Table 1. Statistical analysis was then used to determine if the acoustic properties and density differ significantly by different levels of grade loss, that is by whether a 2 by 4 was not degraded by warp (D0), lost one grade because of warp (D1), lost two grades because of warp (D2), or lost 3 to 4 grades because of warp (D3).

RESULTS AND DISCUSSION

Acoustic properties compared with board warp

Figure 2a shows the relationships between acoustic speed and the crook, bow, and twist of 2 by 4s. The data were analyzed based on acoustic speed groups (boards were divided into five groups based on acoustic speed: group 1, <1.68 km/s (5,500 ft/s); group 2, 1.68 to 1.98 km/s (5,500-6,500 ft/s); group 3, 1.98 to 2.29 km/s (6,500-7,500 ft/s); group 4, 2.29 to 2.59 km/s (7,500-8,500 ft/s); and group 5, >2.59 km/s (8,500 ft/s). Each data point represents the average values of the acoustic speed and warp of one group. Regression analysis indicated strong relationships between acoustic speed and the crook and bow of the 2 by 4s. As acoustic speed increased, both crook and bow decreased. A

TABLE 1. *Warp limits for 2.44-m-(8-ft-) long 2 by 4s under the Structural Light Framing Grading rules (WWPA 1998).*

Grade	Warp limits (mm (in.))		
	Crook	Bow	Twist
Select structural	6.4 (0.250)	12.7 (0.500)	9.5 (0.375)
#1	6.4 (0.250)	12.7 (0.500)	9.5 (0.375)
#2	9.5 (0.375)	19.1 (0.750)	12.7 (0.500)
#3	12.7 (0.500)	25.4 (1.000)	19.1 (0.750)

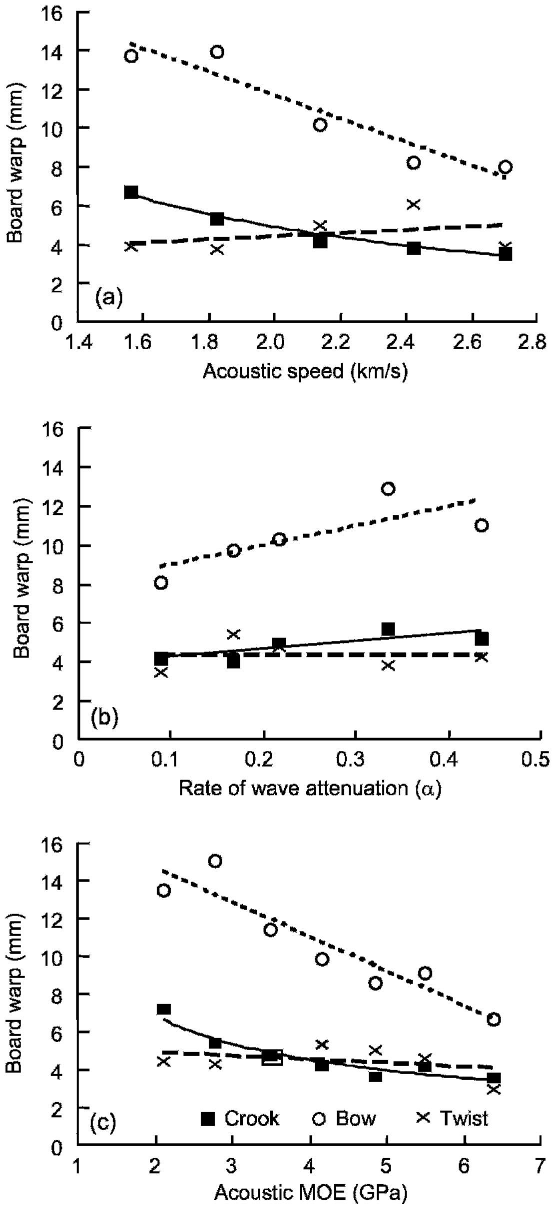

FIG. 2. Relationship between (a) acoustic speed lengthwise, (b) rate of wave attenuation, and (c) acoustic modulus of elasticity (MOE) of green ponderosa pine 2 by 4s and warp measured after drying.

power regression line was found best fit to speed–crook relation with a coefficient of determination (R^2) of 0.976, whereas the speed–bow data can be fit to a linear regression line with a coefficient of determination (R^2) of 0.897. Twist, on the other hand, showed no significant relation to the acoustic speed.

Figure 2b is a plot of average rate of wave attenuation plotted against average warp of 2 by 4s as the boards were divided into four groups based on wave attenuation range (group 1, <0.15; group 2, 0.15 to 0.25; group 3, 0.25 to 0.35; and group 4, >0.35). The results showed positive correlations between wave attenuation of green 2 by 4s and the crook and bow of the boards. Both crook and bow increased when rate of wave attenuation increased, indicating that warp-prone boards tended to have relatively higher rate of wave attenuation than less warp-prone boards or boards not prone to warp. The linear regression analysis resulted in a coefficient of determination of 0.624 and 0.609 for α-crook and α-bow relations, respectively. No relationship was found between twist and wave attenuation.

