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Properties of four domestic hardwood species

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This study aimed to evaluate the physical and mechanical properties of red oak (*Quercus* spp.), white oak (*Quercus* spp.), hard maple (*Acer saccharum*) and yellow-poplar (*Liriodendron tulipifera*) and compare them to values from past publications. Mechanical testing was conducted on small, clear, defect-free specimens from red oak, white oak, hard maple and yellow-poplar following the standard ASTM D143. Percentage of latewood, moisture content, specific gravity, modulus of elasticity (MOE), modulus of rupture (MOR), compression parallel and perpendicular to the grain and Janka hardness were determined. Results indicated that mechanical properties for red oak, white oak, hard maple and yellow poplar have not changed substantially because the average values remain in a range that is very close to the ones published in past studies. Thus, values from the Wood Handbook can still be used for engineering purposes.

Keywords: mechanical properties, red oak, white oak, yellow poplar, hard maple.

DEDICATION

I dedicate this thesis to the memory of my father, Hugo A. Carmona and my beloved little dog, Luna. The two beings I loved the most. Even though you are not physically with me, I carry you in my heart everywhere I go.

To my family in Venezuela. My mother, Mary, and my siblings, Maria and Moisés who always have been there for me. Even across distance, we stay together. You are my engine to keep going.

To the University of Los Andes. I owe them a part of who I am..

To my Venezuelan friends (now around the world) for giving me so many hours of their time to listen to me on the phone when I needed to talk.

To my husband Austin Irby and his family, especially his grandmother Linda Irby. I will always be grateful for the emotional support, as well as, the help you gave me since I arrived in the USA.

Lastly, but not less important, to Prof. Vincent and Lana Monet, my two adorable Mississippian puppies, for the companionship, fun and happiness provided during my research and writing process. They have made my living experience in the USA more fulfilling.

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CHAPTER I

INTRODUCTION

The load that a wood structure can resist depends on the direction in which the force is applied in relation to the fiber's direction. Other properties, such as, wood anatomical properties, specific gravity, and chemical makeup, influence the load-carrying capability of a determined species. The wood performance under a specific load can also be affected by insects, fungus, animal attacks, tree diseases, seasonal degrading, humidity, temperature, duration rate of the load, and moisture content, etc. (Koch, 1985).

Testing is important because of the variety of factors that influence the mechanical behavior of wood. In general, testing results are used to develop design values to engineer structural applications that are compliant with building codes and regulations. The present study focused on the evaluation of physical and mechanical properties of four hardwoods: red oak (*Quercus* spp.), white oak (*Quercus* spp.), hard maple (*Acer saccharum*) and yellow poplar (*Liriodendron tulipifera*). These species are of special economic interest for the stairway industry in the United States.

Despite the fact that hardwoods possess ideal mechanical characteristics for structural applications, currently hardwood species (with some exceptions) do not have assigned allowable design properties to engineer structural applications that comply with the building codes and standards in the United States (Bendtsen *et al.* 1975; Koch, 1985; Cooper 2014).

Approximately 100 years ago, the USDA Forest Service, Forest Products Laboratory conducted large studies on the physical and mechanical properties of hardwoods and other species. Currently, the values most used are the ones published in the *Wood Handbook* (Kretschmann, 2010). This research intends to evaluate the physical properties of wood such as moisture content, percentage of latewood, and specific gravity, as well as conduct mechanical tests to verify the values of modulus of elasticity (MOE), modulus of rupture (MOR), compression and Janka hardness of red oak, white oak, hard maple and yellow poplar.

The Stair Builders Manufacturers Association (SMA), an association dedicated to the improvement of the stairway industry in North America, donated the material for this research. Boards were obtained from different sawmills located in the Northeast, Upper Midwest, Southeast, Mid-South, Appalachian, and Southeastern regions of the United States. The material was transported to the Franklin Laboratory at Mississippi State University to conduct mechanical testing using Universal Instron Machines (Instron Model 5566, Norwood, USA) and following the standard ASTM D143 (ASTM, 2014) for small clear specimens.

Since the market is demanding design values for hardwoods to engineer products that are beyond the common uses, the SMA is interested in conducting testing to calculate those values. SMA is aware of the importance of mechanical testing to quantify design values for appearance grade hardwoods (Cooper, 2014). This study constitutes a step forward to achieve this goal. Test results will benefit the stairways industry and the entire hardwood industry.

Data collection was completed on 365 kiln dried, defect-free, and straight-grained boards. These characteristics are necessary to build stairways made of hardwoods. Data collection included the width, length, thickness, weight, rings per inch, percentage of latewood, mill location, moisture content, and temperature of each board. Specimens were cut into appropriate sample sizes necessary to conduct the tests. The small clear samples were processed into six different sample sizes in accordance with the "secondary method" explained in section 8.1 of the ASTM-D 143-14 (2014). The secondary method was selected by default because the boards were 1-inch thick and mimicked the previous work done by the USDA Forest Products Laboratory. From each board, samples were cut as follows: one sample for specific gravity, two samples for static bending (one radial and one tangential labeled "A" and "B" respectively), one for Janka hardness, and two for compression (one parallel to the grain and one perpendicular to the grain). Overall, approximately 2,190 clear samples were tested.

The next chapter contains the information and results obtained from the tests conducted for red oak and white oak. In Chapter III, the reader will find the information regarding the physical and mechanical properties of clear wood of hard maple and yellow-poplar. Summaries of property values were organized in tables including estimations of mean properties, range of variation and the relevant statistical information. Additionally, the reader will find comparisons with other results found in the literature review.

Comparisons are intended to bring together the results obtained from other mechanical testing related to the four species selected for this study. It is the author's expectation that the information provided here will serve as basis for confirmation or update of the mechanical property values of the species studied.

CHAPTER II

PHYSICAL AND MECHANICAL PROPERTIES OF CLEAR WOOD FROM RED OAK AND WHITE OAK

Introduction

Oak (*Quercus*) is a genus composed of a diverse group of tree species that have been reported as one of the most widely used hardwoods in Europe and North America (Merela and Čufar 2013). In the United States, red oak (*Quercus* spp.) grows naturally in eastern and central states while white oak (*Quercus* spp.) distribution includes the South, South Atlantic, and Central States (Kretschmann, 2010). Red oak and white oak have been identified as species of great economic interest for the stairway industry; thus, the characterization of their mechanical properties is required for wooden structural applications. Past investigations have demonstrated that both red oak and white oak wood are hard and strong in bending and endwise compression (Brown *et al.* 1949). These characteristics make them suitable as structural materials; however, currently these species do not have assigned allowable design properties to engineer structural applications that comply with building codes and standards (Bendtsen *et al.* 1975; Cooper 2014).

