Ultrasonics 66 (2016) 86–90

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Potential of ultrasonic pulse velocity for evaluating the dimensional stability of oak and chestnut wood

Türker Dündar [a,*], Xiping Wang [b], Nusret As [a], Erkan Avcı [c]

[a] Istanbul University, Faculty of Forestry, Bahcekoy, Sariyer, 34473 Istanbul, Turkey
[b] USDA Forest Service, Forest Products Laboratory, One Gifford Pinchot Drive, Madison 53726-2398, WI, United States
[c] Muğla Sıtkı Koçman University, Faculty of Technology, Kötekli, 48000 Muğla, Turkey

ARTICLE INFO

Article history:
Received 3 May 2015
Received in revised form 12 November 2015
Accepted 13 November 2015
Available online 27 November 2015

Keywords:
Ultrasonic velocity
Dimensional stability
Shrinkage
Specific gravity
Wood

ABSTRACT

The objective of this study was to examine the potential of ultrasonic velocity as a rapid and nondestructive method to predict the dimensional stability of oak (*Quercus petraea* (Mattuschka) Lieblein) and chestnut (*Castanea sativa* Mill.) that are commonly used in flooring industry. Ultrasonic velocity, specific gravity, and radial, tangential and volumetric shrinkages were measured on seventy-four $20 \times 20 \times 30\text{-mm}^3$ specimens obtained from freshly cut oak and chestnut stems. The ultrasonic velocities of the specimens decreased with increasing moisture content (MC). We found that specific gravity was not a good predictor of the transverse shrinkages as indicated by relatively weak correlations. Ultrasonic velocity, on the other hand, was found to be a significant predictor of the transverse shrinkages for both oak and chestnut. The best results for prediction of shrinkages of oak and chestnut were obtained when the ultrasonic velocity and specific gravity were used together. The multiple regression models we developed in this study explained 77% of volumetric shrinkages in oak and 72% of volumetric shrinkages in chestnut. It is concluded that ultrasonic velocity coupled with specific gravity can be employed as predicting parameters to evaluate the dimensional stability of oak and chestnut wood during manufacturing process.

1. Introduction

As building and engineering materials, wood has the advantages of being economical, low in processing energy, renewable, strong, and aesthetically pleasing. However, some wood characteristics limit its use, among them the swelling and shrinking of wood as it takes up and loses moisture [16]. Dimensional stability is a measure of the extent of swelling or shrinkage resulting from moisture movement in wood below fiber saturation point (FSP). Dimensional stability of wood products during use affects their function and service life and is therefore of huge economic value to the forest industry. Dimensional changes of wood caused by sorption are anisotropic and dependent on the anatomical direction of wood [19]. Wood shrinkage also depends on microstructural and molecular features of the cell wall. These include microfibril angle (MFA), the angle at which the cellulose fibrils wind in the cell walls, as well as physical properties of the surrounding matrix. Longitudinal shrinkage of wood is generally quiet small (0.1–0.2% of the green condition when oven dried). This small change is often neglected in the manufacture and subsequent use of the wood products. However, transverse shrinkages in tangential and radial directions are of major importance. Tangentially, wood shrinks from 6% to 12% of the green dimension when dried from green to the oven-dry condition for hardwood [6]; while in the radial direction the corresponding shrinkage is roughly one half of the tangential shrinkage for a given wood specimen. This differential of radial-tangential shrinkage is one of the primary factors causing shape distortion during seasoning of lumber and during ultimate use. This is one of the most important challenges to the hardwood flooring industry where the dimensional stability of the products is critical.

