EFFECT OF LATEWOOD PROPORTION ON MECHANICAL PROPERTIES OF FINNISH PINE WOOD MODIFIED WITH COMPRESSION DRYING

Mika T. Mikkola

Researcher
E-mail: mmikkola1@gmail.com

*Rami K. Korhonen**

Associate Professor
Department of Applied Physics
University of Eastern Finland
POB 1627
FI-70211 Kuopio, Finland
E-mail: rami.korhonen@uef.fi

(Received June 2012)

Abstract. Mechanical and structural changes caused by compression drying of Finnish pine wood (*Pinus sylvestris* L.) were studied. Elastic modulus, yield stress, Brinell hardness, and latewood proportion were determined for eight boards. Radial compression during the drying process was found to increase latewood proportion by approximately 18% as a result of earlywood deformation. Elastic modulus and yield stress were higher in the radial direction (128 and 2.25 MPa) than in the tangential direction (99 and 2.09 MPa) for green samples, whereas they were higher in the tangential (288 and 4.74 MPa) compared with the radial direction (201 and 3.59 MPa) for dried specimens. Elastic modulus, yield stress, and Brinell hardness correlated significantly ($R^2 = 0.65$, $p < 0.05$; $R^2 = 0.73$, $p < 0.01$; $R^2 = 0.69$, $p < 0.01$, respectively) with latewood proportion. Compression drying enhanced the tangential mechanical properties and surface hardness of Finnish pine wood as a result of increased latewood-to-earlywood ratio.

Keywords: Drying, Scots pine, latewood proportion, modulus of elasticity, yield stress, hardness.

INTRODUCTION

The drying process is a crucial part of efficient manufacturing of lumber. Drying involves removing both free water and some bound water from wood. Careful pacing is required as well as close control of several factors. At least temperature, RH, and air circulation have to be considered to avoid drying defects and fulfill requirements of the end product. However, high quality is usually related to a long drying time and high energy consumption.

Compression drying or modification is a method in which wood boards are mechanically compressed between heated metal plates during the drying process. Compression force induces hydrostatic and vapor pressure, which drives both free water and steam through the capillary structure of wood. Below fiber saturation point, diffusion of bound water occurs through the network of cell walls and cell cavities. Both mechanisms bring water to the surface where it is removed by controlled air circulation. Compression drying has been shown to decrease drying time and warp remarkably (Simpson et al 1988).

Density of wood is primarily determined by the ratio between the volume of the cell wall and the volume of the cell cavities and pores, because specific gravity of the cell wall substance is nearly constant (Hakkila 1966). Latewood is thereby a major factor determining density of wood because of thicker cell walls and smaller cell lumens compared with earlywood. Density is well known to correlate with the mechanical properties of wood and can be used as an indirect description of the strength. Many methods have been created

* Corresponding author

to increase wood density by compression (Kollmann et al 1975; Inoue et al 1993; Boonstra and Blomberg 2007; Kamke and Sizemore 2008). Rapid drying combined with mechanical compression may often lead to drying defects such as honeycomb. However, in modern dryers, water movement inside the wood may be controlled by adjusting RH and consequent equilibrium moisture content by means of water mist or steam, thereby avoiding steep liquid gradients, which are a major factor in drying defect development. A controlled drying schedule is a potential way to decrease defects and still retain the advantage of greatly decreased drying time.

Wood can be generally described as an orthotropic material because it has different mechanical properties in the directions of three mutually perpendicular axes: longitudinal, radial, and tangential. The transverse (radial–tangential plane) compression behavior of wood is highly dependent on its anatomical structure resulting in an inhomogeneous deformation in the cellular matrix. Bodig (1965a) divided the stress–strain curve into three distinct regions in transverse compression: linear elastic, plastic, and densification. Tabarsa and Chui (2000) studied radial compression of softwoods and found that these characteristic zones are related to the deformation of earlywood, collapse of earlywood, and deformation of latewood. During radial compression, nonuniform deformation starts in the weakest structures in earlywood, which deforms much faster and more than latewood (Bodig 1963, 1965a, 1965b, 1966; Tabarsa and Chui 2001). Thus, earlywood density has been suggested to be mainly responsible for strength in the radial direction (Tabarsa and Chui 2001), whereas in tangential compression, latewood bands reinforce the material and support the load in combination with earlywood. Kennedy (1968) concluded that in softwoods, the amount of latewood controls compressive strength in the tangential direction. However, it is not well known how the mechanical and structural properties change as a result of compression drying and how they are related to each other.

