RELATIONSHIP BETWEEN SPEED OF SOUND AND MOISTURE CONTENT OF RED OAK AND HARD MAPLE DURING DRYING

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ABSTRACT

The transit time for sound was measured both perpendicular and parallel to the grain of red oak and hard maple during drying under constant temperature (27°C (80°F)) and varying relative humidity conditions. Transit time perpendicular to the grain increased slightly with decreasing moisture content initially during drying but then decreased with decreasing moisture content. Transit time parallel to the grain remained nearly constant with moisture content initially during drying but then decreased. Transit time became sensitive to moisture content change at average moisture contents well above 30%. The relationship between relative transit time and moisture content showed three linear regions that could be characterized by a three-component regression equation. These results suggest that speed of sound measurements have good potential for control of hardwood kiln schedules in which changes in kiln conditions are made at moisture contents above 30%.

Keywords: kiln drying, nondestructive testing, kiln control.

INTRODUCTION

Hardwood kiln schedules are generally controlled from the moisture content of sample boards. This is often done manually by kiln operators entering the kiln periodically to weigh sample boards and make moisture content calculations. This is inefficient because the weighings usually cannot be timed to make changes in kiln conditions at optimum times. Furthermore, sample boards are often positioned in the kiln more for the convenience of multiple retrievals by the operator rather than to faithfully represent the lumber in the kiln.

In recent years, systems have been introduced to automatically change kiln conditions at optimum times as required by kiln schedules. One common system uses electrodes embedded in the lumber to sense changes in electrical conductivity, which is correlated with moisture content. However, this system can obtain inaccurate readings because of the change in contact resistance between the electrodes and wood as drying and shrinking occur. A more fundamental limitation is the insensitivity of conductivity to changes in moisture content above the fiber saturation point. In a red oak dry kiln schedule, for example, there are five changes in kiln conditions before the fiber saturation point is reached. Electrodes have not been successful in detecting the moisture contents where these changes need to be made and thus are not useful until moisture contents are below about 30%. Chen et al. (1994) have developed a correlation between meter readings and moisture contents above 30% based on the oven-dry weight method, which may have potential use in kiln control.

Another system uses load cells that can weigh individual sample boards located within sample board pockets. Although not in common use, this system is capable of sensing moisture content at all levels from green to dry. One limitation, however, is corrosion of

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the load cells from wood volatiles driven off during drying. Another limitation is the positioning of the sample boards in the kiln. Sample board pockets are usually located at the edges of the lumber stacks and do not accurately reflect the moisture content of boards near the center of the stack.

The purpose of this study is to explore another alternative: the use of ultrasonic nondestructive evaluation (NDE) to estimate moisture content during kiln drying. Several studies, which will be discussed in the following sections, have established that speed of sound in wood increases (or transit time decreases) as moisture content decreases and that this relationship applies even above the fiber saturation point. In the current study, we attempt to define the relationship in a more quantitative way, and we attempt to identify characteristics of the relationship that might make it useful for hardwood kiln schedule control.

BACKGROUND

Gerhards (1975) found that the speed of sound through wood varies with moisture content even above the fiber saturation point. James et al. (1982) took advantage of this phenomenon to explore the use of speed of sound for monitoring moisture content of lumber during kiln drying. Their results were based on one set of sensors arranged to measure the speed of sound along the length of a single board during drying. They found continuous decreases in the transit time of sound in red pine from 377×10^{-6} s/m (115×10^{-6} s/ft) at 120% moisture content to 223×10^{-6} s/m (68×10^{-6} s/ft) at 7% moisture content. In sugar maple, transit time decreased from 302×10^{-6} s/m (92×10^{-6} s/ft) at 62% to 230×10^{-6} s/m (70×10^{-6} s/ft) at 7%. The nature of the response of speed of sound to moisture content changes led them to conclude that moisture gradients during drying have a dominating effect. In their sensor arrangement, the dry shell and the wet core were parallel to the direction of sound transmission. Figure 1 shows the electrical circuit analogy of series

