UNDERSTANDING EFFECTS OF DRYING METHODS ON WOOD MECHANICAL PROPERTIES AT ULTRA AND CELLULAR LEVELS

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Abstract. Conventional kiln and vacuum drying are commonly used in industry to dry wood. In this study, an attempt was made to develop a better understanding of the effects of both drying methods on the mechanical properties of wood at the ultra and cellular structure levels. Dynamic mechanical analysis (DMA) and nanoindentation (NI) were used together with standard static bending tests according to American Society for Testing and Materials D143 to assess the respective effects of both drying methods on the performance of yellow birch (*Betula alleghaniensis* Brit.) wood, an important species in the Canadian wood industry. Measurements of EMC at different RH levels showed that vacuum drying consistently yielded greater EMC values. Vacuum-dried wood also exhibited superior modulus of elasticity and modulus of rupture performance. Tests conducted by DMA demonstrated that the chemical structure of wood had undergone more changes during conventional kiln drying than during vacuum drying. Elastic modulus and hardness measured by NI revealed that the impact of wood drying can be detected at the cell wall level as well. The results of this study showed that special attention should be paid to the effects of specific drying methods on the chemical structure of wood, because the chemical changes occurring in the kiln impact the quality of the final products.

Keywords: Yellow birch wood, mechanical properties, drying method, nanoindentation, dynamic mechanical analysis.

INTRODUCTION

Drying is an important step in the wood product manufacturing and value-added process. Improper drying generates cracking problems, rupture of the cellular structure, discoloration, and other physical distortion, which devalue the final product, causing substantial losses for the wood industry. For most applications, "green" or water-saturated wood needs to be dried to a MC level that is in equilibrium with the final product's environment in service. Because this occurs below the FSP, the drying process involves a transition from the activated to the nonactivated state (glassy state) for wood components such as

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hemicellulose and lignin (Takamura 1968). Hence, destabilization of the wood components in the cell wall occurs.

Drying accounts for 40% to 70% of the energy consumed in the entire wood product manufacturing process (Zhang and Liu 2006). This is a major investment that is justified by the resulting benefits, because drying typically improves wood properties such as dimensional stability, compatibility with coatings or adhesives, and mechanical properties. In addition, drying improves workability, acoustic properties, and electrical conductivity, as well as resistance to biodegradation (Gu et al 2004). Great final MC variability in lumber may lead to defects that decrease value (Cai and Hayashi 2007) and decrease wood mechanical properties (Gu et al 2004). Conventional kiln drying and vacuum drying are the most commonly used methods in the wood industry.

Vacuum drying offers many advantages compared with the conventional method, particularly with the hardwood species preferred in the manufacture of furniture, flooring, and other such applications. For example, it can significantly shorten the drying time below the FSP, it is suitable for large timber sections, it decreases the risk of discoloration, and it has good energy efficiency (Welling 1994; Ressel 1999). However, vacuum drying methods are not suitable for timber with high initial MCs (Welling 1994). In addition, surface and internal checking can be significant problems, especially at high drying temperatures. This occurs because of insufficient moisture movement from the center of the wood section to the surface during the vacuum drying process, which leads to steep moisture gradients and checking (Kanagawa et al 1993; Avramidis et al 1994).

Yellow birch (*Betula alleghaniensis* Brit.) was the species selected for this study. In relation to its density, it provides adequate strength and wear-resistance properties for many furniture and flooring products (Jalava 1945; Wagenführ 1996; Heräjärvi 2002). The responsiveness of sawn and dried wood to ambient RH is a concern, because it affects dimensional changes during further processing and in the end products (Isomäki et al 2002).

Conventional kiln and vacuum drying are both used with birch timber (Möttönen 2005). Traditional air drying, which is considered to result in high-quality sawn timber, is predominantly perceived as too slow and too dependent on weather and seasonal conditions to meet the demands of modern woodworking facilities and product requirements (shrinking–swelling, joints, tolerances). In addition, air drying cannot usually achieve the low MC levels required by industrial processes. The drying process affects wood performance. Artificial drying methods of different severity will differently influence the various properties of dried lumber (Edvardsen and Sandland 1999; Sehlstedt-Persson 2000). Suchy et al (2010) stated that drying influences the supramolecular arrangement of cellulose. Although drying does not alter cellulose crystallinity or cellulose crystalline structure, it does have an effect on the size of microfibril bundles and, consequently, on the accessibility for water of cellulose.

