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

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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

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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 ($38 \times 89 \times 2440\ \text{mm}^3$) 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):

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

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