Oaks are ring-porous hardwoods with high density in the latewood part of the growth ring. Because the changes in the ring width of oaks have been more associated with change in the width of latewood, the percentage of latewood increases alongside ring width. Generally, this allows the wood density of oak as well as other strength properties to increase as the growth rate increases. However, the density of some trees may decline with further increase in width ring generated from a fast growth rate (Nepveu, 1993). Variations in latewood density can be associated with variation in the latewood structure as well as the changes in the proportions between earlywood and latewood (Rao *et al.* 1997).

Red oak and white oak have great aesthetic qualities that make them appealing for different uses such as furniture, bowling pins, stairways, interior paneling, general millwork, cabinets, among others. Both are also widely used for flooring because of their hardness and other characteristics that make them ideal for this purpose. Other uses for white oak and red oak include railroad ties, fence posts, poles, boxes, pallets, mine timbers, *etc*. (Brown *et al.* 1949).

Currently, the staircase industry in U.S. is seeking to develop design values for domestic hardwood commonly used in stairways with the expectation of increasing their use in domestic wood construction. Testing to verify the physical and mechanical properties is necessary to compare the wood used today with data from past publications (Newlin and Wilson 1917; Markwardt and Wilson 1935).

Despite the variations that can be found in wood due to the influence of several factors, such as climate, the region of growth, the wood anatomy, silvicultural, and manufacturing practices, the Staircase Manufacturers Association (SMA) made efforts to provide oak boards of the highest quality used by SMA members to manufacture staircases. The present study aims to evaluate growth characteristics and physical and mechanical properties and compare them with the results obtained from previous studies. In that sense, the main goal of this research is i) to determine the growth characteristics (rings per inch and percentage of latewood; ii) to test physical properties (moisture content and specific gravity); iii) to test mechanical properties of small clear wood specimens (static bending, compression parallel and perpendicular to the grain, and Janka hardness); and iv) to compare the results from both species with the published values in earlier studies.

Materials and Methods

Materials and Sample Preparation

The material came from the Northeast, Upper Midwest, Southeast Mid-South, Appalachian, and Southeastern regions, and the boards were donated by staircase manufacturers. The boards were kiln dried, defect-free, and straight-grained. These characteristics are generally required by stairway manufacturers. Boards were kept in a controlled environment (21 °C and 65 % relative humidity (RH)) for several weeks before initial testing.

Prior to the physical and mechanical tests, each board was labeled with the initial of the species name and a unique number to organize the boards per species and facilitate the data collection. The boards were originally 1.14-inch thick (2.89 cm), 5.48 inches (13.9 cm) wide, and 37.8 inches (96 cm) long. Rings per inch (RPI), percentage of latewood (LW), manufacturing location, moisture content (MC), and temperature were collected from 90 red oak and 91 white oak boards. Width, length, thickness, and weight were recorded to calculate the density of each board.

Rings per inch were calculated by counting the number of the rings and dividing by the thickness or the width, depending on the grain orientation of the piece (radial or tangential). Percentage of latewood was determined using a 1 inch × 1-inch (2.54 cm × 2.54 cm) dot grid. The percentage of latewood was estimated by dividing the number of dots that fell on LW by the total number of dots in the grid. Both measurement techniques followed Southern Pine Inspection Bureau (SPIB) standard grading rules (SPIB 2014). Board density was determined using the bulk weight and the bulk volume at approximately 12%. Moisture content was determined using a moisture meter from Wagner, model MMC 220 (Wagner Meters, Rogue River, USA).

After initial measurements, each board was cut into physical and mechanical properties specimens in accordance with the “secondary method” of specimen preparation explained in Section 8.1 of ASTM-D 143-14 (2014). The secondary method was selected by default because the boards were 1-inch thick.

From each board, one specific gravity, two static bending (radial and tangential), two compression (one parallel and one perpendicular), and one Janka hardness specimens were cut following the scheme in Fig. 2.1.

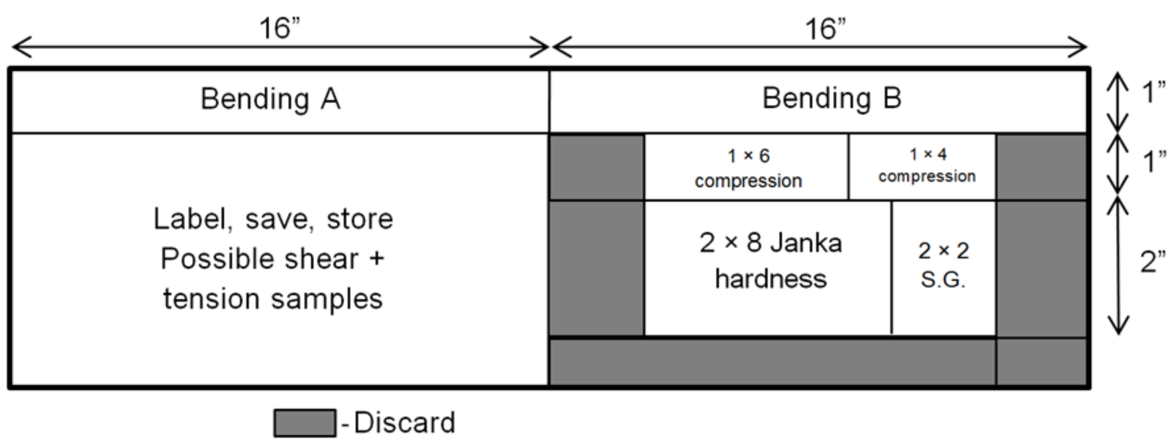


Figure 2.1 Cutting scheme of small clear wood specimens from the boards.

Testing Procedures

Tests of specific gravity, static bending, compression parallel and perpendicular to grain, and Janka hardness were conducted. Each specimen was weighed and measured before testing. The mechanical tests were performed using Instron universal testing machines (Instron Model

5566, Norwood, USA) with the Bluehill 3 software (Instron, Norwood, USA) to control operations. The data generated were recorded directly into a Structured Query Language (SQL) database to minimize typing errors.