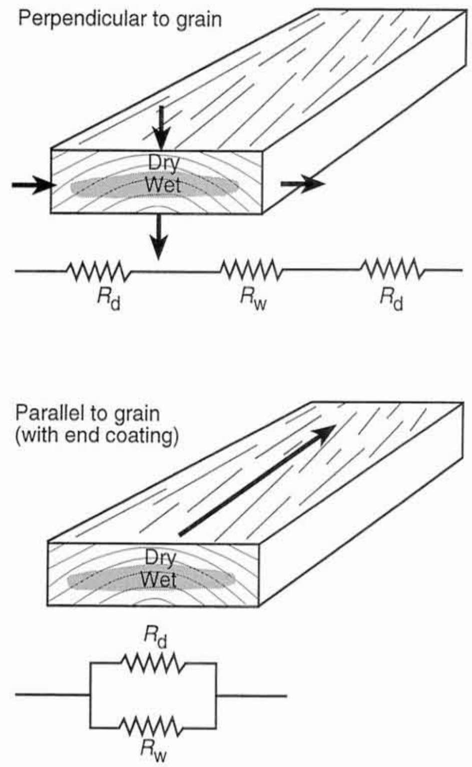

FIG. 1. Electrical analogy of series and parallel arrangements of wet (R_w) and dry (R_d) wood.

and parallel arrangements of wet and dry zones. Therefore, as soon as drying began, the dry shell, where speed of sound was faster than the wet core, began to influence measured speed through the board.

One somewhat vague result of James' study (James et al. 1982) was the treatment of the effect of temperature on speed of sound. Side experiments showed that the speed of sound decreased as temperature increased. However, their attempt at calibration suffered because of the experimental difficulties of equilibrating wood at moisture contents above about 25%. The temperature effect is potentially important because some changes in kiln conditions are temperature increases. However, they did show one curve of transit time compared with elapsed drying time, and the points where temperature increases were made are barely noticeable in the steady decline of transit time during drying. Therefore, at this point, we do not know if a temperature correction factor is necessary.

Even if temperature compensation were to become a problem, there is still a place for NDE-based kiln control. In most hardwood schedules, the first dry bulb temperature change does not occur until 30% moisture content. All changes up to that point (and there typically are 4 to 6 changes) are decreases in wet bulb temperature, so no dry bulb temperature compensation is even necessary. A dual system could then have embedded electrodes take over from 30% down to final moisture content.

Mishiro (1995, 1996a, b) conducted several studies on the relationship between speed of sound and moisture content. Most of these studies were conducted such that the dry shell and wet core were in series to the direction of sound transmission. Surface coatings were applied to restrict drying to only appropriate surfaces. As applied to kiln control, this arrangement would correspond to measuring speed of sound through the thickness of a wide board during drying. Mishiro found a range of relationships depending on species. In most species, the increase in speed from green to the fiber saturation point was not very large and even decreased in two species. However, the increase in speed from fiber saturation to 0% moisture content was much greater.

Huang and Chen (1996) found a continuous increase in the speed of sound from 200% to about 10% moisture content (shell and core in parallel). The total increase was about 2.5 times. Kabir et al. (1997) found an increase in speed of sound with decrease in moisture content in all three grain directions. In all three directions, the increase was small and gradual from green to approximately the fiber saturation point and then increased sharply from there to lower moisture contents. It was not clear whether the shell and core were in series, in parallel, or a combination resulting from no surface coatings on the small 20-mm (0.79-in.) cubes.

Brashaw et al. (1996) applied stress wave NDE to sort green southern pine and Douglas-fir veneer into stress grade for manufacture into engineered wood composites. Stress wave velocities in green and dry veneer were strongly correlated, indicating that the method can give an accurate sort.

EXPERIMENTAL PROCEDURE

Experiments described in the literature include both series and parallel arrangements of a wet core and dry shell. Although the literature suggests that the parallel arrangement will result in higher sensitivity to the decrease in transit time of sound with decrease in moisture content above the fiber saturation point, we examined both the parallel case (along the length of an end-coated board) and a hybrid series–parallel arrangement (across the width of a board with end coating but no edge coating).