Traditionally shrinkage has been correlated with density [20]. This correlation is not particularly strong and represents a general trend for sound wood of different species [20,13]. X-ray lumber density scanning is successful in grading structural lumber based on prediction of stiffness and strength, but no shrinkage prediction capability has been established [18]. Some studies investigated the potential of near infrared (NIR) spectroscopy as a tool for shrinkage prediction. It was reported that for 5-year old *Eucalyptus urophylla* × *E. Grandis* hybrids, tangential shrinkage could be modeled with 82% accuracy by NIR [1], whereas weak correlations with radial shrinkage (0.45) and longitudinal shrinkage (0.35) precluded

* Corresponding author. Tel.: +90 212 3382400x25362; fax: +90 212 2261113.
E-mail addresses: dundar@istanbul.edu.tr (T. Dündar), xwang@fs.fed.us (X. Wang), nusretas@istanbul.edu.tr (N. As), erkanavci@mu.edu.tr (E. Avcı).

http://dx.doi.org/10.1016/j.ultras.2015.11.007
0041-624X/

similar predictions. For mahogany (*Swietenia macrophylla*), 63% of the variation in volumetric shrinkage could be predicted by NIR [21]. Neutron imaging is able to simultaneously image moisture and moisture-induced deformation fields with high spatial and temporal resolution [7,15,17,12]. Sanabria et al. [17] reported that applied to the investigation of hygroscopic gradients in softwood growth rings, Adaptive Neutron Radiography Correlation (ANRC) provided an excellent agreement with gravimetric moisture content (0.9% rms error) and optic surface strain measurements (0.5% error). Nuclear magnetic resonance and X-ray radiography also allow visualization of both free water and bound water in wood in submilimeter scale [4].

A number of studies also suggest that acoustic wave techniques may be used to assess the dimensional stability of structural lumber. Wang and Simpson [22] evaluated the potential of acoustic analysis as presorting criteria to identify warp-prone boards before kiln-drying. Dimension lumber ($38 \times 89 \times 2440\ mm^3$) sawn from open-grown small-diameter ponderosa pine trees was acoustically tested lengthwise at green condition. They found that the amount of warp in the form of crook and bow that developed during drying decreased as green board measurements of acoustic speed and dynamic MOE increased and rate of wave attenuation decreased. The results also showed a statistically significant correlation between acoustic properties of the boards and the grade loss because of exceeding warp limits. Ivkovic et al. [10] investigated a range of wood properties that can be measured with relative ease and low cost for their ability to predict wood stiffness, strength, and shrinkage in juvenile wood of radiata pine. With respect to shrinkage prediction, they found that density and MOE had a weak relationship with radial and tangential shrinkages (r^2 = 0.13–0.16), while acoustic velocity and MOE had a strong negative non-linear relationship with longitudinal shrinkage of the inner ring samples (r^2 = 0.78 and 0.58 respectively). Based on their findings, they recommended that acoustic velocity combined with increment core density be used as practical measurement parameters for predicting stability in young trees.

In a recent paper [5], we reported the findings of a laboratory study on predicting transverse shrinkages of two softwood species (Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*)) with ultrasonic measurements. Both specific gravity of wood and peak energy of the received ultrasonic signals were not good predictors of radial and tangential shrinkages for Sitka spruce and western hemlock. However, ultrasonic velocity was found to be a significant predictor of transverse shrinkages for both species.

The goal of this study was to further examine the potential of ultrasonic measurement as a rapid and nondestructive method to predict the dimensional stability of two hardwood species, oak and chestnut grown in Turkey. The specific objectives were to (1) examine the relationships between transverse shrinkages (radial, tangential, and volumetric shrinkages) and specific gravity, ultrasonic velocity of oak and chestnut specimens; (2) determine the best nondestructive parameters for predicting transverse shrinkages of oak and chestnut.

2. Materials and methods

2.1. Specimen preparation

Oak (*Quercus petrea* (Mattuschka) Lieblein) and chestnut (*Castanea sativa* Mill.) wood that are commonly used in floor industry were used to prepare specimens. A total of four5-cm-thick disks were taken from freshly cut oak and chestnut tree stems, two from each species. The disks were immediately placed in a plastic bag in order to maintain green condition and then transported to the wood testing laboratory at the Faculty of Forestry, Istanbul University. The wood specimens for shrinkage measurements were prepared from pith to bark of the disks. The sizes of the specimens were 20 by 20 by 30 mm with the 30-mm dimension along the grain. A total of 74 specimens were obtained, including 36 oak and 38 chestnut. A special care was taken to prevent moisture loss from the samples throughout the sample preparation process.