The objective of this study was to examine how the structure of Finnish pine wood changes in compression drying and how the modification affects mechanical properties of wood.

MATERIAL AND METHODS

Eight plain sawn sapwood boards of Scots pine (*Pinus sylvestris* L.) from two different batches were used in this study. Cross-sectioned dimensions were 40 × 155 and 50 × 100 mm for batches one and two, respectively. All boards were sawn to two 600-mm-long pieces, one of which was used as a fresh control and another one that was dried. Moisture content of all dried boards was determined by the oven-dry method (CEN 1993).

Compression Drying

Both batches were compression-dried using a commercial dryer (Korwensuun Konetehdas Oy, Kuopio, Finland) (Fig 1). Drying was carried out between honeycombed cell plates, each made of several metal rods side by side, which allowed air and humidity circulation through the grating. Rods were oriented perpendicular to the long axis of the boards, and each rod had circular holes that improved moisture escape from the wood. Hydraulic force compression was executed in a multilayer cell in the drying kiln in which temperature, humidity, airflow, and compression pressure could be controlled. Drying details are given in Table 1.

Microscopy

Specimens for microscopic evaluation were taken at the center of the board, where annual rings were oriented parallel to the surface, from both sides of the cutting interface of green and dried boards (Fig 2). Approximately 5- × 10-mm samples were taken containing the whole thickness of the board to compare latewood and earlywood proportions in dried and nondried specimens. Before microscopic analysis, all samples were prepared with a razor blade and sandpaper to create flat surfaces. Latewood proportion was determined from nondried and dried samples

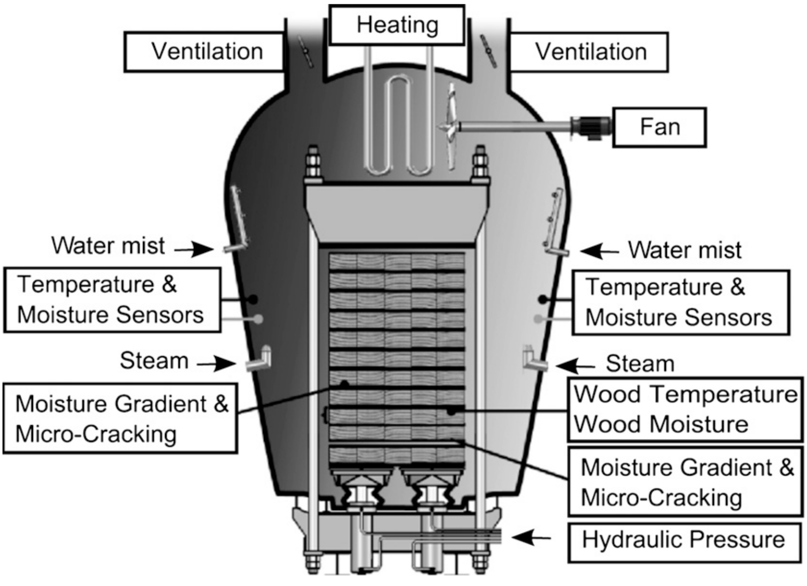

Figure 1. A schematic representation of the compression drying apparatus.

with a Zeiss Axio Imager 2 microscope and digital camera (Carl Zeiss MicroImaging GmbH, Jena, Germany). Images from every latewood ring were captured at 2.5× magnification, and the width of the ring was measured using AxioVision image acquisition and processing software. Latewood proportion for each sample was calculated as a ratio of total length of latewood and sample height, which was determined with an electronic caliper.

Mechanical Testing

Test specimens were prepared near the cutting interface at the center line of the board (Fig 2). Wood blocks with dimensions of approximately 25 × 25 × 25 mm were prepared from defect-free sapwood. Two samples were prepared from each green and dried board: one for radial and one for tangential measurement. The remainder of each dried board was used for Brinell hardness measurements (surface stiffness) and determination of moisture content at the moment of testing. All samples were stored in plastic until they were measured to maintain moisture content.