There were five groups of experimental specimens, as follows:

Group 1: Four standard 25-mm- (nominal 1-in.-) thick quartersawn red oak boards, 152 mm by 0.762 m (6 in. wide by 30 in. long), dried from green to 55% moisture content at 27°C (80°F) and 80% relative humidity, from 55 to 35% at 27°C and 65% relative humidity, and from 35 to 6% at 27°C and 30% relative humidity. The impulse was applied across the width of the boards.

Group 2: Five standard 25-mm- (nominal 1-in.-) thick flatsawn red oak boards, 76.2 mm by 0.356 m (3 in. wide by 14 in. long), dried as in Group 1. The impulse was applied along the length of the boards. The boards were end-coated with neoprene. The neoprene coating prevented end-drying and confounding of the speed of sound measurements by a dry zone at the end of the boards.

Group 3: Six standard 25-mm- (nominal 1-in.-) thick flatsawn red oak boards, 76.2 mm by 0.356 m (3 in. wide by 14 in. long), dried as in Group 1. Impulses were applied along the length and across the width of the boards. The boards were end-coated with neoprene.

Group 4: Five standard 38-mm- (nominal 1-

½-in.-) thick flatsawn hard maple boards, 165 mm by 0.356 m (6½ in. wide by 14 in. long), dried from green to 6% at 27°C (80°F) and 30% relative humidity. Impulses were applied as in Group 3. Boards were end-coated with neoprene.

Group 5: Five standard 38-mm- (nominal 1-½-in.-) thick flatsawn hard maple boards, 6½ in. wide by 14 in. long (165 mm by 0.356 m), dried from green to 13% at 27°C (80°F) and 65% relative humidity. Impulses were as in Group 3, and boards were end-coated with neoprene.

In addition to measuring speed of sound in boards as they were drying, measurements were also made on another group of specimens at equilibrium moisture contents of approximately 6, 12, and 24% and green. There were three specimens per moisture content.

All oak boards were from the same log. Maple boards were taken from mill-run lumber and thus came from several logs. Drying was done in temperature and relative humidity controlled rooms. Moisture sections were used to estimate when to change the relative humidity.

Speed of sound transmission measurements were taken with the experimental apparatus shown in Fig. 2, which shows measurements taken across the width of a board. The apparatus consisted of two 84-kHz rolling transducers coupled to an ultrasonic transmitter and receiving unit (Fuller et al. 1995). Each specimen was marked so that transducer roller positioning could be closely reproduced for each measurement. Transit times were recorded manually, at short time intervals early in drying and at increasingly longer time intervals as drying rate diminished during drying. Boards were also weighed each time the transit time was measured. At the end of drying, all boards were oven-dried so that the moisture content corresponding to each transit time could be calculated. Board measurements were also taken at each transit time so that any shrinkage could be included in the calculation of transit time per unit length of travel.

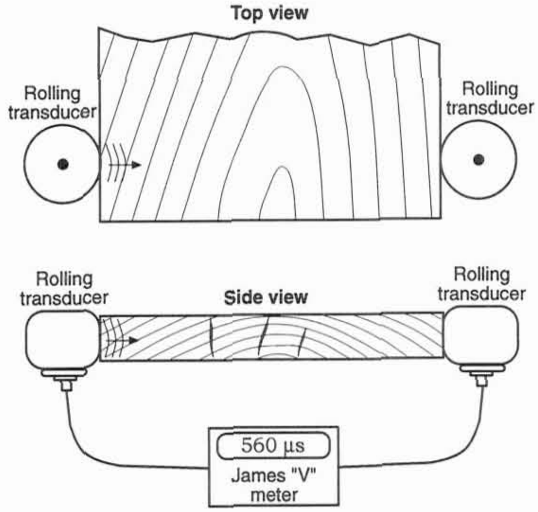

FIG. 2. Speed of sound transducer aligned for measurement across the width of a board.