Thiam et al (2002) stated that drying influences the mechanical properties of wood in three ways, namely through the direct effect of moisture loss, internal drying stresses and strains, and the direct effects of temperature on the wood component. Oloyede and Groombridge (2000) studied the mechanical properties of Caribbean pine dried at air ambient temperature in a conventional oven at two elevated temperatures, and in a microwave oven at different power settings. Tensile tests indicated that microwave drying decreased the strength of the dried specimens by as much as 60%. Möttönen et al (2004) studied the effects of drying methods (conventional, vacuum, and air) on mechanical properties of silver birch. The Brinell hardness values they recorded were greater for the vacuum-dried specimens although their average final MCs were greater than those of conventionally dried wood.

The effects of drying methods on mechanical properties have been studied extensively by means of traditional mechanical tests, but their effects on

the mechanical properties of wood at the cellular level have not yet been fully addressed. Also, no attempt has been made to draw firm conclusions on the effects of drying methods on mechanical properties such as measured at the ultra and cellular structure levels. In this study, a nanoindentation (NI) technique and static bending tests were used to measure the mechanical properties of wood at the ultra and cellular levels.

NI, otherwise known as instrumented or depth-sensing indentation (Oliver and Pharr 1992; Fisher-Cripps 2011), has become a well-established technique to characterize the mechanical properties of materials on a very small scale, as is the case of wood cell walls. More specifically, the test assesses the mechanical properties of the cell wall S_2 layer, which constitutes about 80% of the total cell wall thickness and is the major contributor to the mechanical properties of the cell wall. The NI technique therefore enabled us to probe any change in cell wall properties caused by the drying process and helped us understand the behavior of wood during drying. NI has already been used to study the effects of seasonal growth response (earlywood vs latewood; Wimmer et al 1997), cell wall lignification (Gindl et al 2002), melamine modification (Gindl and Gupta 2002), and adhesive bonding (Gindl et al 2004) on the mechanical properties of single cell walls.

In addition, dynamic mechanical analysis (DMA) was used in this study to monitor the changes imposed on the viscoelastic properties of wood. DMA can also provide information on the changes affecting wood as it dries. The information obtained by DMA facilitated interpretation of the NI and static test results. Jiang and Lu (2008, 2009), Jiang et al (2008), and Zhan et al (2009) used DMA to evaluate the effects of drying on wood properties.

The main objective of this study was to contribute to a better understanding of how vacuum drying and conventional kiln drying methods affect wood mechanical properties. Such information is essential to optimize the drying process and choose the most appropriate method for a given end use.

MATERIALS AND METHODS

Yellow birch (*B. alleghaniensis* Brit.), grown in the province of Quebec, Canada, was chosen as the test wood species. The specimens were dried by two methods, vacuum drying and conventional drying, in industrial facilities using proprietary temperature regimes and then conditioned at 50% RH and 20°C for 4 wk prior to further processing.

EMC Measurement

To assess the impact of the two drying methods on EMC, small birch wood specimens (25 × 25 × 25 mm) were dried by conventional and vacuum drying and then conditioned at three different RH levels (40%, 50%, and 60%) at 20°C until constant mass. The specimens were subsequently dried down to constant weight in an oven at 102°C. For each set of conditions, 20 samples were tested.

Static Bending Tests

The static bending tests were conducted according to American Society for Testing and Materials D143-14 (ASTM 2014) on 25- × 25- × 410-mm specimens, at the rate of 20 specimens for each set of conditions. The specimens were center-point loaded across a 360-mm span, the load being applied through a bearing block to the tangential surface nearest the pith. The load was applied continuously throughout the test at a rate of 2.5 mm/min. Real-time load and displacement data were used to determine the modulus of rupture (MOR) and modulus of elasticity (MOE). Calculation of MOE was based on the data within the linear region of the load-displacement curve, which was found to be within 20-40% of the maximum load for all specimens.