Specific Gravity (SG)

The SG specimen's sizes were 1 × 2 × 2 $inch^3$ (2.54 × 5.08 × 5.08 cm^3). The dimensions of each specimen were collected, and then the specimens were oven dried (103 ± 2 °C). Oven-dried weights of the specimens were recorded.

Static Bending Tests

Static bending specimens were 1 × 1 × 16 $inch^3$ (2.54 × 2.54 × 40.64 cm^3). The load span was 14 inches (35.6 cm). The test was conducted using center point loading with a test speed of 0.05 inches (0.127 cm) per minute (Fig. 2.2). Tests were performed in radial and tangential directions (Fig. 2.3). For radial specimens, load was applied on one of the radial faces. For tangential specimens, load was applied on the face nearest to the pith. The failure type was recorded for each specimen. Modulus of elasticity was calculated using Eq.2.1. Modulus of rupture was calculated using Eq. 2.2,

$$MOE = \frac{\Delta P \cdot L^3}{4 \cdot \Delta f \cdot b \cdot h^3} \tag{2.1}$$

Where *MOE* is the bending modulus of elasticity (MPa), *ΔP* is the loading increase (N), *L* is the span length (m), *Δf* is the deflection increase (m), *b* is the width (m), and *h* is the depth of the specimen (m). Equation 2 is as follows:

$$MOR = \frac{3 \cdot P \cdot L}{2 \cdot b \cdot h^2} \tag{2.2}$$

Where *MOR* is the bending modulus of rupture (MPa); *P* is the maximum force (N) at the mid-span; *L* is the span length (m); *b* is the width (m); and *h* is the depth (m).

Figure 2.2 Static bending test setup

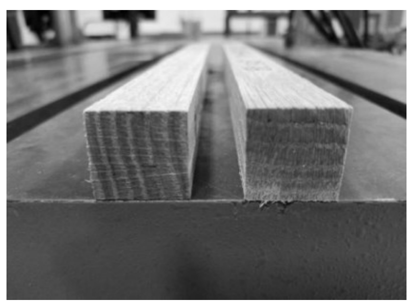
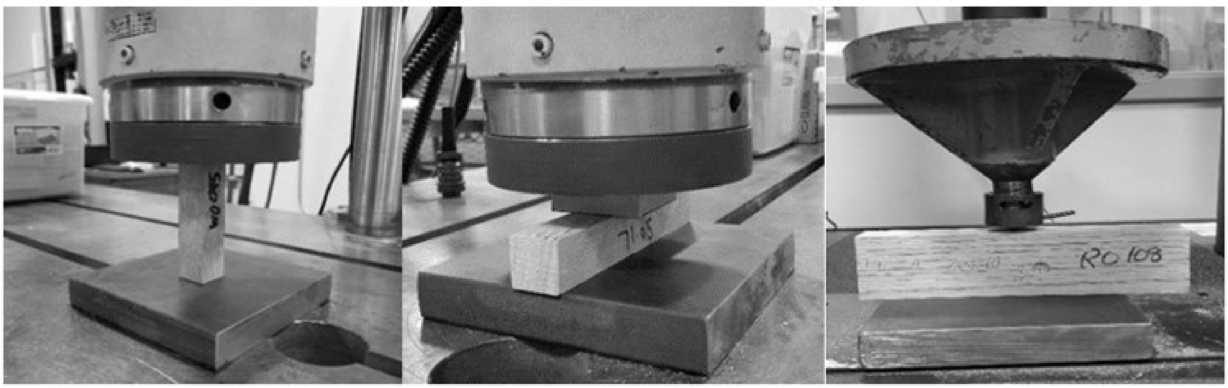


Figure 2.3 Bending tests were conducted in radial and tangential directions. The rings at the end of each sample were used as a guide to identify the direction to test.

Compression Parallel to the Grain

Test specimens measured 1 × 1 × 4 inch^3 (2.54 × 2.54 × 10.16 cm^3). The load was applied at a rate of 0.003 inch/inch (0.00762 cm/cm) of nominal specimen length/min. The type of deformation was recorded for each specimen. Figure 2.4a exhibits the testing setup.



(a) (b) (c)

Figure 2.4 a) Compression parallel to the grain; b) Compression perpendicular to the grain; and c) Janka ball side hardness

Compression Perpendicular to the Grain

Each specimen measured 1 × 1 × 6 inch^3 (2.54 × 2.54 × 15.24 cm^3). The load was applied through a bearing plate 2 - inches (5.08 cm) wide, placed at the top of the specimen in contact with its radial surface (Fig. 2.4b). The speed rate of loading was 0.012 inches (0.305 mm) per min.

Janka Hardness

The tests were performed on 1 × 2 × 6 inch^3 (2.54 × 5.08 × 15.24 cm^3) specimens. During the test, a 0.444-inch (1.13 cm) ball was embedded to half its diameter into each specimen at a rate of 0.25 inch/min (0.6 cm/min). Two penetrations were made on each specimen in their radial surface and two penetrations on the tangential surface. The speed of testing was 0.25 inches (6 mm) per min as indicated in the ASTM D143-14 (ASTM, 2014) (Fig. 2.4c).

Results and Discussions

A summary of the growth characteristics and physical properties of red oak and white oak specimens are given in Table 2.1 The average moisture content of the red oak boards varied between 4.7 and 15.6% with a mean value of 11.0% and a coefficient of variation of 19.96%. Moisture content of white oak boards varied between 8.0 to 17.1% with an average value of 12.5% and a coefficient of variation of 19.34%. Rings per inch for red oak varied between 1.1 and 18.5 with a mean of 7.3 and a coefficient of variation of 48.52%. For white oak, rings per inch varied between 1.3 and 23.9 with a mean of 9.6 and a coefficient of variation of 46.22%.

