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Application of Ultrasonic Technology for Predicting the Final MC of Kiln–dried Softwoods

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Western hemlock and Douglas–fir samples were dried to achieve a wide range of final moisture contents. The parameters related to final moisture content, such as green weight, green moisture content, time of flight (TOF) in green, slope of grain, and basic density, were investigated. For ultrasonic testing, two timers and five pairs of transducers were examined to determine the best combination. Among the evaluated parameters, green weight was the best predictor of final moisture content, although the regression correlation was relatively low. However, correlation was improved when boards were assessed within three grain pattern categories. A two–variable regression model including green weight and TOF showed better correlation with final moisture content than did any of the univariate models. Some multiple regression models with high correlation coefficients were obtained.

Keywords: ultrasonic application, final moisture content, western hemlock, Douglas–fir

INTRODUCTION

The major softwood tree species on the West Coast of the United States, western hemlock and Douglas–fir, are easily dried to a wide range of final moisture contents (Kozlik and Ward, 1981). However, the drying of lumber to non–uniform final moisture contents results in energy loss and higher manufacturing costs. This study seeks to identify the physical properties of green lumber that are best correlated with final moisture content so that lumber can be sorted on the green chain and dried to yield uniform final moisture content.

The presence of wetwood is a principal factor influencing non–uniform final moisture content. Visual sorting can be accomplished with a high degree of accuracy on the green chain, but the practice is not always convenient in high–production mills (Ward and Kozlik, 1975). Other techniques for sorting based on the presence of wetwood have been evaluated, but each suffers from some deficiency. Weighing can be useful but cannot discern wetwood from sapwood. Electric resistance can also be used for sorting, as wetwood has lower electric resistance than green sapwood or normal heartwood due to the presence of extractives. However, the electric resistance of mixed wetwood is not as low as that of adjacent wetwood, thus it is not effective for sorting mixed lumber. There is a strong relationship between the ultrasonic properties of green lumber and wetwood (Ross *et al.*, 1994; Kabir *et al.*, 2006). Other physical properties influencing final moisture content can include green weight, moisture content, density and slope of grain.

The green weight of lumber is related to its green moisture content and density, both of which affect the ultrasonic velocity of the pulse transmitted through the lumber (Gerhards, 1975; Sakai *et al.*, 1990; Ross and Pellerin, 1991; Smulski, 1991; Sandoz, 1993; Booker *et al.*, 1996; Mishiro, 1996a).

In order for the ultrasonic evaluation of wetwood content to be useful for the sorting of lumber in a mill setting, the ultrasonic velocity of lumber must be measurable in the perpendicular–to–fiber direction. Also, since ultrasonic velocity varies with grain orientation and slope, the physical properties must be determined and compensated for (Mishiro, 1996b; Bucur, 2006).

This study evaluates the relationships between the physical properties of green lumber and the final moisture content of kiln–dried lumber. Ultrasonic technology is applied to improve the accuracy of final moisture content prediction.

MATERIALS AND METHODS

Ultrasonic velocity in wood can be measured using the resonant frequency technique as well as with impact and ultrasonic stress wave devices (Gerhards, 1982). In this study, commercial ultrasonic devices known as PUNDIT and STEINKAMP BP5 (BP) were used; the former is made in England and the latter in Germany. Each device consists of a timer, a pulse generator and several pairs of tuned piezoelectric transducers (Fig. 1). The transmitter transducers of the PUNDIT and STEINKAMP devices are activated by their pulse generators every 1/10 and 1.0 second, respectively. The devices both employ resonant transducers with various diameters and frequencies (Table 1). The transducers TD–1,

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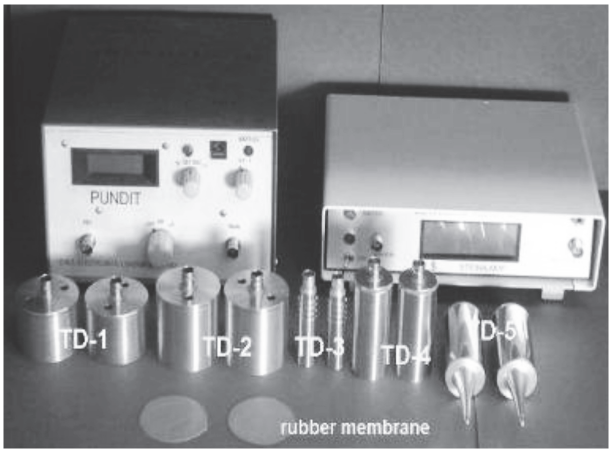