Mechanical testing of green and dried samples in unconfined compression was carried out using an Instron (Norwood, MA) 8874 servohydraulic testing system with a 25-kN load cell and a compression plate of 40-mm diameter. Modulus of elasticity (MOE) and yield stress values were measured for radial and tangential directions. Exact dimensions of the samples were determined with a digital caliper just before measurement. An initial contact between the sample surface and compression plate was considered

Table 1. Details of wood material and compression drying.[a]

Batch	Dimensions (mm)	Number of boards	MC	MC (%)	Density (kg/m^3)	Growth ring width (mm)	Drying time (h)	Compression (kPa)	Compression (%)
	Initial		Initial	Final	Final	Initial		Pressure	Strain
1	40 × 155	4	Green	8.2 (±0.5)	446 (±33)	2.40 (±0.65)	11	686	6
2	50 × 100	4	Green	5.9 (±0.2)	456 (±55)	2.63 (±0.67)	27	680	7

[a] MC, density, and growth ring width are reported as mean ± SD. MC was not determined for green boards. Compression strain is given as residual strain measured immediately after the compression drying process.

MC, moisture content; SD, standard deviation.

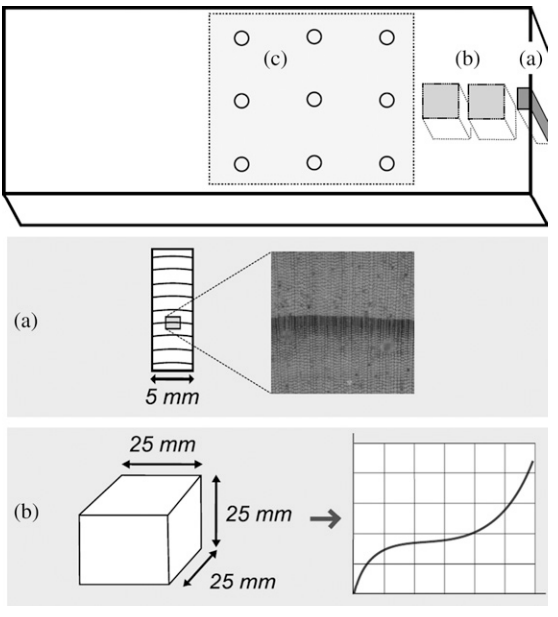

Figure 2. Preparation of test specimens for microscopy (a), stress–strain (b), and Brinell hardness (c) measurements.

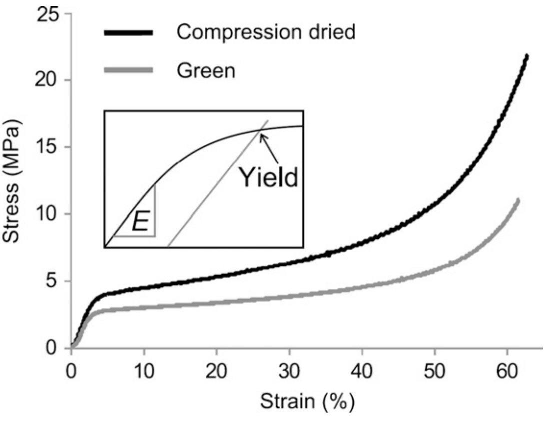

Figure 3. Typical stress–strain curves for green and dried specimen in radial direction.

as a 10-N force was exceeded. All samples were subjected to compressive load using a strain rate of 1 mm/min. Engineering strains were measured as a function of applied force during the measurements. MOE was determined as a stress–strain ratio from the initial, linear part of the stress–strain curve. Yield stress was determined by shifting the linear part of the stress–strain curve by 0.2% to the right, and then yield stress was the value in the y-axis where the shifted line crossed the experimental curve (Fig 3).

Brinell hardness was determined for each board in accordance with CEN (2000). A steel ball of 10-mm diameter was pressed into the boards at a nominal force of 1 kN. The maximum load was reached after 15 s, maintained for 25 s, and then decreased to zero. A magnifying glass equipped with a scale of 0.1 mm was used to measure diameters of the residual indentations on the face of the board parallel and perpendicular to grain.