ANALYTICAL METHODS

If we are able to use a relationship between sound transit time and moisture content in kiln schedule control, being able to mathematically describe the relationship will be useful in the control system. The transit time and moisture content data taken in this study were converted to a relative transit time. Relative transit time is defined as the transit time at any moisture content divided by the initial transit time at the green moisture content. After plotting the data, it became apparent that it could be described as shown in Fig. 3. All curves of relative transit time compared with moisture content showed three linear phases and can be described by the following set of equations:

Phase 1, $M_2 < M < M_g$

$$T_r = (c(M_g - M) + d(M - M_2)) \div (M_g - M_2) \quad (1)$$

Phase 2, $M_1 < M < M_2$

$$T_r = (b(M_2 - M) + c(M - M_1)) \div (M_2 - M_1) \quad (2)$$

Phase 3, $M_d < M < M_1$

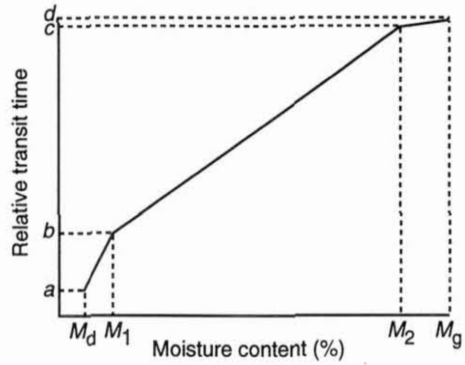

FIG. 3. General nature of the relationship between relative transit time and moisture content, showing regions and location of coefficients of regression Eqs. (1) through (3) (M_g is green moisture content (%), M_2 is moisture content at end of Phase 1 (%), M_1 is moisture content at end of Phase 2 (%), M_d is moisture content at end of Phase 3 (%), a is relative transit time at M_d, b is relative transit time at M_1, c is relative transit time at M_2, d is relative transit time at M_g).

$$T_r = (a(M_1 - M) + b(M - M_d)) \div (M_1 - M_d) \quad (3)$$

where T_r is relative transit time, M_g is green moisture content (%), M_2 is moisture content at end of Phase 1 (%), M_1 is moisture content at end of Phase 2 (%), M_d is moisture content at end of Phase 3 (%), a is relative transit time at M_d, b is relative transit time at M_1, c is relative transit time at M_2, d is relative transit time at M_g.

RESULTS AND DISCUSSION

Average green and dry transit times are given in Table 1 for each experimental group. Relative transit time and moisture content data for each specimen were fit by regression analysis to Eqs. (1) through (3), and the relationships are shown in Fig. 4 for across the width of the boards (perpendicular to the grain) and in Fig. 5 for along the length of the boards (parallel to the grain). The data in Figs. 4 and 5 are averages for all specimens in an experimental group. The regression coefficients of Eqs. (1) through (3) are given in Table 2. In some of the relationships in Figs. 4 and 5, it appears that a simple second degree polynomial might fit the data well and have the advantage of simplicity over Eqs. (1) through (3). However, in all cases, Eqs. (1) through (3) resulted in a lower sum of squared deviations between experimental and regression points. The average ratio of the sum of squares with the second degree polynomial to the sum of squares for Eqs. (1) through (3) was 4.0, indicating the clear superiority of the three-component equation. Furthermore, the linearity of the Phase 2 segment (Eq. (2)) over the moisture content range of interest for impulse along the grain may be more useful in kiln control than a nonlinear relationship.

TABLE 1. *Average speed of sound transmission times for green and dry wood of red oak and hard maple.*

	Perpendicular to grain (μs/m)[a]		Parallel to grain (μs/m)	
	Green	Dry	Green	Dry
Red oak				
Group 1	623	524	—	—
Group 2	—	—	297	230
Group 3	674	572	311	244
Hard maple				
Group 4	661	583	265	221
Group 5	646	597	272	232

[a] μs/m × 0.305 = μs/ft.

The mechanism responsible for the three distinct linear regions of the relative transit time and moisture content relationship is not known. The first transition point between regions, M_2, ranges from about 30% moisture content for hard maple perpendicular to the grain to about 75% for red oak parallel to the grain. So except for the hard maple perpendicular to the grain, M_2 does not seem to be related to fiber saturation point. The second transition point, M_1, ranges from about 11% for red oak parallel to the grain to about 18% for hard maple perpendicular to the grain. This also does not relate to a moisture content of any significance, as for example, the moisture content of about 6% that indicates a change in the way bound water associates with sorption sites in wood (Skaar 1988). It is possible that the difference in the regions is caused by the effects of moisture gradients during drying and the tendency of sound transmission to