Dynamic Mechanical Analysis

Rectangular 40- × 5- × 1-mm specimens were used for the dynamic mechanical experiments. A DMA (Q800, TA Instruments, New Castle, DE) was used for the evaluation of dynamic moduli

and mechanical damping (tan δ). The tests were conducted in single cantilever mode under a range of temperatures (−120°C to 80°C) at a heating rate of 2°C/min. Cooling of the equipment was done with liquid nitrogen. The tests were carried out at a frequency of 1 Hz and a strain rate of 0.05%. Assessments of the linear viscoelastic region (LVR) of wood conducted before the temperature scans indicated that a strain rate of 0.05% was well within the LVR of the wood throughout the temperature range. The DMA measurements were conducted in the radial direction.

Nanoindentation

The NI technique involves penetrating the test material with an indenter and recording penetration depth and load, which allows the stiffness and hardness of the indented location to be subsequently calculated. The indenter head was 100 nm in radius (in the case of a Berkovich indenter, Hysitron TI 900 (Minneapolis, MN)), and the penetration depth could be up to 1 or 2 μm. The resulting indent had a linear dimension in the same order of magnitude as the wood cell wall thickness. The wood cell wall thicknesses were reported to be 5-6 and 9-13 μm, respectively, for the earlywood and latewood of loblolly pine (Barefoot et al 1965). Trustable cell wall thickness values for yellow birch could not be found in the literature. For sure, the NI technique was able to measure the mechanical properties of yellow birch at the cellular level as the images provided by the NI machine showed. Although conventional measurements of mechanical properties only give one value for each test, the NI technique provides an opportunity to measure and compare mechanical properties in very specifically selected areas.

Hardness and the elastic modulus were calculated from the load-displacement data. For an indentation depth (h), the hardness (H) of a specimen can be calculated from the following equation:

$$H = \frac{P_{\max}}{A} \tag{1}$$

where $P_{\max}$ is the load measured at the maximum depth of penetration (h) in an indentation cycle, and A is the projected area of contact between the indenter and the specimen at $P_{\max}$.

In theory, the elastic modulus should be size independent (Cheng and Cheng 2004), but analyzing polymers by NI causes a number of complications referred to as the indentation size effect, which reflects the fact that the elastic modulus tends to increase with the decreasing penetration depth of the indenter pyramid. Viscoelastic creep during unloading may also affect the slope of the unloading curve and thus the calculated elastic modulus.

The combined modulus of the system, or reduced indentation modulus (E_r), was determined from the following expression:

$$E_r = \frac{1}{2}\frac{dP}{dh}\frac{\sqrt{\pi}}{A} \tag{2}$$

where dP/dh is the slope of the tangent to the initial unloading curve in the load-displacement plot. The specimen modulus (E_s) can then be calculated as follows (Oliver and Pharr 1992):

$$E_s = (1 - \nu^2{}_s)\left(\frac{1}{E_r} - \frac{1 - \nu^2{}_i}{E_i}\right)^{-1} \tag{3}$$

where the subscripts s and i represent the specimen (cell wall, S_2 layer, or middle lamella) and indenter, respectively, and ν is the Poisson's ratio. The indenter modulus E_i is constant and equal to 1140 GPa, with a Poisson's ratio of 0.07. A Poisson's ratio of 0.44 was assumed for yellow birch (*B. alleghaniensis* Brit.). A total of 100 indents were performed in the S_2 layer of the fiber cell wall and middle lamella of each specimen. The specimens were placed in the nanoindenter cabinet at room conditions for the duration of the measurements.

The specimens were cut to sizes of 2 mm (T) × 2 mm (R) × 5 mm (L) with sharp blades and equilibrated to about 12% MC. The samples were randomly selected from different parts of the

boards in a way that they could represent both early and latewood. They were then embedded in an epoxy resin formulated as cycloaliphatic epoxy (ERL-4221; 2.5 parts), polycyclodiepoxide (DER-736; 1.5 parts), and nonenyl succinic anhydride. The curing was performed in a vacuum oven at 70°C for 7 h. An ultramicrotome (Leica, Vienna, Austria) was used to produce very smooth, flaw-free surfaces. The resin-embedded specimens were attached to an acrylic block with a 5-min epoxy adhesive. The acrylic block was then mounted on the ultramicrotome. A glass knife was first used to level the specimen surfaces. Then further smoothing was achieved with a diamond knife. All NI experiments were performed on a Triboindenter (Hysitron, Minneapolis, MN) equipped with a pyramidal diamond Berkovich tip. A stepwise load function was applied, consisting of three consecutive loading, holding, and partial unloading steps, as per the protocol described by Tze et al (2007) for continuous stiffness and hardness measurements. The maximum load amounted to 100 μN. The loading time, holding time, unloading time, and maximum indentation force (P_{max}) for each cycle are provided in Fig 1. The separation distance between individual NI points was 0.05 mm.