2.2. Experimental procedure

The initial weight and dimensions of all specimens at green condition were immediately measured and recorded. The weight was measured to the nearest 0.01 g and the dimension was measured to the nearest 0.01 mm.

A Sylvatest Duo (CBS-CBT, Les Ecorces, France) device operating at a frequency of 22 kHz was used to measure the ultrasonic velocity in each specimen. The transmitter probe and the receiver probe were positioned at the opposite faces of a specimen with a constant pressure (50 N) applied to the probes to improve the coupling between the probes and wood. The measurements were made in both radial and tangential direction. For each measurement, the transmitter probe emitted five consecutive pulses through the specimen. An average ultrasound propagation time (UPT) was recorded after each measurement. The ultrasonic velocity (V) of the specimen was calculated based on the average UPT value and the distance between two probes (L):

$$V = L/UPT \quad (\mathrm{m/s}) \tag{1}$$

After initial measurements, all specimens were then sequentially subjected to 90%, 80%, 65%, 50%, and 40% relative humidity (RH) at a constant temperature of 20 °C in a climatic room until they reached constant weight, then followed by oven dry at 103 ± 2 °C for 48 h to reach a 0% MC. When each MC level was reached, the weight and dimension of each sample were measured, followed by ultrasonic measurements in both radial and tangential directions using the Sylvatest Duo device.

2.3. Data analysis

In this study, tangential, radial, and volumetric shrinkages of the specimens were determined from green condition of initial measurement to oven dry condition. The specific gravity (SG) of the specimens was determined based on 12% equilibrium moisture content (EMC) volume and oven dry weight. Single and multiple variable statistical regression analysis were used to determine the following relationships: (1) ultrasonic velocity versus wood moisture content (MC); (2) specific gravity versus tangential, radial, and volumetric shrinkages; (3) ultrasonic velocity in green condition versus tangential, radial and volumetric shrinkages; (4) specific gravity and ultrasonic velocity in green condition versus tangential, radial, and volumetric shrinkages.

3. Results and discussion

3.1. Relationship between specific gravity and transverse shrinkages

Table 1 summarizes the statistics of specific gravity (SG), radial shrinkage (RS), tangential shrinkage (TS), volumetric shrinkage (VS), and tangential to radial shrinkage ratio (TS/RS) for oak and chestnut specimens. The mean specific gravity was found to be 0.612 for oak and 0.515 for chestnut, which is in a good agreement with the values given in the Turkish literature for same species [2,3]. The shrinkage values presented in this table are from FSP to oven dry condition. It was found that tangential shrinkage was

Table 1
Specific gravity and transverse shrinkages of oak and chestnut.

Species	No. of specimens	Initial MC (%)	Specific gravity (12% MC)	Shrinkage from FSP to 0% MC (%)			
				Radial (RS)	Tangential (TS)	Volumetric (VS)	Ratio (TS/RS)
Oak	36	56.4	0.612 (0.063)[a]	5.1 (1.11)	10.8 (1.74)	15.6 (2.23)	2.1
Chestnut	38	69.5	0.515 (0.052)	3.8 (0.77)	8.1 (0.99)	12.0 (1.34)	2.1

[a] The number in parenthesis is standard deviations. FSP: Fiber saturation point, MC: Moisture content.

47% higher than radial shrinkage for both oak and chestnut. The differences were significant at 0.01 level of probability.

The degree of correlation between shrinkage and specific gravity was evaluated by linear regression analysis. The results were given in Table 2. The relationships between SG and shrinkage values were found to be relatively low but significant ($p < 0.01$) except for the shrinkage of chestnut specimens in tangential direction ($r^2 = 0.04$) which was non-significant. The coefficients of determination were higher for oak ($r^2 = 0.373–0.484$) than chestnut ($r^2 = 0.041–0.204$).