Nine indentations were made for each board such that indentations were distributed evenly on the surface area. Thus, three values were measured at the center of the board where annual rings were oriented parallel to the surface, and three values were measured from both sides of the center line where annual rings made approximately a 30° angle with the surface.

Statistical Tests

Because of the relatively small number of samples, a nonparametric Wilcoxon signed rank test was used to compare the mechanical parameters measured in radial and tangential directions. The Pearson correlation was used to determine relationships between latewood proportion and mechanical parameters of compression-dried wood. The Spearman correlation was used to assess the relationship between latewood proportion and Brinell hardness measurements.

RESULTS AND DISCUSSION

Latewood proportion of nondried and dried boards was 17.7 ± 5.9% and 20.7 ± 5.9%, respectively. Densification was a consequence of a nonhomogeneous deformation (Fig 4). In the case of green samples, both MOE and yield stress were higher when loaded in the radial direction, whereas for dried wood, they were higher in the tangential direction (Table 2). There have been a limited number of studies reporting MOE and yield stress values perpendicular to

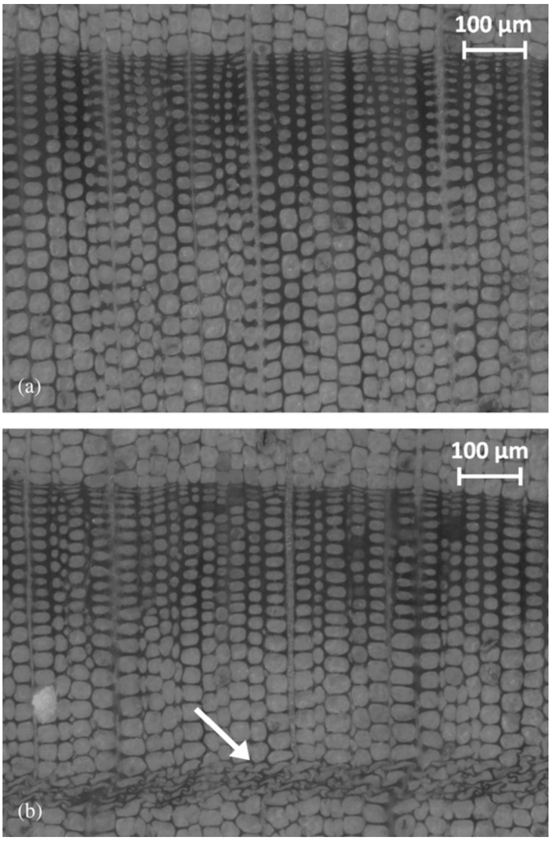

Figure 4. Microscopic image of (a) nondried and (b) compression-dried pine wood.

grain. Schniewind (1959) analyzed the transverse anisotropy of wood using California black oak at 6 and 12% MC in tension. He concluded that MOE in the radial direction was 1.5 to 2 times higher compared with the tangential direction, which is consistent with the results of green samples under compression in this study. Conversely, the results obtained here for the dried samples were opposite. However, Tabarsa and Chui (2001) found that jack pine had higher MOE in the tangential (153 MPa) than in the radial (83 MPa) direction because of wider latewood layers, an observation that is supported by the results of the dried samples in this study (Table 2; Fig 5). Conversely, the results for white spruce were opposite (Tabarsa and Chui 2001).

Compression drying of wood increased the latewood-to-earlywood ratio, which enhanced the mechanical properties more in the tangential than in the radial direction. Significant correlations were found between latewood proportion and MOE–yield stress in the tangential direction (Fig 6). A similar observation was not found in the radial direction. Tabarsa and Chui (2001) observed that deformation in radially compressed softwoods is inversely proportional to cell wall thickness. Therefore, poor correlation is reasonable between latewood proportion and mechanical parameters in radial compression, because the weakest cells (earlywood) collapse and contribute primarily to the radial deformation of wood. These results suggest that an increase in latewood proportion added support in tangential compression, whereas its role in the radial direction was not important. In contrast, earlywood and its properties probably control wood compression in the radial direction.