RESULTS AND DISCUSSION

EMC

Figure 2 shows wood specimen equilibrium MCs at different RH levels. The specimens dried under vacuum had substantially greater equilibrium MCs than did those dried conventionally. These results are in line with previous research. Jiang and Lu (2008) reported that the EMC of Chinese fir was influenced by the drying method. Specimens dried at high temperature exhibited lower equilibrium MCs than did those dried through a freeze vacuum process. Möttönen et al (2004) also observed that the EMC of vacuum-dried wood was higher than that of conventionally dried wood. An explanation for these results lies in an understanding of the chemical reactions occurring during the different drying processes. Not all components of wood have the same affinity to moisture: lignin, cellulose, and hemicellulose absorb 0.60, 0.92, and 1.56 times as much water as a given weight of dry wood, respectively (Berry and Roderick 2005). Hemicelluloses are noncrystalline, highly branched heteropolysaccharides (Sjöeström 1981; Fengel and Wegener 1989). Because of their generally amorphous nature, they contain the greatest

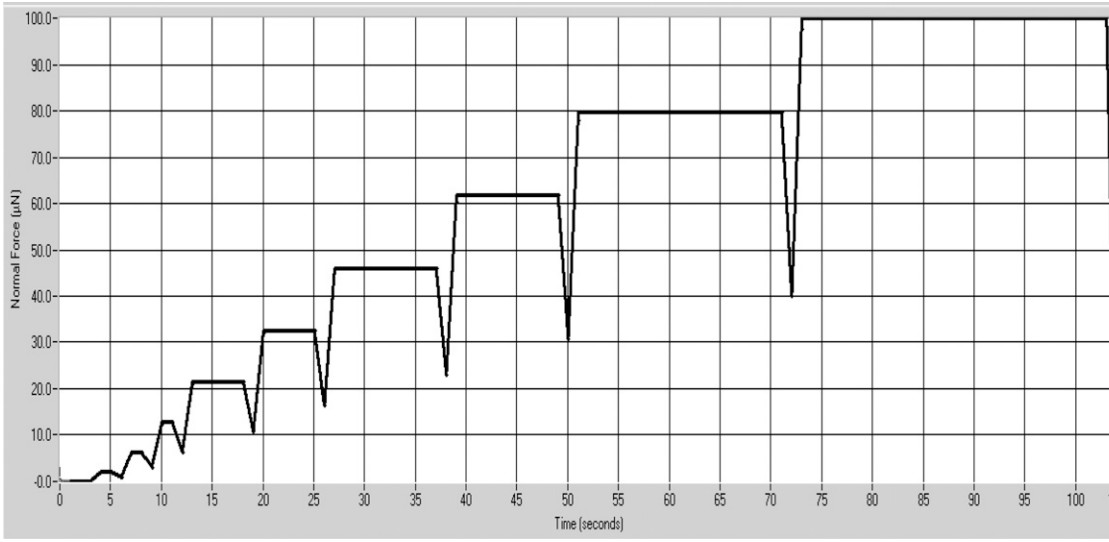

Figure 1. Loading time, holding time, unloading time, and maximum indentation force (P_{max}) for each cycle.

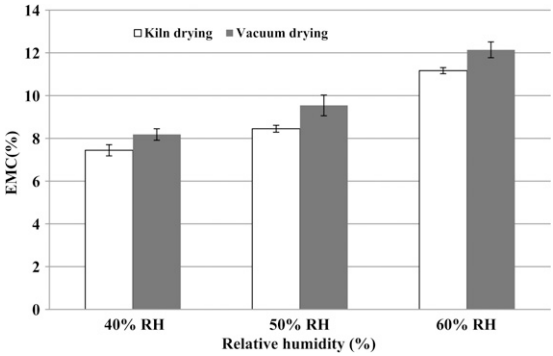

Figure 2. EMC of wood at different RH. The error bars represent standard deviations.

proportion of accessible hydroxyl (OH) groups in the cell wall, and they are less thermally stable than cellulose or lignin (Hill 2006). Given that conventional drying relies on higher temperatures than vacuum drying, the lower equilibrium MCs recorded in the conventionally dried specimens could result from the degradation or alteration of the hemicellulose structure during the conventional drying process.