Table 1.1 Moisture Content (MC), rings per inch, percentage of latewood, board density, and specific gravity values, for red oak and white oak

Species	N	Properties	Mean	Min	Max	SD	CV (%)
Red Oak	90	MC (%)	11.0	4.7	15.6	2.2	19.96
		Rings per inch	7.3	1.1	18.5	3.53	48.52
		% Latewood	71.3	42.2	98.4	12.96	18.17
		Board density ($kg \cdot m^{-3}$)	699	571	853	57.99	8.31
		$SG_{12\%}$	0.65	0.54	0.77	0.05	8.33
White Oak	91	M.C (%)	12.5	8.0	17.1	2.41	19.34
		Rings per inch	9.6	1.3	23.9	4.41	46.22
		% Latewood	67.8	35.9	96.9	14.69	21.66
		Board density ($kg \cdot m^{-3}$)	756	599	887	67.44	8.91
		$SG_{12\%}$	0.71	0.55	0.83	0.06	9.00

SD: Standard deviation; CV: coefficient of variation

The average percentage of latewood of the red oak varied between 42.2 and 98.4% with a mean value of 71.3% and a coefficient of variation of 18.17%. Percentage of latewood of white oak varied between 35.9 and 96.9% with a mean of 67.8% and a coefficient of variation of 21.66%. Density for red oak varied between 571 and 853 with a mean of 699 and a coefficient of variation of 8.31%. For white oak, the density varied between 599 and 887 with a mean of 756 and a coefficient of variation of 8.91%. The mean specific gravity of the red oak was 0.65, with a coefficient of variation of 8.33% and 0.54 and 0.77 as the minimum and maximum average values, respectively. For white oak, the SG mean was 0.71, with a minimum of 0.55 and a maximum of 0.83 and a coefficient of variation of 9.0%.

Coefficient of variation, averages and ranges of variation for all bending tests conducted are listed in the table 2.2. In general, the overall average for bending (MOE) and (MOR) of red oak were higher than white oak specimens. For red oak, MOE and MOR average values were 12,211 MPa and 120 MPa, respectively. White oak average values for MOE and MOR were 11,300 MPa and 113 MPa, respectively. Red oak and white oak samples tested in tangential direction exhibited slightly higher average values of MOE and MOR when compared to the obtained values in radial direction.

Table 2.2 Static Bending MOE and MOR values in radial and tangential directions for red oak and white oak

Species	N	Static Bending (MPa)					
		Direction	**Variable**	**Mean**	**Min**	**Max**	**CV (%)**
Red Oak	90	Radial	MOE	12,024	7,074	17,533	16.33
			MOR	118	65	170	19.67
	89	Tangential	MOE	12,404	8,157	18,133	14.82
			MOR	122	73	162	17.24
	179	Average	MOE	12,211	7,074	18,133	15.61
			MOR	120	65	170	18.49
White Oak	91	Radial	MOE	11,273	6,667	15,961	17.89
			MOR	112	59	153	20.13
	91	Tangential	MOE	11,328	7,915	15,879	16.48
			MOR	115	62	157	17.50
	182	Average	MOE	11,300	6,667	15,961	17.15
			MOR	113	59	157	18.82

The mean MOR, for red oak, in radial and tangential were 118 MPa and 122 MPa respectively. In radial direction, the minimum, maximum, and coefficient of variation values were 65 MPa, 170 MPa, and 19.67% respectively. In tangential direction, the minimum, maximum, and coefficient of variation values were 73 MPa, 162 MPa, and 17.24%, respectively. The average MOR for red oak varied between 65 and 170 MPa with a mean of 120 MPa and coefficient of variation of 18.49%.

For white oak, the mean MOR in radial and tangential were 112 MPa and 115 MPa respectively. In radial direction, the minimum, maximum, and coefficient of variation values were 59 MPa, 153 MPa, and 20.13%, respectively. In tangential direction, the minimum, maximum, and coefficient of variation values are 62 MPa, 157 MPa, and 17.50%, respectively. The average MOR for white oak varied between 59 and 157 MPa with a mean of 113 MPa and coefficient of variation of 18.82%.

Compression parallel and compression perpendicular results for red oak and white oak are listed in Table 2.3. For red oak, compression parallel values ranged from 47 to 80 MPa, with a mean value of 61 MPa and coefficient of variation of 11.47%. For white oak, compression parallel values ranged from 42 to 75 MPa, with a mean value of 60 MPa and coefficient of variation of 12.90%. For compression perpendicular, red oak values ranged from 11 to 33 MPa, with a mean value of 18 MPa and coefficient of variation of 20.84%. For white oak, compression perpendicular values ranged from 11 to 26 MPa, with a mean value of 18 MPa and coefficient of variation of 17.33%.

Table 2.3 Compression parallel and perpendicular values for red oak and white oak

Species	**Direction**	**Compression (MPa)**				
		N	**Mean**	**Min**	**Max**	**CV (%)**
Red Oak	Parallel	81	61	47	80	11.47
	Perpendicular	90	18	11	33	20.84
White Oak	Parallel	91	60	42	75	12.90
	Perpendicular	91	18	11	26	17.33

Janka hardness results for red oak and white oak are listed in Table 2.4. For red oak, Janka hardness values in the radial direction ranged from 3.9 to 10.2 kN, with a mean value of 5.8 kN and coefficient of variation of 19.19%. In the tangential direction, red oak hardness values ranged from 3.8 to 10.5 kN with a mean of 6.3 kN and coefficient of variation of 19.13%. The average hardness for red oak varied between 3.8 and 10.5 with a mean of 6.1 kN and coefficient of variation of 19.55%.

For white oak, Janka hardness values in the radial direction ranged from 2.9 to 9.2 kN, with a mean value of 5.9 kN and coefficient of variation of 21.26%. In the tangential direction, white oak values ranged from 4.0 to 10.4 kN, with a mean value of 6.6 kN and coefficient of variation of 20.22%. The average hardness for white oak varied between 2.9 and 10.4 kN with a mean of 6.3 kN and coefficient of variation of 21.34%.

Table 2.4 Janka hardness values in radial and tangential directions for red oak and white oak

Species	Direction	Janka Hardness (kN)				
		N	Mean	Min	Max	CV (%)
Red Oak	Radial	179	5.8	3.9	10.2	19.19
	Tangential	181	6.3	3.8	10.5	19.13
	Average	360	6.1	3.8	10.5	19.55
White Oak	Radial	180	5.9	2.9	9.2	21.26
	Tangential	180	6.6	4.0	10.4	20.22
	Average	180	6.3	2.9	10.4	21.34

Comparisons with previous publications

When comparing these results with the values published by other authors in previous years, the rings per inch, the percentage of latewood, and specific gravity varied slightly. The rings per inch from the current study for red oak and white oak were lower compared to the literature. From the graph it can be seen that percentage of latewood for red oak and white oak was within the range of the values reported by Newlin and Wilson (1917), Markwardt and

Wilson (1935), and the Wood Handbook (Kretschmann, 2010). Specific gravity was within the range of the values reported previously (See Fig. 2.5 and Fig. 2.6).