Fig. 1. The ultrasonic timers and piezoelectric resonance transducers used in this study. Two rubber membranes of 0.52 mm thickness act as a coupling medium.

Table 1. Diameters and resonance frequencies of the ultrasonic transducers used in this study. The notations are the same as in Figure 1

Transducer	Diameter (mm)	Resonance frequency (kHz)
TD–1	50	54
TD–2	50	37
TD–3	15	130
TD–4	28	50
TD–5	Point	35

TD–2 and TD–3 are provided with the PUNDIT, and TD–4 and TD–5 operate with STEINKAMP.

A clear, quarter–sawn specimen of western hemlock sapwood was selected to determine the best timer and transducer pair combination. The specimen's dimensions were 38, 83 and 349 mm in the radial, tangential and longitudinal directions, respectively. The transit times in the three directions were measured with 13 timer and transducer combinations. Time of flight (TOF) was calculated from the transit time and traveling distance using Eq. [1].

$TOF = t/L \times 1{,}000$, ………………..[1]
where
TOF: time of flight (ms /m)
L: traveling distance (mm)
t: transit time (ms)

Coupling mediums are typically used in ultrasonic measurements to increase the intimacy between the transducers and the specimen as well as to reduce ultrasonic signal delay. For most of the experiments in this study, no coupling medium was applied to the lumber, possibly increasing the transit time. However, for the evaluation of the coupling effect, thin 0.52–mm–thick rubber membranes were inserted between the transducer and the specimen. Liquid coupling agents are popular in other applications but can be absorbed by wood and may effect change in wood properties, thus no liquid coupling agent was used in this study.

Delays in transit time occur due to the resistance in the cables and the transducer itself. Thus, a zeroing calibration was carried out by placing a calibration bar with a known delay time between the transmitting and receiving transducers, and the determined delay time was then factored into later experiments.

Two preliminary tests were conducted, before which it was assumed that a large variation in transit time existed within a slow–drying board. For the first preliminary test, 1,118–mm–long 2×4 western hemlock boards, kiln–dried at 87.8 ˚C dry–bulb and 65.6 ˚C wet–bulb for 60 hours, were used. Because the transit time of ultrasonic sound transmitted through wood is affected by the slope of grain, the sample boards were selected to be evenly allocated according to grain pattern. Boards sawn from a small–diameter log were categorized into three grain patterns, flat–sawn (FL), half–quarter–sawn (HQ) and box–hearted (BH). The FL and BH patterns consist mostly of sapwood and heartwood, respectively, while HQ boards include both sapwood and heartwood (Fig. 2). The numbers of sample boards were 7, 8 and 8 for FL, HQ and BH, respectively. The transit times of the sound through the thickness of each board were measured every 102 mm from one end, thus ten measurements were obtained from each board. A pair of 37 kHz–transducers and a PUNDIT timer were used for this test.

The second preliminary test was conducted to investigate the effect of drying time on variation in the moisture content gradient along the board length. Twelve green 2,896–mm long 2×4 western hemlock boards were

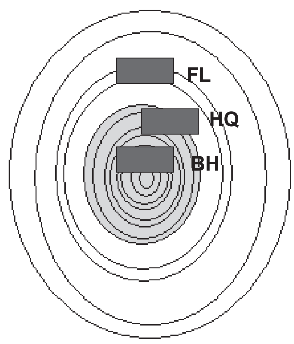

Fig. 2. Diagram of three typical boards taken from different locations of a log. Abbreviations of FL, HQ and BH represent, respectively, flat–sawn, half–quarter–sawn and box–hearted boards.