It has been reported that the hygroscopicity of wood decreases with increasing thermal degradation (Mitchell et al 1953). The lower temperatures prevalent in vacuum drying tend to preserve more hemicelluloses in terms of both amount and structure. Such intact hemicelluloses absorb more moisture, hence the higher equilibrium MCs. Hillis (1984) also reported that, in addition to hemicellulose being degraded at high temperature, when wood is exposed to a temperature of about 100°C, the accessibility of water to remaining OH groups in the hemicellulose may decrease as well. Sik et al (2010) reported that the effects of using high drying temperatures may be caused by 1) enhanced hysteresis, 2) loss of hygroscopic hemicelluloses, or 3) rearrangement–degradation of amorphous cellulose content in the cell wall. They made the conclusions by conducting high-temperature drying on robberwood at different dry bulb temperatures, ranging from 100°C to 150°C.

Static Bending Tests

As shown in Fig 3 and Table 1, the vacuum-dried specimens exhibited greater MOE and MOR than those dried in a conventional kiln. MOE was more severely affected (8% lower with conventional drying than with vacuum drying) than MOR (4% lower). The effects of drying method on MOE were significant at 0.05 levels. However, the effects of drying method on MOR were not found significant (Table 1). It has been reported that the exposure of wood to high temperatures at high MCs sometimes results in thermal degradation causing a loss in mechanical properties such as MOR and MOE (Gerhards and McMillen 1976).

As previously indicated, hemicelluloses are more sensitive than cellulose to high temperatures and appear to play a critical role in the effects of high-temperature drying on mechanical properties. LeVan et al (1990) and Winandy (1995) showed that hemicelluloses are the most thermally and

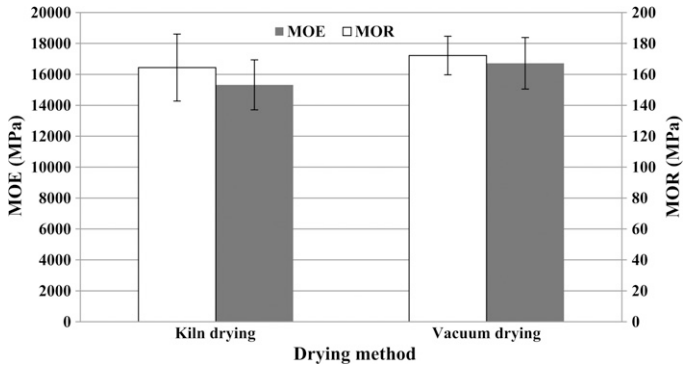

Figure 3. Values of MOR and MOE for vacuum- and kiln-dried wood. The error bars represent standard deviations.

Table 1. Values of measured properties in wood samples dried by traditional kiln and vacuum drying methods.

	Kiln drying	Vacuum drying	*p* value[a]
Static bending tests (MPa)			
MOE	15320.50	16716.47	0.01054*
MOR	164.37	172.17	0.17070
Nanoindentation (GPa)			
Hardness in CC	0.33	0.34	0.00015**
Hardness in S_2	0.28	0.31	4.09188E-06**
Elastic modulus in CC	4.92	5.25	6.34462E-06**
Elastic modulus in S_2	11.67	12.83	0.042490*

[a] Calculated probability; * Significant at the 0.05 level; ** Significant at the 0.01 level.

chemically sensitive component of wood and that changes in the hemicellulose content and structure are primarily responsible for initial strength loss.Within the hemicellulose, the reaction of acetyl groups is one possible cause of permanent strength reduction. After they form acetic acid, the cellulose is depolymerized (the acid hydrolyzes the bonds that connect the glucose monomers). The rate of strength loss increases as the production of acid is accelerated by the high temperature and high MC (Mitchell and Barnes 1986). Another interesting point is that wood is stronger at the lower temperatures typically used in vacuum drying. Therefore, checks and splits are less likely to develop with vacuum drying.