Overall, red oak exhibited slightly higher MOE and MOR values compared to white oak. The MOE values for red oak were similar to the results obtained by Newlin and Wilson (1917) but slightly higher than the values obtained from Markwardt and Wilson (1935) and the Wood Handbook (Kretschmann, 2010). The MOR values for red oak were slightly higher than the ones published by Newlin and Wilson (1917) and Markwardt and Wilson (1935) as well as the Wood Handbook (Kretschmann, 2010) (See Fig. 2.7A and Fig. 2.7B).

The MOE values for white oak were slightly lower than Newlin and Wilson (1917), Markwardt and Wilson (1935), and the Wood Handbook (Kretschmann, 2010). The MOR values for white oak were slightly higher than the ones published by Newlin and Wilson (1917) and Markwardt and Wilson (1935) as well as the Wood Handbook (Kretschmann, 2010). (See Fig. 2.7A and Fig.2.7B).

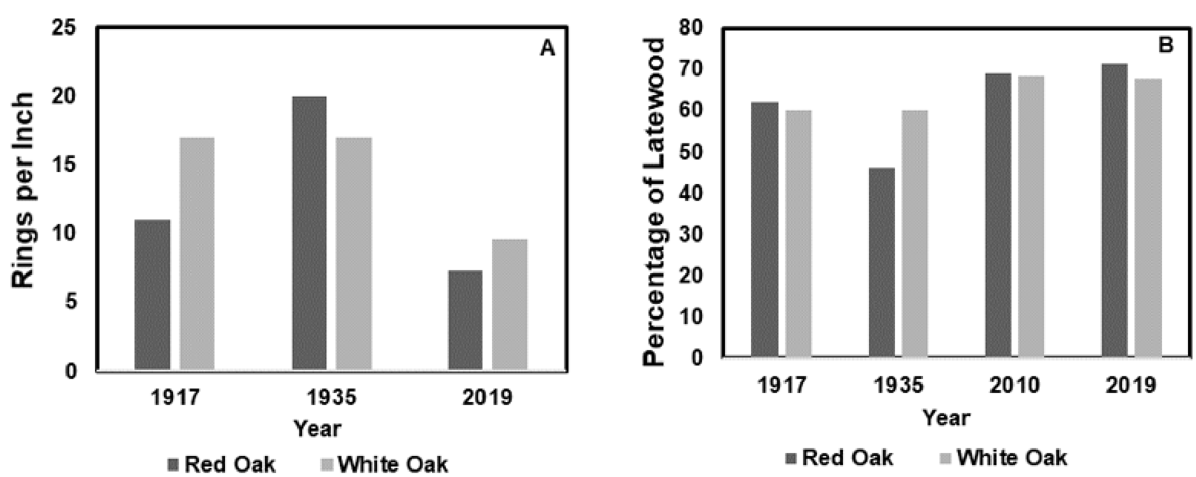


Figure 2.5 A) Comparison of rings per inch and B) comparison of percentage of latewood

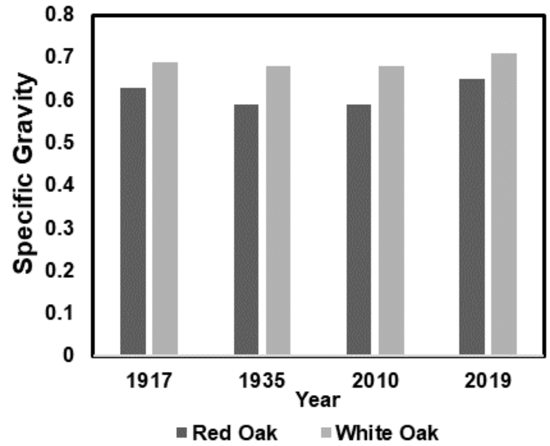


Figure 2.6 Comparison of specific gravity

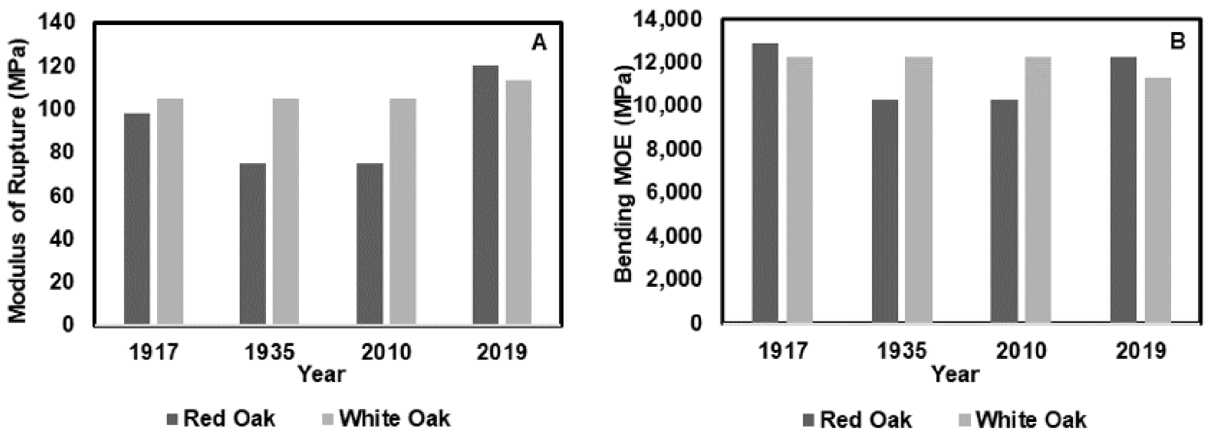


Figure 2.7 A) Comparison of MOR and B) Comparison of bending MOE

Values of compression parallel to the grain, for red oak and white oak, were slightly higher than the ones published by Newlin and Wilson (1917) and Markwardt and Wilson (1935), as well as the Wood Handbook (Kretschmann, 2010). However, for compression perpendicular to the grain, both species showed higher values than the reported for the mentioned authors (See Fig. 2.8 A and 2.8 B).

