RELATIONSHIP BETWEEN LONGITUDINAL STRESS WAVE TRANSIT TIME AND MOISTURE CONTENT OF LUMBER DURING KILN-DRYING

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ABSTRACT

The relationship between longitudinal stress wave transit time and wood moisture content (MC) was examined as a potential means of estimating MC control points in dry kiln schedules for lumber. A linear relationship was found between the relative transit time and the average MC of sugar maple and ponderosa pine boards dried according to typical kiln schedules.

Lumber dry kiln schedules call for changes in drying conditions at various moisture contents (MCs) both above and below the fiber saturation point, which is approximately 30 percent MC. These changes are made during the drying process. Various methods have been applied to estimate these MC-based control points, all of which have some limitations.' Simpson' showed that the transit time of stress waves through boards is strongly correlated to average board MC, and thus, this technique could possibly be used to determine kiln schedule control points. Other researchers have investigated the relationship between stress wave speed and wood MC, and their findings have been discussed.'

Two aspects of the relationship between stress wave transit time and MC are of particular interest regarding kiln control. First, some of the MC control points are above the fiber saturation point, and current remote, nondestructive moisture sensors are not accurate at these MCs. Simpson[1] found that stress wave transit time is linearly related to average MC between green MCs of 85 and 60 percent for northern red oak and sugar maple, respectively, and a final MC of 7 percent. This observation opens up the possibility of remote, nondestructive MC estimation for control of kiln schedules above the fiber saturation point.

The second aspect of interest is that the relationship between the transit time of an impact-induced stress wave and MC is strongest in the longitudinal direction of lumber. This provides the ability to estimate the MC of lumber at any point across the width of a lumber stack because the stress wave impactors and accelerometers can be mounted on the ends of boards and the end of every full-length board in a lumber stack is equally accessible. In typical current industrial kiln-drying systems, sample boards can only be placed on the edges of a lumber stack for either manual or remote monitoring of MC. Edge boards dry faster than boards in the center of a stack, and estimates of edge board MC do not accurately represent the entire stack. This difference is especially important early in drying when the MC is above the fiber saturation point because checking can occur in center boards if kiln schedule changes are made based on the faster drying edge control boards.

The results reported by Simpson' were from short boards at constant temperature near typical ambient room temperatures of about 70°F (21°C). The purpose of this study was to scale the tests up to full-length (8 ft. (2.4 m)) boards (sugar maple and ponderosa pine) dried in an experimental dry kiln according to typical commercial kiln schedules with their higher temperatures.

EXPERIMENTAL PROCEDURE

Species tested were nominal 2-inch-thick by 6-inch-wide by g-foot-long (standard 38-mm by 139-mm by 2.4-m)

[1] Simpson, W.T. 1998. Relationship between speed of sound and moisture content of red oak and hard maple during drying. Wood Fiber Sci. 30(4):405-413.

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sugar maple and nominal 2-inch-thick by 4-inch-wide by B-foot-long (standard 38-mm by 89-mm by 2.4-m) ponderosa pine. Two kiln charges of each species were dried according to the schedules in **Table 1.** One board, free of decay and excessive knots, in each of the four kiln runs was selected to monitor MC during drying. After several courses of boards were stacked for each of the kiln runs, a course was selected to include the monitor board. The monitor board was weighed and then placed at the center position of the width of the course, the rest of that course was filled with boards, and then several additional courses were added.

Figure 1 shows the set-up of the monitor boards. The experimental set-up consisted of two measurement systems: weight and stress wave transit time. The weight measurement system included two load cells inside the kiln and two signal conditioner indicators outside the kiln. Each monitor board was placed on the load cells, one near each end of the board. Stickering around the monitor boards was arranged so that nothing but the weight of the monitoring board was measured by the load cells. The stress wave measurement system included an accelerometer, an air pressure controlled impactor inside the kiln, and an oscilloscope and air pressure control unit outside the kiln. The impactor was mounted on one end of the monitor board and the accelerometer to receive the signal was mounted on the other end. The stress waveform, monitored and recorded by the oscilloscope, consisted of a series of equally spaced pulses whose magnitudes decreased exponentially with time. The stress wave transit time was determined by measuring the average time from peak to peak of the waveform.