It is believed that lignin, a large amorphous polymer, is covalently bonded to hemicellulose (Whistler and Chen 1991). It is also thought that hemicellulose is associated with the cellulose microfibrils, either by physical proximity or by hydrogen bonding. Sweet and Winandy (1999) reported that the chemical–mechanical linkages between the cellulose microfibril and the lignin–hemicellulose matrix, and then the next microfibril, allow for a lateral load to be shared among neighboring microfibrils. "When the cellulosic microfibrils and lignin–hemicellulose matrix act as a continuum, internal stress can be efficiently distributed across the cell wall and throughout the entire fiber. It is this ability for intrafiber stress distribution and load sharing that enables wood fibers to functionally act as a composite material." The decreases in MOR and MOE observed in kiln-dried wood in this study were therefore most likely caused by damage or destruction of chemical–mechanical linkages between the cellulose microfibril and the lignin–hemicellulose matrix. An attempt was made to trace the degradation in the S_2 layer by a scanning electron microscope (SEM). Because the degradation of hemicellulose was at its very early stages, the SEM analysis could not reveal any sign of degradation.

Viscoelastic Properties

Relaxation behavior in wood has been reported on by a number of researchers, including Kelley et al (1987), who used DMA and differential scanning calorimetry to identify glass transitions associated with amorphous components (lignin and hemicellulose) in the wood cell wall.

They believed that the chemical components were the most important factor affecting dynamic viscoelasticity. It was also reported that wood can undergo chemical and structural changes during the drying process (Price and Koch 1980; Hinterstoisser et al 1992). This implied that the wood chemical components would vary with different drying methods, which would lead to different viscoelastic properties.

Figure 4 shows storage modulus (E') vs temperature for wood specimens dried by the two methods (vacuum and conventional drying). In both groups, E' decreased as the temperature increased, which can be explained by the fact that the kinetic energy of wood molecules is very low under low temperature conditions; only the motion of some small units such as side chains, branched chains, and functional groups can be observed under exterior forces. With increasing temperature, the thermal motion energy of wood

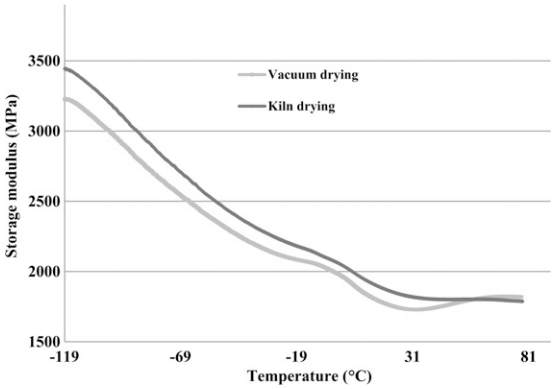

Figure 4. Temperature spectra of storage modulus (E') for vacuum- and kiln-dried wood.

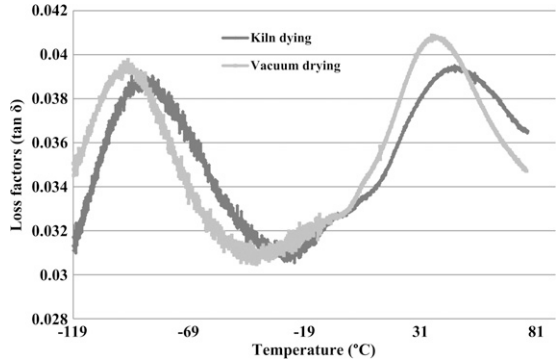

Figure 5. Temperature dependency of loss factors (tan δ) for vacuum- and kiln-dried wood.

molecules increases and a segmented motion occurs, leading to a low E' value (He et al 2000). The E' modulus of wood dried under vacuum (especially at temperatures below 50°C) was marginally lower than that of wood dried in a conventional kiln (Fig 4). This should be related to the fact that higher temperatures in the kiln result in cellulose crystallization in the noncrystalline region (Hirai et al 1972).