The relationship between acoustic MOE and warp of 2 by 4s is shown in Fig. 2c. Again, the data were analyzed on a group basis (boards were divided into seven groups based on acoustic MOE range). The regression analysis showed significant relationships between acoustic MOE and two forms of warp—crook and bow. Both crook and bow decreased when acoustic MOE increased. Similar to speed–warp relationships, a power regression line was found best fit to MOE–crook relation with $R^2 = 0.901$, whereas the MOE–bow data can fit to a linear regression line with $R^2 = 0.871$. No significant relationship was found between twist and acoustic MOE.

In addition to acoustic properties, density of green 2 by 4s was also examined as a predicting parameter for presorting green ponderosa pine 2 by 4s. However, no significant relationships were found between green density and crook, bow, and twist of the boards after drying.

Acoustic properties compared with board grade loss

The green grade distribution of the 2 by 4s tested was 2% Select Structural, 40% #1, 48% #2, and 10% #3. After kiln-drying, it is possible for a Select Structural to lose one, two, three, or four grade levels, going from Select Structural to #1, #2, #3, or less than #3. Similarly, a #1 can lose one, two, or three grade levels, but a #3 can only lose one grade level.

Tables 2 through 5 show the results of statistical analyses to determine if the acoustic properties and density differ significantly by different levels of grade loss. In all tests, the data failed to pass either the normality or equal variance tests, so the analysis was the Kruskal–Wallis one-way analysis of variance on ranks, which analyzes the data in terms of medians rather than means.

As shown in Table 2, the median value of acoustic speed (C) decreased significantly as grade loss increased from D0 to D1, D2, and D3. Also, for individual comparisons, median C values were significantly different for D0 compared with D3, D0 compared with D2, D0 compared with D1, and D1 compared with D3. The median value of rate of wave attenuation (α) (Table 3) increased significantly as grade loss increased from D0 to D1, D2, and D3, but it was an overall effect because none of the individual comparisons alone showed a significant difference. The median value of acoustic MOE (Table 4) decreased significantly as grade loss increased from D0 to D1, D2, and D3. The individual comparisons for D0 compared with D3, D0 compared with D2, and D0 compared with D1 were significantly different. The median value of green density (Table 5) does not differ with grade loss. The relationships between grade loss and acoustic speed, rate of wave attenuation, and acoustic MOE are shown graphically in Figs. 3a, b, and c.

Potential of acoustic speed for presorting warp-prone boards

Acoustic speed (C) had the highest Kruskal–Wallis test statistic (Tables 2 through 5), and we might assume that it is the best parameter to use for sorting. We might choose a value of $C = C_s$ (cut-off acoustic speed for sort) as the sort point. In other words, 2 by 4s with values of C less than C_s are considered warp-prone and diverted from kiln-drying and Structural Light Framing use, and 2 by 4s with values of C greater than C_s are placed in the Structural Light Framing sort to be kiln-dried and graded.

Although the data of this study might be considered somewhat limited to result in the basis for a fully developed sorting strategy, we can illustrate how a sorting strategy might be developed. Figure 4 shows how cut-off acoustic speed affects sorting errors. Sorting errors were characterized as percentage of no-warp-prone boards mistakenly sorted out and percentage of warp-prone boards mistakenly allowed in sort. As cut-off acoustic speed increases, the percentage of non-warp-prone 2 by 4s that are mistakenly sorted out of the group to be dried and graded increases, but the percentage of warp-prone boards that are mistakenly allowed in the sort to

TABLE 2. *Results of Kruskal–Wallis one-way analysis of variance on ranks and Dunn's pairwise multiple comparison tests (Glanz 2002) for testing differences in median values of acoustic speed (*C*) lengthwise through green ponderosa pine 2 by 4s between grade losses of 0, 1, 2, or 3–4 levels in the Structural Light Frame Grading rules (WWPA 1998).*

Kruskal–Wallis one-way analysis of variance on ranks[a]					
		Acoustic speed (m/s (ft/s))		Dunn's multiple comparison test	
Degrade level[b]	N	Median	Mean	Comparison	$P < 0.05$
D0	385	2,146 (7,040)	2,133 (6,999)	D0 vs. D3	Yes
D1	80	1,897 (6,223)	1,942 (6,372)	D0 vs. D2	Yes
D2	42	1,745 (5,725)	1,779 (5,835)	D0 vs. D1	Yes
D3	25	1,713 (5,620)	1,694 (5,559)	D1 vs. D3	Yes
				D1 vs. D2	No
				D2 vs. D3	No

[a] Kruskal–Wallis test statistic $H = 82.62$, and $P = <0.0001$, indicating that the median values of C differ significantly by degrade level.
[b] D0, not downgraded because of warp; D1, lost 1 grade level because of warp; D2, lost 2 grade levels because of warp; D3, lost 3 or 4 grade levels because of warp.