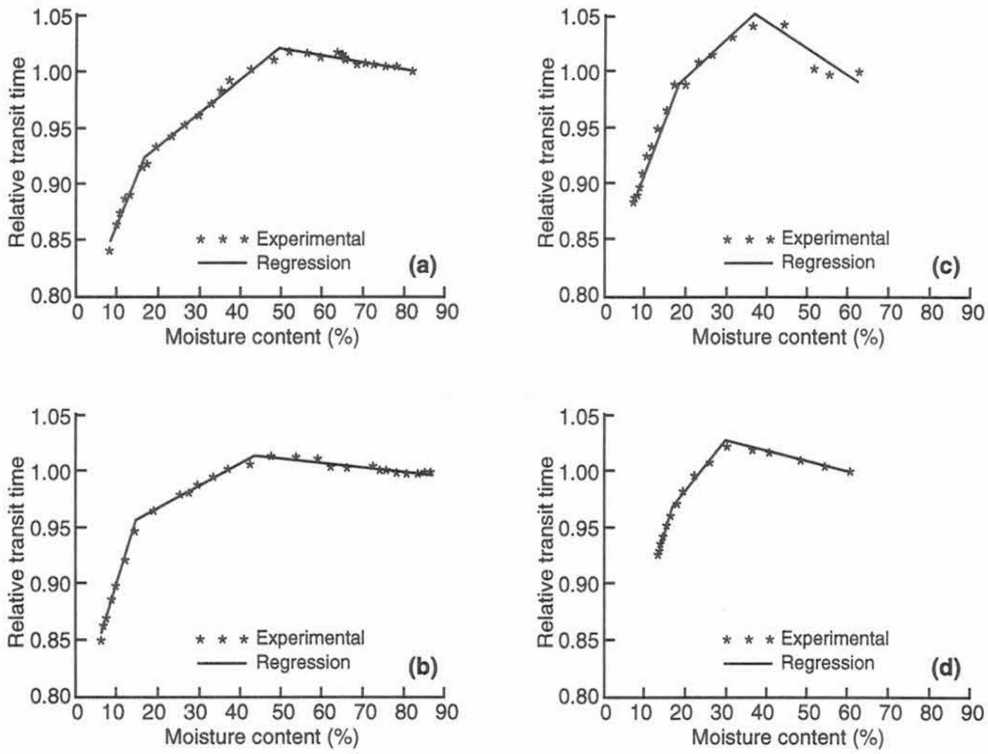

FIG. 4. Relationship between relative transit time and moisture content perpendicular to the grain for (a) red oak, Group 1; (b) red oak, Group 3; (c) hard maple (30% relative humidity), Group 4; and (d) hard maple (65% relative humidity), Group 5.

seek out the dryer wood for its path. The series and parallel arrangements of wet and dry regions may also be involved.

The general shapes of the relative transit time and moisture content curves in Figs. 4 and 5 are different for perpendicular and parallel to the grain data. In all groups, the first phase of the relationship perpendicular to the grain shows an increase in transit time with decreasing moisture content. The relationship perpendicular to the grain was consistent with that found by Mishiro (1966b)—that is, an initial increase in transit time with decreasing moisture content, followed by a decrease for the rest of the moisture content range. Parallel to the grain, the transit time in this first phase was nearly constant with moisture content or showed a slight decrease.

In general, the Phase 2 linear part of the curves parallel to the grain comprised a larger part of the total moisture content range than perpendicular to the grain, especially with red oak. This is a significant observation, because Phase 2 is the moisture content range of most interest for kiln schedule control, especially above the fiber saturation point. For red oak, Phase 2 covers the moisture content range of approximately 75 to 12%, and for hard maple, it covers from about 45 to 17%. Perpendicular to the grain, Phase 2 does not start until below 50% moisture content for red oak and until below 40% for hard maple; in both cases, this is too late for the first change in kiln conditions according to recommended schedules (Simpson 1991). This range is also significant because it is where honeycomb is most likely to occur, and the need for good kiln control is especially important.