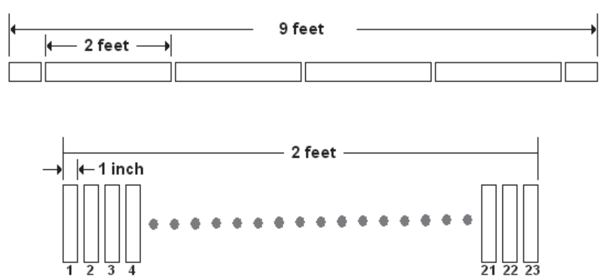

Fig. 3. Diagram of sample boards and test specimens for the experiment of longitudinal moisture distribution. 1 inch = 25.4 mm. 1 feet = 304.8 mm.

obtained from a local saw mill and were cut into four 610–mm boards from each board (Fig. 3). The four matched boards were allocated to four drying times: 12, 24, 36 and 48 hours and were end–coated with a rubber–based paint to prevent moisture loss.

A laboratory kiln with a chamber of 813–mm–width, 686–mm–height and 1,118–mm–length was used to dry the boards. A single drying condition of 87.8 ˚C dry–bulb and 65.6 ˚C wet–bulb was applied for 48 hours. For the second preliminary test, 48 610–mm boards were stacked in the kiln with 19–mm–thick stickers. During drying, each of the four matching boards was taken out of the kiln once every 12 hours. The boards were cooled in a large plastic bag and cross–cut into 23 25–mm slice samples (Fig. 3). The slice samples were weighed, dried in an oven, and their moisture contents were retrospectively calculated based on the oven–dry weights.

After the two preliminary tests, the experiments for predicting the final moisture contents of kiln–dried boards were conducted with two softwood species, western hemlock and Douglas–fir. Green 1,219–mm–long and 51–mm–thick boards were taken to the Lumber Drying Lab at Oregon State University. The widths of the western hemlock and Douglas–fir boards were 152 and 102 mm, respectively. 25–mm–long samples were cut from each end of the board and were immediately stored in a plastic bag for later measurement of basic density. The remaining 1,118–mm–long board was then end–coated with rubber based paint.

The boards were weighed on a digital balance with an accuracy of 5 grams. Three spots evenly–distributed along the length of each board were marked, and the boards were measured for thickness and transit time at the marked locations. The transducers were pushed against the boards by hand to ensure they were not placed against knots or checks, thus improving the transmission of the ultrasonic signals. The two parameters of thickness and transit time were used to calculate TOF using Eq. [1]. The timer and transducer combination selected in the earlier test included the STEINKAM and two transducer pairs rated at 50 kHz–50 kHz and 37 kHz–130 kHz (transmitter–receiver). No coupling media were used.

The 1,118–mm–long boards were stacked in the lab kiln and dried at 87.8 ˚C dry–bulb/65.6 ˚C wet–bulb. Twenty and 40 stacked boards and drying times of 40 hours and 36 hours were used for western hemlock and Douglas–fir, respectively. After being kiln–dried, the stacked boards were weighed and their transit times and thicknesses were measured at the designated locations. The 1,118–mm–long boards were then oven–dried at 103 ˚C and their final moisture contents were calculated.

The 25–mm–long density samples were weighed on a balance with an accuracy of 0.01 grams. Their green volumes were measured using the water displacement method, after which they were oven–dried and weighed. The slope of grain of each of the density samples was measured using a protractor.

Five physical parameters were obtained from each of the green boards, green weight (GW, kg), green moisture content (GM, %), green TOF (TOF, us/m), slope of grain (SG, degree), and basic density (BD, g/cm^3). The parameters were statistically analyzed to investigate their correlations with the final moisture contents of the oven–dried samples.

RESULTS AND DISCUSSION

The amplitudes of ultrasonic signals vary with the combination of timers and transducers. Better combinations yield clearer and higher amplitude signals, resulting in lower TOF (Kang and Booker, 2002). For the tests in this study, the ultrasonic signals were transmitted perpendicular to the fiber direction, in the radial and tangential directions. The sum of the TOFs in these two directions was used as a criterion for selecting the timer and transducer combination. The first three combinations in Table 2 show lower TOF values than the other combinations: PUNDIT and TD3–TD3 or TD2–TD3 and STEINKAMP and TD4–TD4.