3.2. Ultrasonic velocity in relation to moisture content

Fig. 1 shows the relationships between ultrasonic velocity and moisture content for oak and chestnut. Ultrasonic velocities in both tangential and radial direction were found to increase continuously as MC decreased when the MC below the FSP. Above the FSP, ultrasonic velocity remained almost constant. This is in agreement with the velocity trend reported in other studies [14,23,8] and similar to the influence of moisture content on modulus of elasticity [9,11]. Power regression model was found to best fit to the velocity-MC data when MC is below FSP as seen on Fig. 1. The correlation was stronger in radial direction ($r^2 = 0.80$ for oak and 0.78 for chestnut) than in tangential direction ($r^2 = 0.75$ for oak and 0.68 for chestnut). Ultrasonic velocity-MC relationship indicates that, velocity of green wood can be adjusted to a velocity value at any MC below FSP and also velocity measured in green condition could be used to predict radial and tangential shrinkages of chestnut and oak.

3.3. Relationship between ultrasonic velocity and transverse shrinkages

The results of linear regression analysis for the transverse shrinkages and ultrasonic velocity in green condition relations are tabulated in Table 3. The radial and tangential shrinkages decreased linearly with increasing ultrasonic velocity for oak. The correlation was stronger in radial direction ($r^2 = 0.67$) than in tangential direction ($r^2 = 0.52$). A similar relationship was found in chestnut with a coefficient of determination (r^2) of 0.70 in radial direction and 0.56 in tangential direction as shown in Table 3. Note that the shrinkage–velocity data obtained in radial and tangential directions fit to the same general trend within each species. Examination of the shrinkage–velocity models indicated that the linear correlation coefficients (b) were close in radial and tangential directions for both oak and chestnut.

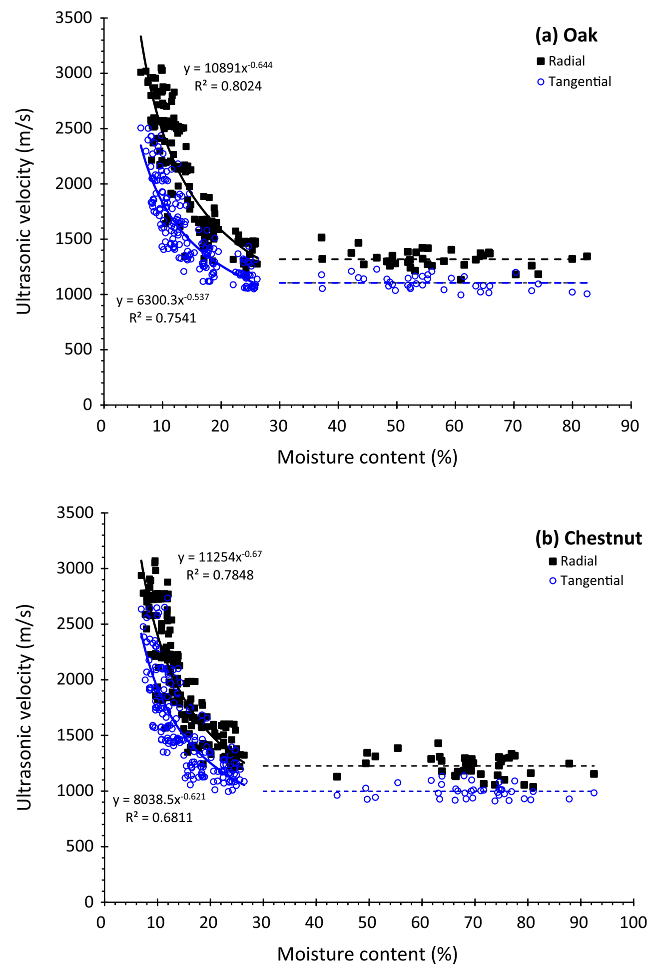

Fig. 1. Relationships between ultrasonic velocity and MC for oak and chestnut.

The velocity calculated as average of tangential and radial velocity explained 65% of the volumetric shrinkage for oak and 64% of the volumetric shrinkage for chestnut according to the

Table 2
Results of linear regression analysis of shrinkage and specific gravity relationships for oak and chestnut.