Figure 6 shows the relationship between relative transit time and boards with equilibrium

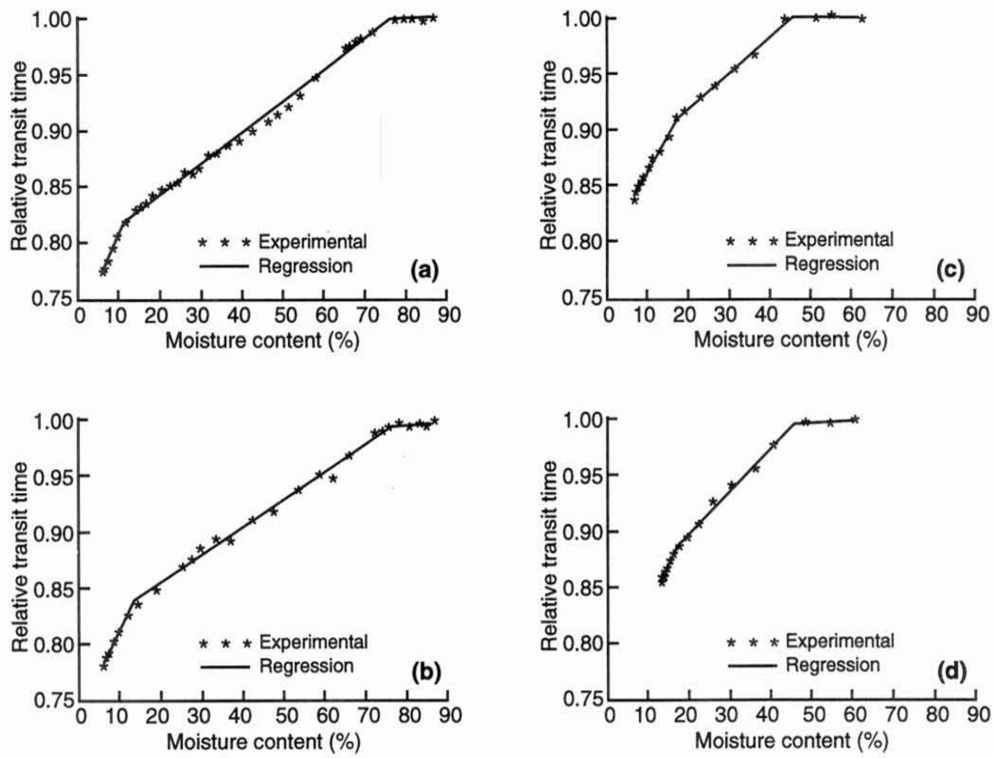

FIG. 5. Relationship between relative transit time and moisture content parallel to the grain for (a) red oak, Group 2; (b) red oak, Group 3; (c) hard maple (30% relative humidity), Group 4; and (d) hard maple (65% relative humidity), Group 5.

moisture content (no moisture content gradient). As was observed in the measurements made during drying, transit time perpendicular to the grain does not decrease with equilibrium moisture content as much as it does parallel to the grain. The reason for this difference may be the different arrangements of cell walls and cell lumens that the sound waves traverse when traveling perpendicular or parallel to the grain.

POTENTIAL OF RESULTS IN KILN CONTROL

This study was intended to be exploratory, and as such, the results are not yet in enough depth to be applicable to kiln control. Lack of diversity in the source of experimental boards, small specimen size, unknown effects of knots or checks, and low, single-temperature drying conditions preclude such use. However, it is useful to consider how data similar to those collected in this study but broadened as just noted might be used in kiln control.

As noted in the previous section, it appears that impulse applied so that sound travels parallel to the grain has better potential than if applied perpendicular to the grain. This is a fortunate result because it means that conventional kiln samples and their placement limitations can be eliminated. Transducers can be placed on the ends of production boards in the lumber stack. This avoids the necessity of cutting and handling sample boards and locating them on the edges of the lumber stack. It therefore opens up new possibilities in monitoring moisture content in lumber any place through the width of a stack. The slower drying boards in the central parts of a stack have been inaccessible for kiln control, which is es-

TABLE 2. *Coefficients of regression equation relating relative transit time to moisture content.*