The ratio between the loss modulus and the storage modulus is called the mechanical loss factor, damping parameter, or tan δ. The damping properties of a polymeric material represent the balance between the elastic and viscous phases in its structure. The loss factor is sensitive to molecular motions, transition relaxation processes, structural heterogeneities, and the morphology of multiphase systems. The mechanical damping or internal friction values (tan δ) reflect the amount of energy dissipated as heat during deformation. Figure 5 displays loss factors (tan δ) vs temperature for wood dried by the two methods. Two peaks of relaxation observed at about −90°C and 40°C were labeled γ and α, respectively.

The γ relaxation process can be attributed to the motions of methyl groups in the amorphous region of cell walls (Kelley et al 1987; Sugiyama and Norimoto 1996; Jiang and Lu 2006). In this study, the γ relaxation temperature for conventionally dried wood was higher than for vacuum-dried wood (−91°C vs −96°C). The drying process drove the OH groups in the cellulose cell wall closer together, resulting in weak cellulose-to-cellulose bonds. When water adsorption occurred at lower MCs, the introduction of water molecules caused part of these weak bonds to break down and some OH groups to be released (Bowyer et al 2003). Apparently, the motion of methyl groups in the amorphous region of vacuum-dried wood cell walls occurred easily and needed less activation energy, resulting in a lower temperature for γ relaxation. Another explanation could be that monomolecularly absorbed water in the case of conventionally dried wood (one per site) increased the size of the compound groups composed of methyl groups present in the cell wall components and adsorbed water molecules (Sugiyama and Norimoto 2006). Because the motion of compound groups has to overcome more potential barriers, the γ relaxation of conventionally dried wood occurs at a higher temperature than with vacuum-dried wood.

The α relaxation process occurred at a higher temperature in conventionally dried wood than in vacuum-dried wood (42°C vs 37°C). The α relaxation process was probably related to the glass transition of low-molecular-weight hemicelluloses. Hemicelluloses and lignin have distinct glass transition temperatures, and wood therefore softens gradually across a temperature interval rather than at a specific temperature.

Backman and Lindberg (2001), Mano (2002), and Jiang and Lu (2008, 2009) also assigned the

α relaxation process to the glass transition of low-molecular-weight hemicelluloses. As already mentioned, hemicelluloses contain the greatest proportion of accessible OH content of the cell wall and they are less thermally stable than cellulose or lignin (Hill 2006), which explains the higher level of degradation experienced by some hemicelluloses during conventional drying. As a result, relaxation required more energy and occurred at a higher temperature. At the lower temperatures used in vacuum drying, the hemicelluloses remained undamaged and the α relaxation process required less energy and therefore peaked at a lower temperature.

Nanoindentation

The NI tests were conducted in both the secondary wall (S_2) and the middle lamella (CC) of vacuum- and kiln-dried wood specimens. The test results for hardness, shown in Fig 6 and Table 1, indicate that, in both layers, vacuum drying yielded significantly greater hardness values than kiln drying. Several researchers using traditional hardness testing methods also reported on the effects of drying process. Hansson and Antti (2006) studied the effects of drying method and temperature on the hardness of Norway spruce (*Picea abies* Mill.). Their results on conventional and microwave drying showed a significant difference in the hardness of wood parallel to the grain. Möttönen et al (2004) studied the effects of drying methods (conventional, vacuum, and air) on the mechanical properties of silver birch (*Betula pendula* Roth). They recorded greater Brinell hardness values for vacuum-dried wood.

As shown in Fig 7 and Table 1, the elastic modulus obtained in this study for CC and S_2 in wood dried under vacuum was significantly greater than in conventionally dried wood. The difference in the elastic modulus was more pronounced in the S_2 layer (0.317 and 0.287 GPa for vacuum drying and conventional drying, respectively). Hill (2014) demonstrated that degradation of the hemicelluloses is responsible for changing the modulus of the cell wall. Konnerth et al (2010) reported that the hardness and elastic modulus of the cell wall are very sensitive to the chemical and structural characteristics of the wood components. The DMA measurements and EMC values showed that conventional drying induced some degradation or modification of the hemicelluloses. The observed variations in hardness and elastic modulus in S_2 originated in the hemicelluloses, and the changes they underwent were caused by the drying process. The impact of drying methods on the elastic modulus was less remarkable in the CC layer because of its high lignin concentration and the high thermal stability of lignin. Unlike cellulose, hemicelluloses have a lower degree of polymerization (only 50-300) with side groups attached to chain molecules; they are essentially amorphous. Side groups are linked via hydrogen bonds to the paracrystalline cellulose regions and covalently to lignin (Whistler and Chen 1991). At the molecular level, cellulose microfibrils are thought to be encrusted by lignin and hemicelluloses. The contribution of hemicelluloses to wood