Species	y Transverse shrinkage (%)	x Specific gravity	Regression model: $y = a + bx$				p
			a	b	r^2	SEE	
	Tangential (TS)	SG	−0.268	17.096	0.373	1.402	<0.001
Oak	Radial (RS)	SG	−1.762	11.185	0.387	0.889	<0.001
	Volumetric (VS)	SG	−0.405	24.785	0.484	1.618	<0.001
	Tangential (TS)	SG	−6.097	3.838	0.041	0.980	0.222*
Chestnut	Radial (RS)	SG	−0.053	7.447	0.255	0.673	0.001
	Volumetric (VS)	SG	−6.033	11.521	0.204	1.204	0.004

* Not significant. SEE: Standard error of estimation, SG: Specific gravity, MC: Moisture content.

Table 3
Results of linear regression analysis of ultrasonic velocity and shrinkage relationships for oak and chestnut.

Species	*y* Transverse shrinkage (%)	*x* Ultrasonic velocity (m/s)	Regression model: $y = a + bx$				*p*
			a	*b*	r^2	SEE	
Oak	Tangential (TS)	V_T	23.136	−0.011	0.525	1.220	<0.001
	Radial (RS)	V_R	20.632	−0.012	0.670	0.653	<0.001
	Volumetric (VS)	V[a]	44.669	−0.024	0.650	1.332	<0.001
Chestnut	Tangential (TS)	V_T	15.514	−0.007	0.563	0.661	<0.001
	Radial (RS)	V_R	12.187	−0.007	0.702	0.426	<0.001
	Volumetric (VS)	V[a]	26.053	−0.012	0.641	0.809	<0.001

[a] Calculated as average of V_T and V_R. SEE: Standard error of estimation.

Table 4
Results of multiple variable regression analysis of shrinkage, ultrasonic velocity and specific gravity relationships for oak and chestnut.

Species	*y* Shrinkage (%)	x_1 Specific gravity	x_2 Ultrasonic velocity (m/s)	Regression model: $y = ax_1 + bx_2 + c$					*p*
				a	*b*	*c*	r^2	SEE	
Oak	Tangential (TS)	SG	V_T	10.000	−0.009	14.274	0.627	1.097	<0.001
	Radial (RS)	SG	V_R	7.690	−0.010	13.663	0.839	0.463	<0.001
	Volumetric (VS)	SG	V	14.148	−0.018	29.031	0.770	1.095	<0.001
Chestnut	Tangential (TS)	SG	V_T	3.230	−0.007	13.778	0.592	0.648	<0.001
	Radial (RS)	SG	V_R	3.247	−0.006	9.681	0.743	0.401	<0.001
	Volumetric (VS)	SG	V	7.196	−0.011	21.202	0.716	0.729	<0.001

SEE: Standard error of estimation, SG: Specific gravity, MC: Moisture content.

linear regression model. This indicated that ultrasonic measurement in green condition has a good potential to be used as a non-destructive method for predicting the transverse shrinkages of oak and chestnut wood.

3.4. Multiple variable regression model

The results of multiple variable linear regression analysis of the relationships between shrinkage and ultrasonic velocity and SG are shown in Table 4. The coefficients of determination increased considerably in all directions except for the tangential direction of chestnut when the ultrasonic velocity and SG were used together to predict shrinkages. For example, the ultrasonic velocity explained 65% for oak and 64% for chestnut alone (Table 3), it was raised 77% for oak and 72% for chestnut when the ultrasonic velocity and SG were used together (Table 4).

3.5. Prediction of transverse shrinkages

The results of this study showed that specific gravity alone was not a good predictor of shrinkage as indicated by weak correlations. Ultrasonic velocity, on the other hand, was found to be a significant predictor of transverse shrinkages in oak and chestnut and therefore has a good potential to be used as a field method to evaluate the dimensional stability of standing trees. Wave propagation is controlled by the mechanical properties of the material and material characteristics such as anatomical structure, grain orientation, microfibril alignment etc.. There are also physical links between material shrinkage and material characteristics. The strong correlation between the ultrasonic velocity and shrinkage can be explained that the same characteristics that affect shrinkage, also affect acoustic wave propagation in wood. The best results for prediction of shrinkages of oak and chestnut were obtained when the ultrasonic velocity and SG were used together. Fig. 2 shows the plot of predicted shrinkage values and measured shrinkage values for oak and chestnut. The multiple parameter prediction model explained 84% of radial shrinkage, 62% of tangential shrinkage, and 76% of volumetric shrinkage in oak. As for chestnut, it explained 74% of radial shrinkage, 60% of tangential shrinkage, and 71% of volumetric shrinkage.