Experimental group	Coefficients of regression							
	a	*b*	*c*	*d*	M_1	M_2	M_d	M_g
				Perpendicular to grain				
Red oak								
Group 1								
Average	0.8267	0.9245	1.0201	1.0018	16.57	48.97	6.00	81.63
SD[a]	0.0074	0.0127	0.0141	0.0022	0.90	1.01		1.03
Group 3								
Average	0.8509	0.9556	1.0132	0.9975	14.90	43.12	6.00	86.71
SD	0.0083	0.0056	0.0034	0.0020	0.39	1.52		5.29
Hard maple								
Group 4								
Average	0.8707	0.9879	1.0515	0.9898	18.00	36.73	6.00	62.50
SD	0.0063	0.0175	0.0552	0.0144	3.32	7.68		8.07
Group 5								
Average	0.9070	0.9674	1.0268	0.9992	16.76	29.98	12.00	60.82
SD	0.0163	0.0227	0.0280	0.0038	0.78	1.70		7.62
				Parallel to grain				
Red oak								
Group 2								
Average	0.7707	0.8170	0.9976	0.9999	11.27	75.89	6.00	87.22
SD	0.0057	0.0088	0.0070	0.0019	0.91	3.17		3.07
Group 3								
Average	0.7805	0.8375	0.9932	0.9977	12.97	75.72	6.00	86.73
SD	0.0085	0.0122	0.0050	0.0034	1.23	2.18		5.28
Hard maple								
Group 4								
Average	0.8319	0.9041	1.0035	0.9992	16.03	45.92	6.00	62.50
SD	0.0387	0.0371	0.0063	0.0021	2.10	7.65		8.07
Group 5								
Average	0.8462	0.8866	0.9866	1.0006	16.94	42.39	12.00	60.82
SD	0.0340	0.0355	0.0208	0.0037	1.26	0.75		7.62

[a] SD, standard deviation.

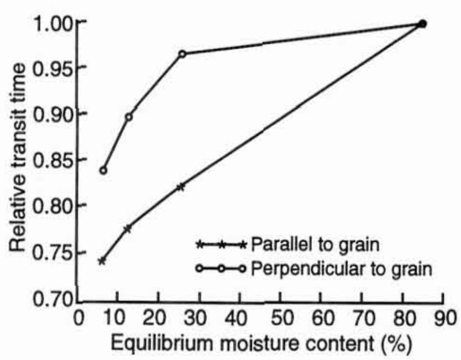

FIG. 6. Relationship between relative transit time and equilibrium moisture content for red oak parallel and perpendicular to the grain.

pecially important during the early part of drying when moisture content is above the fiber saturation point. The moisture content of these boards is critical in schedule step changes. If a step change is made when moisture content is too high, honeycomb can result. The moisture content of kiln samples placed at the edges of a stack are at best poor indicators of moisture content of boards near the center of the stack. These edge sample boards will be at a lower moisture content than boards in the center of the stack. If schedule changes are made according to their low moisture content, the boards in the center will receive the schedule change at a higher moisture content and be at risk of honeycomb. Speed of sound transducers can be applied with equal ease on boards at any location through the width of a stack and therefore have a high likelihood of supplying accurate information with which to make schedule step changes to minimize honeycomb.

Results similar, but in more depth, than those of this study could be used for kiln schedule control, which could be accomplished by using Eqs. (2) and (3) (no schedule changes occur in the region where Eq. (1) applies) to calculate the relative transit times that correspond to moisture contents in kiln schedules. In red oak, the moisture contents where kiln conditions are changed are 50, 40, 35, 30, 25, 20, and 15%. In hard maple, they are 40, 35, 30, 25, 20, and 15% (Simpson 1991).

CONCLUSIONS

The results of this study showed that speed of sound is sensitive to changes in moisture content of lumber during drying. The sensitivity begins at moisture contents above 30%, which is a range not previously accessible to sensors used in nondestructive kiln control.

The results of this study are encouraging enough that further research is planned. The research will include a broader diversity in the source of test material, will employ full-length boards dried by standard kiln schedules, and will attempt to determine if the decrease in transit time with decreasing moisture content is sensitive and constant enough to be used in schedule control.

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