Stress wave transit time and board weight were recorded at various time intervals during kiln-drying. At the end of each kiln run, the monitor boards were ovendried in a high temperature kiln so that MC could be calculated for every load cell reading during drying.

RESULTS

The relationship between stress wave transit time and the average MC of the monitor boards for the four kiln runs is shown in **Figure 2.** Stress wave transit time decreased with MC in all four kiln runs, which confirms the results of the previous study.[1]

The data points in **Figure 2** show induction periods at the start of drying where transit time increased significantly before the relationship settled into the steady decline with MC. This induction period may be due to the effect of temperature on transit time as the wood heats from ambient, which is about 70°F (21°C), to 160°F (71°C). It also may be related to temperature effect on the load cells and stress wave transducers or the establishment of MC gradients near the surface of the boards. This induction period only lasts 2 to 3 hours, which is a small fraction of the total drying time.

For sugar maple, transit times were 102 and 147 µs/ft. (334 and 484 µs/m) for initial MCs of 74 and 57 percent, respectively. For ponderosa pine, the tran-

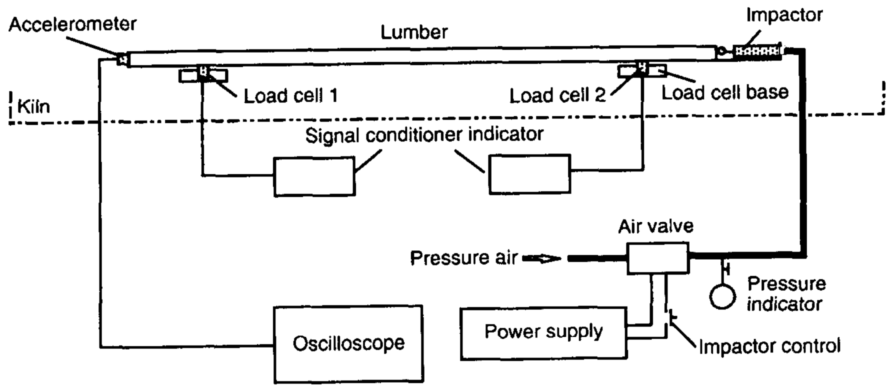

Figure 1. - Experimental set-up for monitoring MC of lumber during kiln-drying.