Table 2. TOFs in longitudinal, tangential and radial directions of small specimens, measured with combinations of two different timers and five different transducers

Timer	Transducer type		TOF–l	TOF–t	TOF–r	TOF–t+TOF–r
	Transmitter	Receiver				
PUNDIT	TD3	TD3	163	645	468	1,113
PUNDIT	TD2	TD3	163	670	513	1,183
BP	TD4	TD4	165	683	511	1,194
BP	TD5	TD5	162	683	547	1,231
PUNDIT	TD2	TD2	165	672	561	1,233
PUNDIT	TD1	TD3	166	694	566	1,260
PUNDIT	TD2	TD4	169	694	589	1,283
PUNDIT	TD2	TD5	166	718	568	1,286
PUNDIT	TD4	TD4	174	693	600	1,293
PUNDIT	TD1	TD5	173	765	595	1,360
PUNDIT	TD1	TD1	169	754	616	1,370
PUNDIT	TD1	TD4	171	763	616	1,378
PUNDIT	TD5	TD5	177	764	647	1,411

Table 3. Averages and standard deviations of the transit times obtained from the boards categorized according to grain pattern

Board no.	Flat–sawn, FL		Half quarter–sawn, HQ		Box–hearted, BH	
	Average (μs)	Standard deviation (μs)	Average (μs)	Standard deviation (μs)	Average (μs)	Standard deviation (μs)
1	25.5	1.7	27.6	2.8	23.4	2.2
2	25.3	0.7	24.8	0.7	23.5	1.6
3	24.0	1.3	24.2	1.0	23.1	1.1
4	24.7	1.0	27.0	2.6	25.0	1.5
5	26.4	1.1	25.3	1.3	21.2	1.6
6	26.0	0.6	27.5	1.5	25.2	1.8
7	25.2	0.7	25.3	2.5	28.0	2.3
8			28.9	1.7	23.2	1.4
Average	25.3	1.0	26.3	1.8	24.1	1.7

Regardless of its having the lowest TOF, the PUNDIT and TD3–TD3 combination was not used because it was difficult to simultaneously push both of the small–diameter transducers against the sides of the board. Since they offer the benefits of low TOF values and ease of placement, the combinations of PUNDIT and TD2–TD3 and of STEINKAMP and TD4–TD4 were selected for the tests.

The rubber membrane coupling reduced the TOF for the combination of STEINKAMP and TD4–TD4 by less than 2.3%. However, the coupling increased the TOF for the other combinations, most notably by 15.3% for the combination of PUNDIT and TD2–TD2, which had the largest transducer diameter and the lowest resonance frequency. These results imply that, for most transmitter and receiver combinations, the rubber membrane attenuated the transmitted ultrasonic signals to such an extent that any benefit offered by the improved intimacy between the board and transducers was more than offset. Therefore, the experiments were conducted without coupling media.

The averages and standard deviations of the transit times of the kiln–dried western hemlock boards are listed in Table 3 according to grain pattern. Each value is the average of ten measurements in a board. Statistical t–tests revealed that the average transit times were significantly different among the three grain patterns. It could be postulated that the average transit time is positively related to the average moisture content of the board within a grain pattern, and that a board with a high standard deviation will be dried less uniformly. It is notable that the standard deviations of the FL boards were not more than 1.7 ms, but that three out of the eight HQ boards had standard deviations greater than 2.5 ms. This result is consistent with past research showing that the wetwood of western hemlock is generally located on the border between the sapwood and heartwood (Kozlik and Ward, 1981).

It is more clearly shown in Fig. 4. The average moisture contents of the drying boards, at four different drying times, were plotted against the initial moisture content. The slopes of the linear regressions between the two variables decreased with drying time. Linear correlations between the variables existed at drying times of 12 and 24 hours but not at 36 or 48 hours, suggesting that the variation in moisture content among the drying boards, regardless of their initial moisture content, was significantly reduced after 36 hours.