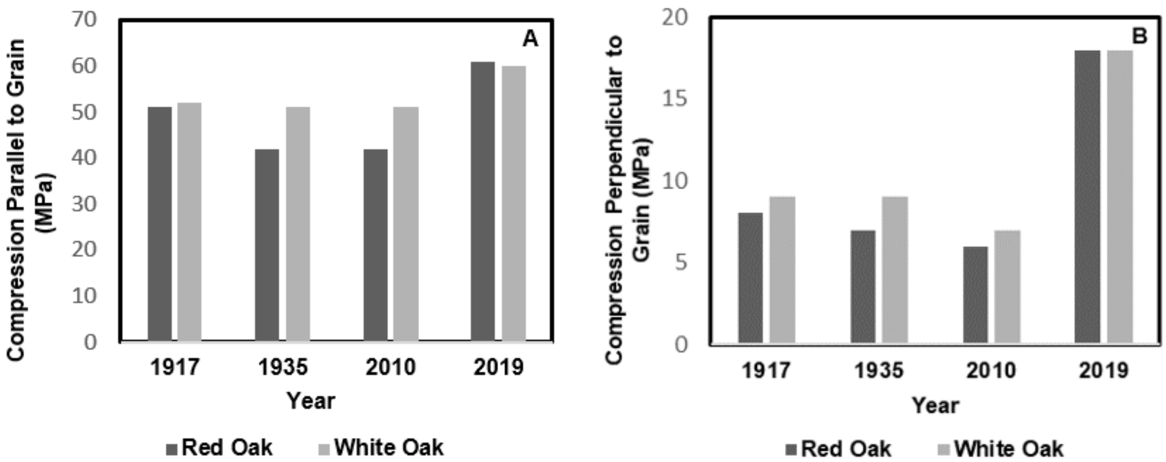


Figure 2.8 A) Comparison of compression parallel to grain and B) comparison of compression perpendicular to grain

Values of Janka hardness, for red oak, were slightly higher than the ones reported by Newlin and Wilson (1917), Markwardt and Wilson (1935) as well as, the *Wood Handbook* (Kretschmann, 2010). White oak hardness values were within the range reported by the mentioned literature (See Fig. 2.9). Northwest Hardwoods (2018) recommends the rating of 4.74 kN for red oak and 6.05 kN for white oak as its industry benchmark.

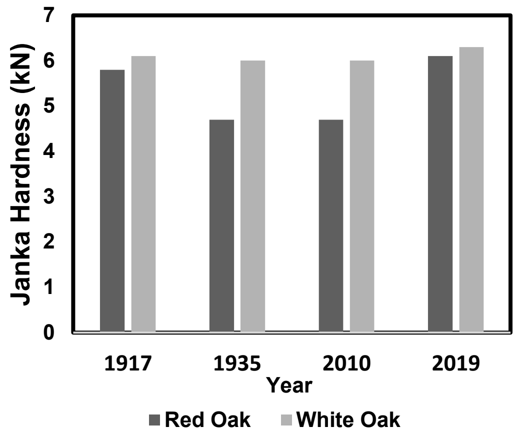


Figure 2.9	Comparison of Janka hardness

Mean Comparisons

Two-sample *t* tests were performed to determine if there were significant mean differences in growth characteristics, physical, and mechanical properties between red oak and white oak, as shown in Table 2.5. The *t* test was performed using the average values (radial and tangential of each property).

Table 2.5	Two-Sample *t*-test for growth characteristics, physical, and mechanical properties

Test	Species	N	Mean	SD	*t*	df	p-value
Rings per Inch	Red oak	178	7.27	3.62	5.35	352	< .0001
	White oak	176	9.55	4.21			
Percentage of Latewood (%)	Red oak	178	71.30	12.96	2.37	352	0.02
	White oak	176	67.81	14.69			
Density ($kg \cdot m^{-3}$)	Red oak	89	699	57.99	6.04	175	< .0001
	White oak	88	755	67.44			
Specific Gravity	Red oak	90	0.65	0.05	6.14	175	< .0001
	White oak	87	0.71	0.06			
Bending MOE (MPa)	Red oak	179	12,211	1907	4.50	359	< .0001
	White oak	182	11,300	1939			
Bending MOR (MPa)	Red oak	179	120	22.2	2.88	359	0.004
	White oak	182	113	21.4			
Compression Parallel (MPa)	Red oak	81	61	7.0	6.14	175	< .0001
	White oak	91	60	7.7			
Compression Perpendicular (MPa)	Red oak	90	18	3.9	0.01	179	0.98
	White oak	91	18	3.2			
Janka Hardness (kN)	Red oak	360	6.1	1.1	2.32	707	0.02
	White oak	360	6.3	1.3			

$\alpha = 0.05$, 2-tailed; df: degrees of freedom

For rings per inch, the mean RPI values for red oak and white oak small clear specimens were 7.27 and 9.55, respectively. A two-sample *t* test revealed significant difference between the two means at the 0.05 level ($p < .0001$). For percentage of latewood, the mean value for red oak was 71.30 while the mean for white oak was 67.81. A two-sample *t* test between these means revealed a significant difference between the red oak and white oak percentage of latewood ($p = 0.02$).

The mean SG values for red oak and white oak small clear specimens were 0.65 and 0.71, respectively. A two-sample *t*-test revealed a significant difference between the two means for specific gravity at the 0.05 level ($p = < .0001$). The mean density value for red oak was 699 while the mean density for white oak was 755. A two-sample *t*-test revealed a significant difference between the two means density at the .05 level ($p < .0001$).

As shown in Table 5, the mean MOE values for the red oak and white oak small clear specimens were 12,211 MPa and 11,300 MPa, respectively. A two-sample *t*-test revealed a significant difference between the two means at the 0.05 level ($p < .0001$). The corresponding mean MOR values of 120 MPa and 113 MPa for red oak and white oak, respectively, are shown in Table 5. The *t*-test for MOR comparison revealed a significant difference ($p = 0.004$).