Moisture content should have an effect on MOE and yield stress. In this study, moisture contents of the dried sample boards were not exactly the same. However, moisture content is a physical property of the cell wall material, whereas wood behavior under compressive load from different directions is primarily dependent on

Table 2. Compression test results.[a]

	Green	Green	Green	Compression dried	Compression dried	Compression dried
	n	MOE (MPa)	Yield stress (MPa)	n	MOE (MPa)	Yield stress (MPa)
Radial	8	128 (±44)	2.25 (±0.73)	8	201 (±75)	3.59 (±0.76)
Tangential	8	99 (±21)	2.09 (±0.83)	8	288 (±68)	4.74 (±0.92)
Change		0.77	0.93		1.43	1.32
p value		0.036	0.484		0.017	0.012

[a] MOE and yield stress values (mean ± SD), relative change, and *p* value (Wilcoxon signed rank test, two-tailed) between radial and tangential directions. MOE, modulus of elasticity; SD, standard deviation.

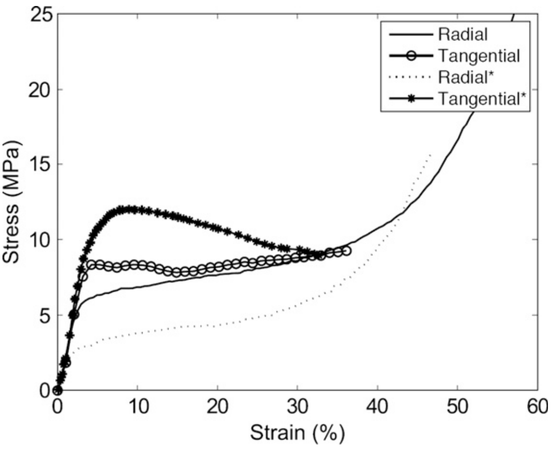

Figure 5. Representative stress–strain curves of Scots pine, as measured in radial and tangential directions in this study, and corresponding measurements for Jack pine in Tabarsa and Chui (2001).*

the structure and composition of wood. Also, one board had a higher latewood proportion than the other sample boards. This specific board was processed equally with the other boards. Thus, the reason for the high latewood proportion is unknown. Deviation from the other samples slightly affected the correlation analysis, although it did not change the conclusions. Conversely, the correlation was calculated for both the radial and tangential measurements, but only the tangential direction showed a statistically significant correlation.

Unlike MOE and yield stress measured in the radial direction, a significant correlation was found between latewood proportion and hardness measured by applying load perpendicular to grain (Fig 7). Linear relationships between density and hardness have been reported earlier

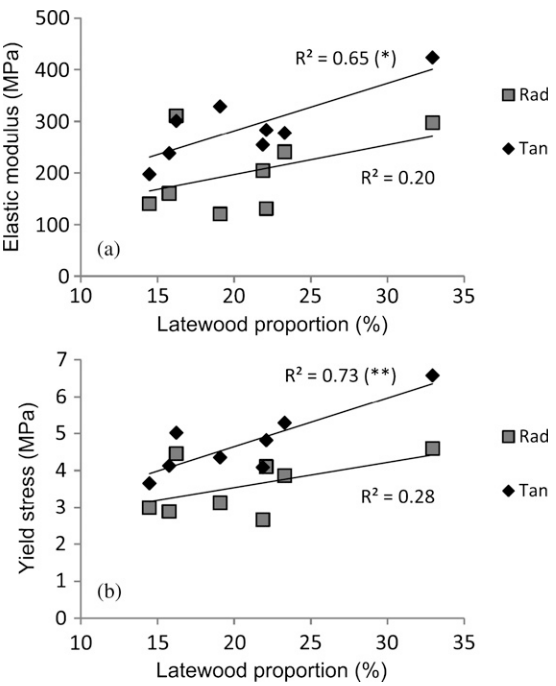

Figure 6. Correlation between (a) latewood proportion and modulus of elasticity (MOE) as well as between (b) latewood proportion and yield stress of dried samples. *Significant at the 0.05 level (Pearson, two-tailed). **Significant at the 0.01 level (Pearson, two-tailed).