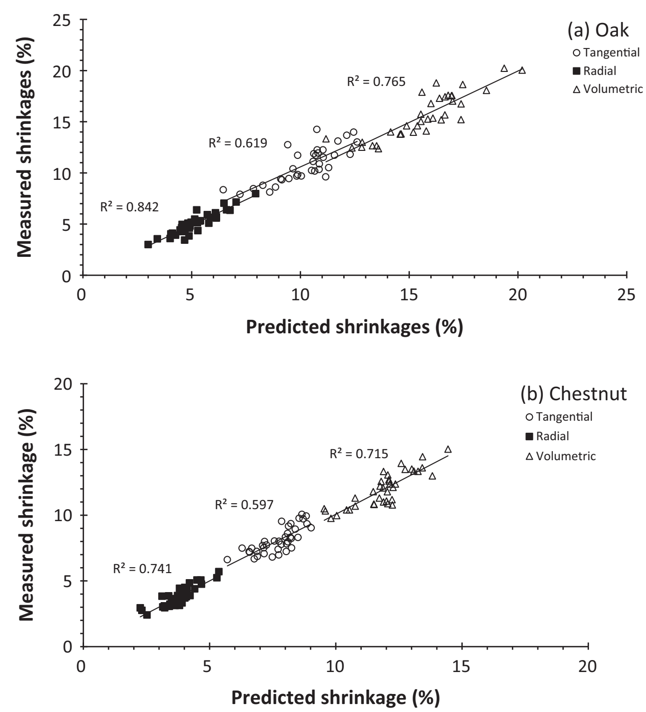

Fig. 2. Relationships between predicted shrinkages and measured shrinkages for oak and chestnut.

4. Conclusions

Specific gravity was found to show relatively weak relationships with the transverse shrinkages and was not a good predictor of dimensional stability. Both tangential and radial shrinkages decreased linearly in a similar trend with increasing ultrasonic velocity.

The best results for prediction of shrinkages of oak and chestnut were obtained when the ultrasonic velocity and SG were used together. The multiple parameter prediction model explained 84% and 74% of radial shrinkage, 62% and 60% of tangential shrinkage, and 76% and 71% of volumetric shrinkage in oak and chestnut, respectively.

Ultrasonic velocities in both tangential and radial direction were found to increase continuously as MC decreased when the MC below the FSP. Above the FSP, ultrasonic velocity remained almost constant. Power regression model was found to best fit to the velocity-MC data when MC is below FSP. The correlation was stronger in radial direction (r^2 = 0.80 for oak and 0.78 for chestnut) than in tangential direction (r^2 = 0.75 for oak and 0.68 for chestnut).

The results of this study indicated that ultrasonic velocity was a significant predictor of transverse shrinkages and therefore has a good potential to be used as a field method to evaluate the dimensional stability of wood. The best prediction of the transverse shrinkage of oak and chestnut can be achieved when both ultrasonic velocity and specific gravity are used as predicting parameters through multiple variable regression models.

References

[1] H. Bailleres, F. Davrieus, F.H. Pichavant, Near infrared analysis as a tool for rapid screening of some major wood characteristics in a eucalyptus breeding program, Ann. For. Sci. 59 (2002) 479–490.

[2] A. Berkel, Ağaç malzeme teknolojisi Cilt I. I.U. Orman Fakultesi Yay. No. 147, Kutulmuş Matbaası, Istanbul, 1970.

[3] A.Y. Bozkurt, Y. Göker, Fiziksel ve mekanik ağaç malzeme teknolojisi. I.U. Orman Fakultesi Yay. No. 388, Istanbul, 1987.

[4] S.V. Dvinskikh, M. Henriksson, L.A. Berglund, I. Furó, A multinuclear magnetic resonance imaging (MRI) study of wood with adsorbed water: estimating bound water concentration and local wood density, Holzforschung 65 (2011) 103–107.