For compression parallel and perpendicular to the grain, the mean for red oak was 61 MPa and 18 MPa, respectively. For white oak, the mean in compression parallel and perpendicular to the grain was 60 MPa and 18 MPa, respectively. A two-sample *t*-test revealed a significant difference between the means for compression parallel to the grain ($p =< .0001$) and no significant difference between the two means for compression perpendicular to the grain ($p= 0.98$). The mean Janka hardness values for red oak and white oak were 6.1 kN and 6.3 kN, respectively. A two-sample *t*-test revealed a significant difference between the two means for hardness at the 0.05 level ($p = 0.02$).

Conclusions

1. The mechanical properties for red oak and white oak have not changed substantially because the average values remained in a range that was close to those published in the past 100 years. Thus, the values from the *Wood Handbook* can still be used for engineering purposes.

2. The MOE and MOR values for the species evaluated in the present study were similar to the ones published in past studies.

3. The number of rings for both species decreased when compared with past studies.

4. Compression perpendicular to the grain for both species was higher than the values published in other studies.

5. Overall, red oak exhibited slightly higher MOE and MOR values when compared to white oak. In general, the evaluated mechanical properties values of red oak were significantly different from the white oak.

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CHAPTER III

PHYSICAL AND MECHANICAL PROPERTIES OF HARD MAPLE (*Acer saccharum*) AND YELLOW POPLAR (*Liriodendron tulipifera*)

Introduction

Harwood timber is a resource that is strong, sustainable and aesthetically attractive. Hardwoods are used in numerous structural applications such as furniture parts, stairs, tool handles, bowling pins, baseball bats, parallel bars, stair railings, highway guardrail posts, and pallets. Although they are usually used for small-scale structures and non-load bearing applications, there is a growing interest for combining structural performance with aesthetic design.

Hard maple (*Acer saccharum*) is a wide-ranging species that grows in the eastern United States (mainly Mid-Atlantic States) and the Upper Midwestern Lake states. The sapwood is creamy white with a slight reddish-brown tint and the heartwood varies from light reddish brown to dark brown. Maple wood is hard and heavy with straight grain and good strength properties. Some uses include flooring, furniture, paneling, cabinets, millwork, stairs, handrails, doors, woodenware, sporting and athletic goods, among others (Wiemann, 2010; Hardwood Manufacturers Association, 2019).

Yellow poplar (*Liriodendron tulipifera*) grows in the eastern United States. Its wood is medium density with low bending, shock resistance, stiffness, and compression values. The sapwood is usually white. The heartwood is yellowish brown, and sometimes it has parts with purple, green, black, blue, or red. The presence of these colors does not affect its physical properties. It is used for lumber, veneer, pulpwood, light construction, furniture, kitchen cabinets, doors, paneling, moulding and millwork, edge-glued panels, turnings, musical instruments and carvings (Koch, 1985; Wiemann, 2010; Hardwood Manufacturers Association, 2019).

In the stairway industry, some hardwood species have been identified as having the greatest economic impact due to their historically excellent performance. However, unlike other materials, hardwoods of oven-dried appearance grade lack design values necessary for the creation of products that meet the standards (Cooper, 2014). The information available at this time related to the hardwoods mechanical properties comes from studies conducted nearly 100 years ago (Newlin and Wilson, 1917; Markwardt and Wilson, 1935). For this reason, performing mechanical tests to verify the properties of these species is important to maintain current information that fulfills the regulations and building codes.

Mechanical and physical properties of wood are influenced by a variety of factors such as weather, moisture, geography, soil, silvicultural practices, and harvesting decisions. These properties vary according to the axis of measurement (longitudinal, radial or tangential) due to the anisotropic nature of wood. Mechanical properties are the basis of design values, which estimate the structural performance of specific material sizes and qualities. Some of the most common mechanical properties measured through structural testing procedures are modulus of elasticity (MOE), modulus of rupture (MOR), maximum stress in compression parallel to grain (Fc), compression perpendicular to grain (Fc-perp), shear strength parallel to grain (Fv), tension parallel to grain, hardness, and specific gravity (Kretschmann, 2010).

Modulus of elasticity (MOE) and modulus of rupture (MOR) are important properties to determine the use of wood. MOE helps to describe stiffness and is a good overall predictor of wood strength (França *et al*., 2016). MOR, on the other hand, is a measure that indicates the bending strength of a board or structural member. MOR represents the maximum load a wooden specimen can withstand in bending before rupture (Kretschmann, 2010).

Mechanical testing is necessary to understand the behavior of wood. Previous studies such as the one made by Newlin & Wilson (1917), Markwardt and Wilson (1935) and Kretschmann (2010), have characterized the physical properties such as rings per inch (RPI), moisture content (MC), percentage of latewood (LW), specific gravity (SG) and the strength properties such as modulus of elasticity (MOE), bending strength (MOR), compression and hardness of hard maple and yellow poplar. The most recent and accepted property values are the ones published in the Wood Handbook (Kretschmann, 2010).

Variation in the values can be associated with different factors such as the modernization of the technology used to perform the tests, the temperature conditions or moisture content at the time of the test, the methods of data collection, the character of some forests that change over time, and even the variability from each tree from where the test specimens were obtained (Kretschmann, 2010).

The lumber industry is aware of the uncertainty associated with the average values of the mechanical properties of wood species, which is why they invest large amounts of money to carry out periodic tests to obtain the most accurate and reliable design values (Southern Forest Products Association, 2019). As part of the contribution to maintaining the validity and reliability of these values, the Stairbuilders Manufacturers Association (SMA) in conjunction with USDA Forest Service, Forest Products Laboratory, has funded the conduction of tests to evaluate the mechanical properties of the most important species for the stairway industry.

The purpose of this study was to investigate the physical and mechanical properties of hard maple and yellow poplar to supplement available information on these species. Specific objectives were i) to determine the growth characteristics (rings per inch and percentage of latewood); ii) to test physical properties (moisture content and specific gravity); iii) to test mechanical properties of small clear wood specimens (static bending, compression parallel and perpendicular to the grain, and Janka hardness); and iv) to compare the results from both species with the published values in earlier studies.

Materials and Methods

Materials and Sample Preparation

Material was obtained from the Northeast, Upper Midwest, Southeast, Mid-South, Appalachian, and Southeastern regions of the United States. Kiln dried, defect-free, and straight-grained hard maple and yellow poplar with dimensions of 1.11-inch (2.81 cm) by 5.4 inches (13.71 cm) by 14.9 inches (96.5 cm) (thickness, width, length) boards were donated by staircase manufacturers. Boards were kept in a controlled environment (21 °C and 80% relative humidity (RH)) for several weeks before initial testing.