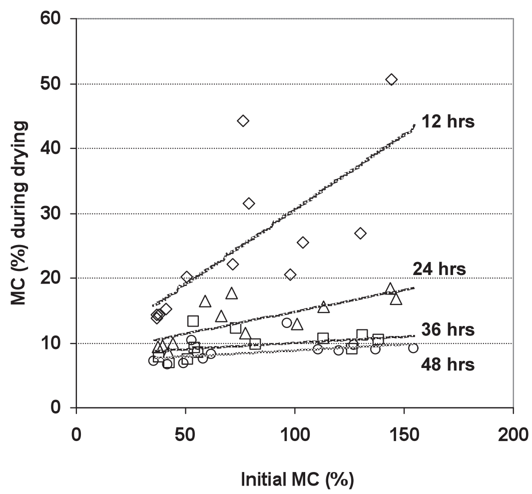

Fig. 4. Plots of the average moisture contents of the drying boards after 12, 24, 36 and 48 hours of drying time against their initial moisture contents, showing that average moisture content variation among the boards decreased with drying time.

In addition to the TOF obtained with the ultrasonic test method, four other parameters of green boards were evaluated for correlation with the final moisture contents of the board specimens. Statistical analyses were conducted with the data obtained from the kiln–dried 1,118–mm–long boards. Univariate correlations of the five parameters with the final moisture contents were computed using a SAS statistical program package. Analysis of the specimens in each run revealed that GW was best correlated with final moisture content in both species, although its coefficient of determination (R^2) for western hemlock was only 0.49 (Table 4). The R^2 value of 0.75 for Douglas–fir indicates a reasonably strong correlation.

The specimens were then divided according to grain

Table 4. The univariate coefficients of determination (R^2) of five physical parameters of green boards with their final moisture contents. Abbreviations of FL, HQ and BH represent, respectively, flat–sawn, half–quarter–sawn and box–hearted boards

Species	Grain pattern	Green weight GW	Green MC GM	Slope of grain SG	Green TOF TOF	Basic density BD
Western hemlock	OVERALL	0.49	0.30	0.15	0.11	0.00
	FL	0.87	0.85	0.39	0.20	0.11
	HQ	0.90	0.92	0.00	0.01	0.24
	BH	0.99	0.97	0.16	0.15	0.02
Douglas–fir	OVERALL	0.75	0.60	0.13	0.16	0.28
	FL	0.95	0.82	0.29	0.55	0.03
	HQ	0.44	0.58	0.03	0.11	0.01
	BH	0.37	0.00	0.06	0.14	0.32

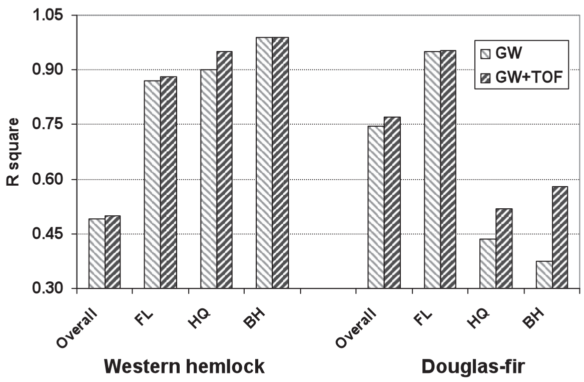

Fig. 5. Comparison of R^2s of one– and two–variable regression models. Abbreviations of FL, HQ and BH represent, respectively, flat–sawn, half–quarter–sawn and box–hearted boards, while that of GW represents green weight.

pattern (Fig. 2), and the univariate statistical analyses were repeated. The correlation coefficients of the hemlock GW values, by grain pattern, were significantly increased relative to the analysis of the ungrouped samples, with R^2 values ranging from 0.87 and 0.99, while the correlation coefficients of Douglas–fir were reduced, except for that of FL (Table 4). For Douglas–fir, the R^2 values for HQ and BH were only 0.44 and 0.37, respectively; multi–variable models were evaluated to determine a better predictor of final moisture content.