[5] T. Dundar, X. Wang, R.J. Ross, Prediction of transverse shrinkages of young-growth Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*) with ultrasonic measurements, Wood Mat. Sci. Eng. 8 (4) (2013) 234–241.

[6] FPL, Wood handbook—Wood as an engineering material, General Technical Report FPL-GTR-190; USDA Forest Service, Forest Products Laboratory, Madison, WI, 2010.

[7] M.S. Gilani, M. Griffa, D. Mannes, E. Lehmann, J. Carmeliet, D. Derome, Visualization and quantification of liquid water transport in softwood by means of neutron radiography, Int. J. Heat Mass Transfer 55 (2012) 6211–6221.

[8] R. Gonçalves, O.A.E. Costa, Influence of moisture content on longitudinal, radial, and tangential ultrasonic velocity for two Brazilian wood species, Wood Fiber Sci. 40 (4) (2008) 580–586.

[9] D. Green, D. Kretschmann, Moisture content and the properties of clear southern pine. Research Paper FPL-RP-531. USDA Forest Service, Forest Products Laboratory, Madison, WI, 1994.

[10] M. Ivkovic, W.J. Gapare, A. Abarquez, J. Ilic, M.B. Powell, H. Wu, Prediction of wood stiffness, strength, and shrinkage in juvenile wood of radiate pine, Wood Sci. Technol. 43 (2009) 237–257.

[11] F.F.P. Kollman, W.A. Cote, Principles of Wood Science and Technology. Solid Wood, vol. 1, Springer Verlag, Berlin, Germany, 1968.

[12] C. Lanvermann, S.J. Sanabria, D. Mannes, P. Niemz, Combination of neutron imaging (NI) and digital image correlation (DIC) to determine intra-ring moisture variation in Norway spruce, Holzforschung 68 (1) (2014) 113–122.

[13] M. Leonardon, C.M. Altaner, L. Vihermaa, M.C. Jarvis, Wood shrinkage: influence of anatomy, cell wall architecture, chemical composition and cambial age, Eur. J. Wood Prod. 68 (2010) 87–94.

[14] A. Mishiro, Ultrasonic velocity and moisture content in wood II. Ultrasonic velocity and average moisture content in wood during desorption (1): moisture content below the fiber saturation point, Mokuzai Gakkaishi 42 (1996) 612–617.

[15] S. Rosner, M. Riegler, P. Vontobel, D. Mannes, E.H. Lehmann, B. Karlsson, C. Hansmann, Within-ring movement of free water in dehydrating Norway spruce sapwood visualized by neutron radiography, Holzforschung 66 (2012) 751–756.

[16] R.M. Rowell, W.B. Banks, Water repellency and dimensional stability of wood, General Technical Report FPL-50, USDA Forest Service, Forest Products Laboratory, Madison, WI, 1985.

[17] S.J. Sanabria, C. Lanvermann, F. Michel, D. Mannes, P. Niemz, Adaptive neutron radiography correlation for simultaneous imaging of moisture transport and deformation in hygroscopic materials, Exp. Mech. 55 (2015) 403–415.

[18] G. Schajer, Lumber strength grading using X-ray scanning, For. Prod. J. 51 (1) (2000) 43–50.

[19] C. Skaar, Wood-water relations. Springer series in wood science, Springer Verlag, Berlin, 1988.

[20] O. Suchsland, The Swelling and Shrinking of Wood—A Practical Technology Primer, Forest Products Society, Madison, WI, 2004.

[21] A.M. Taylor, S.H. Baek, M.K. Jeong, G. Nix, Wood shrinkage prediction using NIR spectroscopy, Wood Fiber Sci. 40 (2008) 301–307.

[22] X. Wang, W.T. Simpson, Using acoustic analysis to presort warp-prone ponderosa pine 2 by 4s before kiln-drying, Wood Fiber Sci. 38 (2) (2006) 206–214.

[23] S.Y. Wang, C.M. Chiu, C.J. Lin, Variations in ultrasonic wave velocity and dynamic young's modulus with moisture content for taiwania plantation lumber, Wood Fiber Sci. 34 (3) (2002) 370–381.