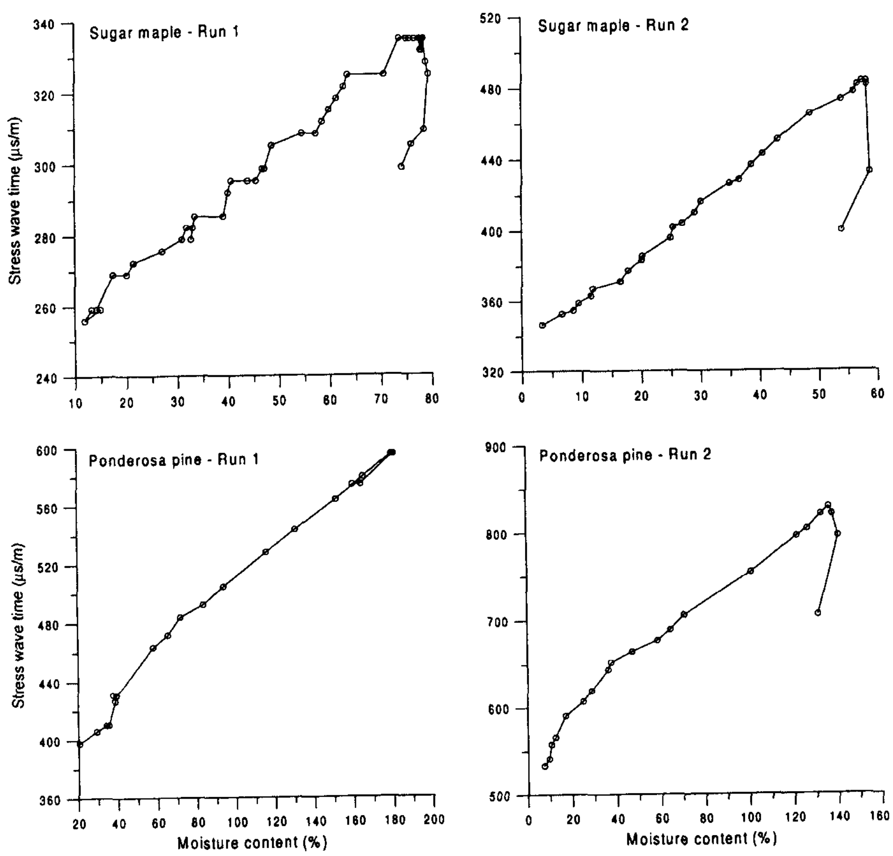

Figure 2. - Stress wave transit time compared with MC during four kiln runs (two with sugar maple and two with ponderosa pine) (1 µs/m = 0.305 µs/ft.).

sit times were 181 and 253 µs/ft. (595 and 828 µs/m) for initial MCs of 180 and 137 percent, respectively. This difference in transit time, which is probably due to natural variability in properties, would make it difficult to correlate MC with transit time for the purpose of kiln control. For example, at 40 percent MC, the transit time for sugar maple run 1 was approximately 88 µs/ft. (290 µs/m), and for run 2, it was 134 µs/ft. (440 µs/m), which is a difference of about 35 percent based on the larger of the two transit times. For ponderosa pine run 1, the transit time at 40 percent MC was about 131 µs/ft. (430 µs/m), and for run 2, it was 192 µs/ft. (630 µs/m), a difference of about 30 percent based on the larger of the two transit times. These wide differences would seriously affect the ability of the correlation to be used for kiln control.

TABLE 1. -Kiln schedules used to correlate stress wave transit time to moisture content during drying.

Time	Dry-bulb temperature		Wet-bulb temperature	
(hr.)	(°F)	(°C)	(°F)	(°C)
Sugar maple				
0 to 24	160	71	153	67
24 to 48	160	71	150	66
48 to 60	160	71	145	63
60 to 72	160	71	135	57
72 to 84	170	77	130	54
84 to end	180	82	130	54
Equalize	180	82	170	77
Ponderosa pine				
0 to 24	160	71	140	60
24 to 36	165	14	140	60
36 to end	170	77	140	60

The data can be analyzed in another way that reduces the differences in transit times. Instead of working with raw stress wave transit times, the transit times were transformed to relative transit times: T/T_0, where T is transit time at any MC and T_0 is the initial transit time before drying begins. In addition, T_0 was taken to be the transit time after the induction period when the transit time has stabilized. This relationship is shown for the four test runs in **Figure 3.** All of the relationships appear linear. This basis for analysis reduces the discrepancy between the two test runs of each species when 40 percent MC is reached. The 40 and 35 percent discrepancies noted when using raw transit times was reduced to about 4 and 5 percent when relative transit times were used. This level may be close enough for kiln control. Data from only two tests on each species, however, is not enough to make firm conclusions on the viability of stress wave transit times as a basis for kiln control. These results are encouraging enough to justify further study to see how well a master T/T_0 and MC relationship for a species, derived from sufficient data, will identify MC change points in a kiln schedule.