A regression model with more variables may allow for better correlation among its component measurements, but it may also be more complicated to collect the variables. Among the five parameters, GW and TOF are easier to measure in practice on the green chain. The two–variable regression models showed slightly improved correlations with final moisture content compared to those of the models correlating only GW and final moisture content (Fig. 5). The correlation coefficients for the HQ and BH of Douglas–fir boards, which had the lowest R2 values in the univariate analysis, showed the most improvement according to multivariate analysis, although the R^2 values were still less than 0.6. Thus, for western hemlock, a three–variable regression model was employed to evaluate the combined board types of the OVERALL bin, and the model was also used to evaluate correlation for the HQ and BH Douglas–fir board types. These three–variable models were optimized by board type and for the OVERALL bin for western hemlock. For Douglas–fir, the three–variable model yielded the significantly improved R^2 values of 0.85 and 0.71 for HQ and BH compared to the results of the univariate and two–variable regression models, respectively. Again, the correlation coefficient for the OVERALL bin of western hemlock was not significantly improved (Table 5). It was noted that the third variable in the three three–variable regression models varied among board type or bin and included

Table 5. Optimized multiple regression equations for the three grain patterns of western hemlock and Douglas–fir. Abbreviations of FL, HQ and BH represent, respectively, flat–sawn, half–quarter–sawn and box–hearted boards, while those of GW, GM and BD, respectively, the wood properties of green weight, green moisture content and basic density

Species	Grain pattern	Optimized multiple regression equation	R^2
Western hemlock	OVERALL	7.075 GW + 0.00992 TOF – 0.1114 GM–18.86	0.60
	FL	2.964 GW – 0.01372 TOF + 7.36	0.88
	HQ	2.694 GW + 0.01146 TOF – 9.30	0.95
	BH	9.616 GW – 0.00090 TOF – 25.66	0.99
Douglas–fir	OVERALL	3.905 GW + 0.00574 TOF – 4.02	0.77
	FL	3.793 GW – 0.00228 TOF + 2.35	0.95
	HQ	−1.770 GW + 0.01981 TOF + 0.0689 GM – 3.76	0.85
	BH	6.422 GW + 0.01057 TOF + 20.881 BD – 19.99	0.71

either GM or BD.

The optimum multiple regression equations and R^2 values for all specimens used in this study are listed in Table 5. For western hemlock, the R^2 value of OVERALL did not exceed 0.6 even with the three–variable regression model. However, for Douglas–fir, an R^2 value of 0.77 was achieved with the two–variable regression model. This implies that the evaluated wood properties were more uniform in Douglas–fir than in western hemlock, and that a univariate regression model can be employed for the prediction of final moisture content in Douglas–fir more effectively than it can for that of western hemlock.

Depending on species, however, confining the modeling of final moisture content by grain pattern may significantly increase the predictive capacity of the regression model. This was especially notable for western hemlock in this study. Sorting boards according to their predicted final moisture contents could be profitable in practice, and it would be preferable to complete board sorting on the green chain and before kiln–drying. Modern technology including digital image processing may simplify the identification of board grain patterns on the green chain, and thus sorting and modeling consistent with the methods described herein may have commercial application.

CONCLUSIONS

This study sought to predict the final moisture contents of kiln–dried western hemlock and Douglas–fir boards using ultrasonic and physical properties measured before kiln–drying. The properties included green weight, green moisture content, green TOF, slope of grain, and basic density. The study makes the following conclusions.

1. Two specific combinations of timers and transducers were determined to be best suited for the methods employed in this study.
2. For all boards of each species, green weight was the best predictor of final moisture content. However, the correlation coefficients (R^2) for western hemlock and Douglas–fir were only 0.49 and 0.75, respectively. The correlation coefficients were significantly improved for most categories when the boards were categorized according to grain pattern and species.
3. The two–variable regression models including green weight and TOF yielded slight improvements in correlation coefficients compared to those of their univariate counterparts.
4. This study offers optimum multiple regression models by board type (western hemlock) or overall (Douglas–fir) that predict the final moisture contents of the evaluated species with high correlation coefficients. The models could be refined and applied to sorted boards in a commercial application, with the end goal of decreasing energy consumption and manufacturing cost.

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