TABLE 3. *Results of Kruskal–Wallis one-way analysis of variance on ranks and Dunn's pairwise multiple comparison tests (Glanz 2002) for testing differences in median values of wave attenuation rate (α) of green ponderosa pine 2 by 4s between grade losses of 0, 1, 2, or 3–4 levels in the Structural Light Frame Grading rules (WWPA 1998).*

Kruskal–Wallis one-way analysis of variance on ranks[a]					
		Wave attenuation rate		Dunn's multiple comparison test	
Degrade level[b]	N	Median	Mean	Comparison	$P < 0.05$
D0	385	0.227	0.233	D0 vs. D3	No
D1	80	0.238	0.245	D0 vs. D2	No
D2	42	0.244	0.248	D0 vs. D1	No
D3	25	0.260	0.262	D1 vs. D3	No
				D1 vs. D2	No
				D2 vs. D3	No

[a] Kruskal–Wallis test statistic $H = 8.50$, and $P = <0.0367$, indicating that the median values of δ differ significantly by degrade level.
[b] D0, not downgraded because of warp; D1, lost 1 grade level because of warp; D2, lost 2 grade levels because of warp; D3, lost 3 or 4 grade levels because of warp.

TABLE 4. *Results of Kruskal–Wallis one-way analysis of variance on ranks and Dunn's pairwise multiple comparison tests (Glanz 2002) for testing differences in median values of acoustic MOE of green ponderosa pine 2 by 4s between grade losses of 0, 1, 2, or 3–4 levels in the Structural Light Frame Grading rules (WWPA 1998).*

Kruskal–Wallis one-way analysis of variance on ranks[a]					
		Acoustic MOE (GPa (10^6 lb/in^2))		Dunn's multiple comparison test	
Degrade level[b]	N	Median	Mean	Comparison	$P < 0.05$
D0	385	4.07 (0.59)	4.14 (0.60)	D0 vs. D3	Yes
D1	80	3.31 (0.48)	3.45 (0.50)	D0 vs. D2	Yes
D2	42	2.83 (0.41)	2.96 (0.43)	D0 vs. D1	Yes
D3	25	2.69 (0.39)	2.83 (0.41)	D1 vs. D3	No
				D1 vs. D2	No
				D2 vs. D3	No

[a] Kruskal–Wallis test statistic $H = 62.8$, and $P = <0.0001$, indicating that the median values of MOE_{SW} differ significantly by degrade level.
[b] D0, not downgraded because of warp; D1, lost 1 grade level because of warp; D2, lost 2 grade levels because of warp; D3, lost 3 or 4 grade levels because of warp.

be dried and graded decreases. The overall percentage of boards that are mistakenly sorted for either of the two reasons remains fairly constant at about 26 to 30%. If the sorting strategy is to minimize the percentage of non-warp-prone boards mistakenly sorted out from being dried and graded, then a low value of C_s should be chosen. If the sorting strategy is to minimize the percentage of warp-prone boards mistakenly allowed in the sort to be dried and graded, then a higher value of C_s should be chosen.

TABLE 5. *Results of Kruskal–Wallis one-way analysis of variance on ranks (Glanz 2002) for testing differences in median values of density of green ponderosa pine 2 by 4s between grade losses of 0, 1, 2, or 3–4 levels in the Structural Light Frame Grading rules (WWPA 1998).*

Kruskal–Wallis one-way analysis of variance on ranks[a]			
		Density (kg/m^3 (lb/ft^3))	
Degrade level[b]	N	Median	Mean
D0	385	898.7 (56.10)	885.9 (55.30)
D1	80	899.0 (56.12)	890.4 (55.58)
D2	42	928.5 (57.96)	919.2 (57.38)
D3	25	923.2 (57.63)	910.9 (56.86)

[a] Kruskal–Wallis test statistic $H = 5.69$, and $P = <0.1278$, indicating that the median values of density do not differ significantly by degrade level.
[b] D0, not downgraded because of warp; D1, lost 1 grade level because of warp; D2, lost 2 grade levels because of warp; D3, lost 3 or 4 grade levels because of warp.