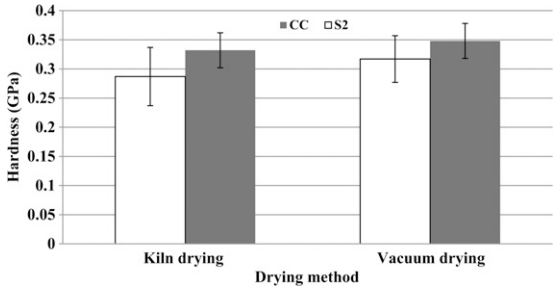

Figure 6. Values of hardness in middle lamella (CC) and secondary wall (S_2) for vacuum- and kiln-dried wood. The error bars represent standard deviations.

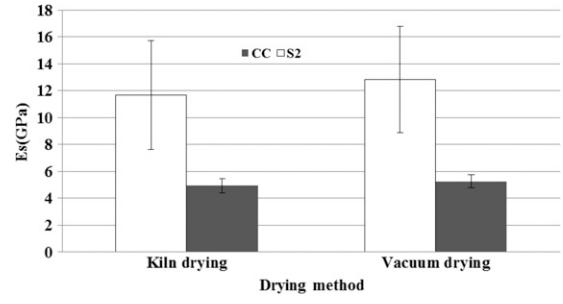

Figure 7. Values of elastic modulus in middle lamella (CC) and secondary wall (S_2) for vacuum- and kiln-dried wood. The error bars represent standard deviations.

strength is still vague. Tests conducted on the biodegradation of wood showed that changes in chemical compositions result in measurable strength decreases before measurable weight loss (Schmidt et al 1978; Wilcox 1978; Imamura 1993; Kim et al 1996). Early studies by Winandy and Morrell (1993) demonstrated a relationship between the degradation of hemicellulose components such as arabinose and mannose and wood strength losses. Winandy and Lebow (2001) and Curling et al (2002) showed that the degradation of shorter branched monomers along the main chains of hemicelluloses appear to be particularly responsible for strength losses in wood exposed to hydrolytic chemical agents or early microbial decay stages. Gindl et al (2004) described hemicelluloses as a matrix-related component. With the assumption that hemicellulose structures remain undamaged during vacuum drying (because of the low temperatures used), the greater hardness and elastic modulus of vacuum-dried wood observed in this study can be justified.

CONCLUSIONS

The importance of drying in the overall wood product manufacturing process and on product performance in service calls for a better understanding of the impact of the various drying processes on physical, chemical, and mechanical properties. In this study, standard bending tests and recent techniques (DMA and NI) were used to characterize wood dried in conventional and vacuum kilns. Such a combination of techniques was meant to provide in-depth knowledge on how the two drying methods alter wood mechanical properties. Drying under vacuum was found to have a lower negative impact on mechanical properties at both the ultra and cellular structure levels. MOR and MOE values obtained for vacuum-dried wood were greater than for conventionally dried wood. The NI tests conducted on the S_2 layer and middle lamella also demonstrated greater elastic modulus and hardness with the vacuum-dried specimens. DMA showed that wood underwent chemical changes during the conventional drying process, with lower EMC levels. The EMC results and DMA measurements confirmed the occurrence of hemicellulose alteration or degradation caused by high temperature exposure (82°C). The mechanical property measurements obtained by NI and standard bending tests showed convergence. Vacuum-dried wood was characterized by greater EMC levels than conventionally dried wood, which may be a source of concern in applications in which high humidity and temperature variations are expected. Conversely, the lower EMC of conventionally dried wood means greater stability in service but at the cost of inferior strength. Given the significance of the chemical changes occurring during the drying process and their impact on wood performance, it is suggested that, in the selection of a drying process and schedule, more attention be paid to minimizing thermal hemicellulose degradation and maintaining the right balance between hydrophobicity and mechanical performance in relation to final application.

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