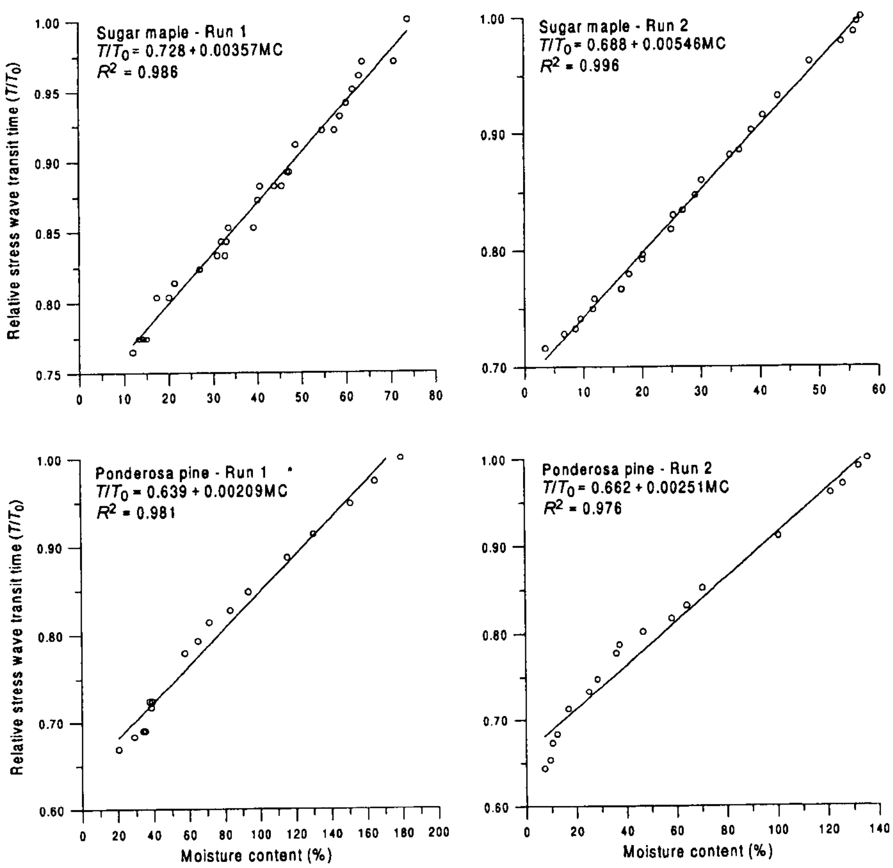

Figure 3. - Relative stress wave transit time compared with MC, showing regression equations, during four kiln runs (two with sugar maple and two with ponderosa pine).

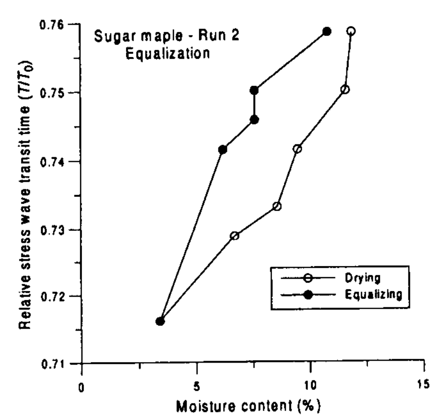

Figure 4.- Response of relative transit time to MC change during equalizing of sugar maple.

Relative transit time can also be used to track progress during equalization **(Fig. 4).** In sugar maple run 2, the monitor board was dried to below 4 percent MC, at which time relative transit time was 0.716, before equalization **(Table 1). Figure 4** shows the progress of equalization back up to about 10 percent MC, with a relative transit time of 0.758.

Conclusions and Recommendations

The stress wave transit time through sugar maple and ponderosa pine in the longitudinal direction decreases linearly with average MC. This relationship can be observed in kiln-drying lumber. Transformation of stress wave transit time data to relative transit times improves the potential of this MC estimation system for use in controlling kiln schedules. Stress wave technology has potential in identifying kiln schedule control points for automatic kiln control. The data collected for this study illustrate the potential, and we recommend that a broader database of relative transit time compared with MC be developed and tested for several species.