CONCLUSIONS

In this study, 2.44-m- (8-ft-) long 2 by 4s sawn from open-grown small-diameter ponderosa pine trees were acoustically tested lengthwise at green condition. Warp was measured after kiln-drying, and its relationships to acoustic properties were examined. The results offer strong evidence that the amount of warp in the

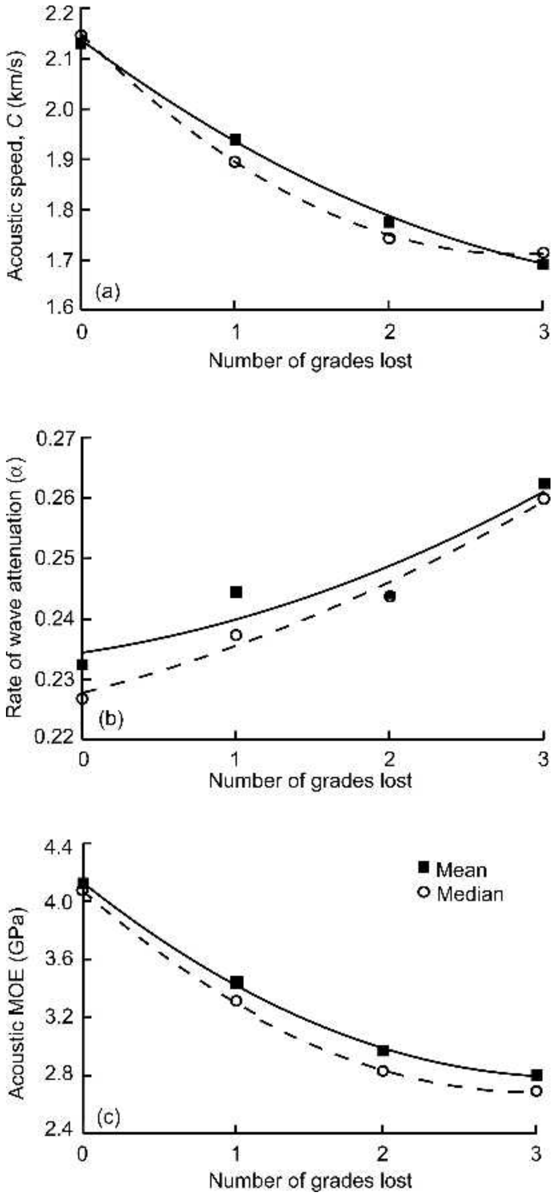

FIG. 3. Relationship between (a) acoustic speed lengthwise, (b) rate of wave attenuation, and (c) acoustic modulus of elasticity (MOE) of green ponderosa pine 2 by 4s and the number of grades lost from warp during kiln-drying.

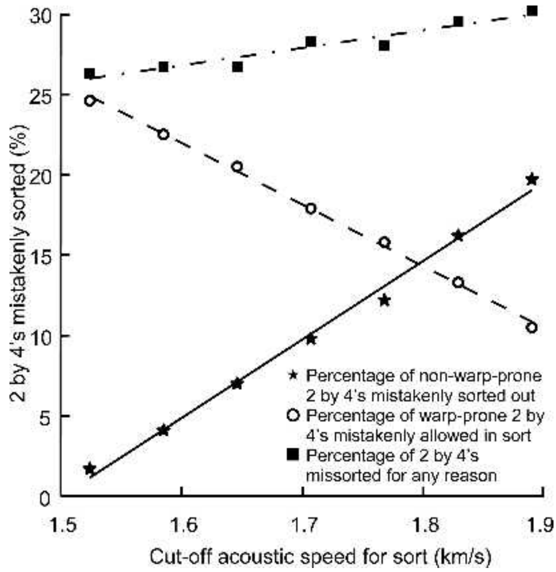

FIG. 4. Relationships between the percentage of ponderosa pine 2 by 4s mistakenly sorted and the cut-off acoustic speed.

form of crook and bow that developed during drying of ponderosa pine 2 by 4s decreased as green board measurements of acoustic speed and acoustic MOE increased and rate of wave attenuation decreased. Twist was found to have no relationship with any acoustic properties of the green boards. The results also show a statistically significant correlation between acoustic properties of green 2 by 4s and the grade loss because of exceeding warp limits. As the number of Structural Light Framing grade losses from the green grade increased, the acoustic speed and acoustic MOE decreased significantly, whereas rate of wave attenuation increased significantly. There is no relationship between green board density and warp and grades lost.

The results of this study indicate that acoustic analysis of green boards has good potential to be used as presorting criteria to identify warp-prone boards before kiln-drying. Based on limited data from green ponderosa pine 2 by 4s, acoustic speed might be the best single parameter to use for sorting, and therefore a cut-off acoustic speed value could be determined as a sort point based on a specific sorting strategy. Further research is planned to investigate the effectiveness of acoustic speed as a single sorting parameter in depth and to develop new sorting criteria through multivariate modeling.

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