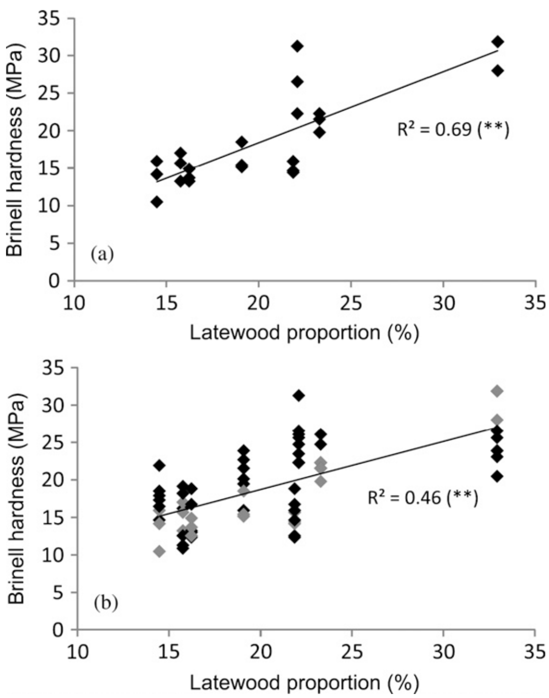

Figure 7. Correlation between latewood proportion and Brinell hardness of dried boards. Brinell hardness measured from (a) three locations on the board center line, ie direction of load is radial and (b) nine locations evenly distributed on the surface of the board where the center line values are marked in grey. *Significant at the 0.05 level (Spearman, two-tailed). **Significant at the 0.01 level (Spearman, two-tailed).

(Kollmann and Côtè 1968; Holmberg 2000; Heräjärvi 2004). This finding was interesting, although the amount of latewood determined in this study covered the whole thickness of the board. This result implies that there was a difference in contribution and presence of forces between indentation and unconfined compression tests: in hardness tests, surface properties were more dominant than the structure deeper in the wood, whereas in unconfined compression, the entire wood was compressed. This is supported by Hirata et al (2001) who measured hardness using a 2-mm-diameter ball tip for three wood species. They reported that by using a small indentor tip, the difference in hardness between earlywood and latewood became more clear. A significant correlation was also found by using all the measurement points on the board surfaces (Fig 7b). However, correlation was not as good as with the measurements only from the center line (Fig 7a). Different annual ring orientation through the board width changes the surface properties and probably adds deviation to the hardness values. Actually, the average hardness value closer to the edges of the boards (annual ring bending toward perpendicular orientation with the sample surface) was 13% higher than that in the center line (Fig 7b).

Deformation characteristics of wood are different when they are subjected to radial and tangential directions (Tabarsa and Chui 2001). Annual ring orientation to the surface changes along the width of the board, and as a result, the direction of loading in drying is a combination of radial and tangential compression. Thus, densification in the sides of the board is likely to differ from what is seen in Fig 4b, which in turn is supposed to affect the material properties and orthogonality of the wood; enhancement in tangential mechanical properties of pine found in this study may be less drastic, whereas radial properties may be affected in the areas with perpendicular annual ring orientation.

Mechanical and structural properties of traditionally dried lumber depend on the quality of the wood, although the wood may be modified for different uses by compression drying. In the wood modification process applied here, compression pressure and strain and other control parameters can be easily controlled and modified, making the end product more versatile compared with traditionally dried wood. Also, the method decreases drying time, which makes it more economical and environmentally friendly than traditional drying. However, control of cellular deformation and its influence on these properties is a complex process that might also turn to a disadvantage of the drying method. Other possible drawbacks could be tension properties when subjecting wood to a perpendicular-to-grain loading and microcracks if subjecting samples to excessive load. Therefore, compression loads, drying times, and other control parameters during the modification process should be optimized for different species of wood and end products. Many of these issues are still under investigation and should be studied more in the future.

CONCLUSIONS

In this study, structural and mechanical properties of compression-dried pine wood were studied. The findings showed that softwood density increased as a result of earlywood deformation in radial compression during a drying process. Thus, the latewood-to-earlywood ratio increased, which enhanced wood strength, especially in tangential compressive loading, and also surface hardness. This suggests that compression drying can be used to modify structural and mechanical properties of wood.

ACKNOWLEDGMENTS

This project was funded by TEKES (The Finnish Funding Agency for Technology and Innovation).

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