Before data collection and testing, each board was labeled with the initial of the species name and a sequential number to identify and organize boards and samples. Rings per inch (RPI) and percent of latewood (LW) were collected on each end of the boards. Mill location, moisture content, and temperature were collected from 92 hard maple and 92 yellow poplar boards. Density was calculated using width, length, thickness, and weight of the boards.

The rings per inch (RPI) were calculated by counting the number of the rings and dividing by the thickness or the width, depending on the grain orientation of the piece (radial or tangential). Percentage of latewood was determined using a 1 inch × 1-inch (2.54 cm × 2.54 cm) dot grid by dividing the number of dots that fell on latewood by the total number of dots in the grid. Both measurement techniques followed Southern Pine Inspection Bureau (SPIB) standard grading rules (SPIB 2014). Board density was determined using the bulk weight and the bulk volume. Moisture content was determined using a moisture meter from Wagner, model MMC 220 (Wagner Meters, Rogue River, USA).

Specimens for specific gravity, static bending, Janka hardness, and compression (parallel and perpendicular to the grain) tests were cut in accordance with the "secondary method" explained in Section 8.1 of ASTM-D 143-14 (2014). The secondary method was selected by default because the boards were 1-inch thick. From each board, six samples were cut as follows: one specific gravity, two for static bending (one radial and one tangential), one Janka hardness, and two compression (one parallel and one perpendicular) (See Fig. 3.1).

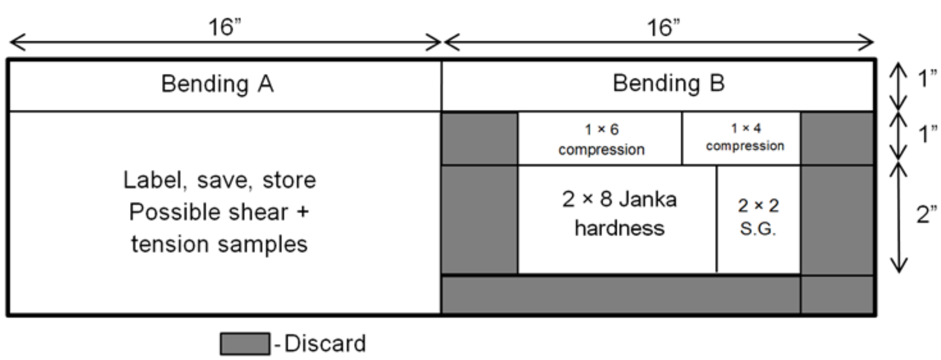

Figure 3.1 Cutting scheme of small clear wood specimens from the boards.

Testing Procedures

The specific gravity (SG), static bending, compression parallel and perpendicular to grain, and hardness tests were performed on Instron universal testing machines (Instron Model 5566, Norwood, USA) following the ASTM-D 143-14 (2014). Each specimen was weighed and measured before testing. All machines were equipped with the Bluehill 3 software (Instron, Norwood, USA) to control testing operations. The generated data were recorded directly into a Structured Query Language (SQL) database. The moisture content of the test specimens was also measured during SG procedure.

Specific gravity (SG)

The SG values were determined on 1 × 2 × 2 inches (2.54 × 5.08 × 5.08 cm) test specimens. For calculation, dimensions of each specimen were collected before and after being oven dried at 103 ± 2°C. Oven-dried weight of the specimens was recorded after the mass was stabilized (See Fig. 3.2).

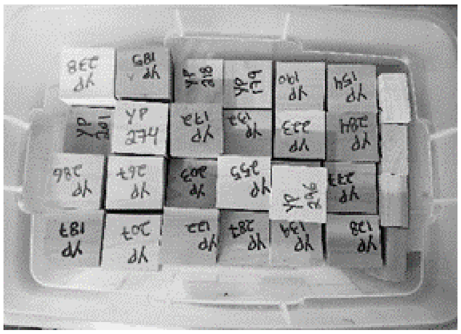

Figure 3.2 Yellow poplar oven-dried samples.

Static bending test

Static bending tests were performed on specimens of the following dimensions: 1 × 1 × 16 inch^3 (2.54 × 2.54 × 40.64 cm^3). Load was applied at the center point with a test speed of 0.05 inches (0.127 cm) per minute (See Fig. 3.3). The load span was 14 inches (35.6 cm). As indicated in the Figure 1, for this test, two samples of static bending were labeled A and B to generate a group of samples to be loaded in radial face and another group to be loaded in the tangential face (See Figure 3.4). Modulus of elasticity was calculated using Eq. 1. Modulus of rupture was calculated using Eq. 2,

$$MOE = \frac{\varDelta P \cdot L^3}{4 \cdot \varDelta f \cdot b \cdot h^3} \tag{3.1}$$

Where *MOE* is the bending modulus of elasticity (MPa); $\varDelta P$ is the loading increase (N); L is the span length (m); $\varDelta f$ is the deflection increase (m); b is the width (m); and h is the depth of the specimen (m). Equation 2 is as follows,

$$MOR = \frac{3 \cdot P \cdot L}{2 \cdot b \cdot h^2} \tag{3.2}$$

Where *MOR* is the bending modulus of rupture (MPa); P is the maximum force (N) at the mid-span; L is the span length (m); b is the width (m); and h is the depth (m).

Figure 3.3 Static bending test setup

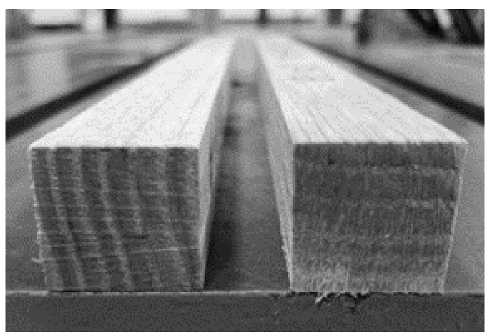

Figure 3.4 Radial and tangential bending specimens.

Compression parallel to the grain

Dimensions for test specimens of compression parallel to grain were 1 × 1 × 4 $inch^3$ (2.54 × 2.54 × 10.16 cm^3). The load was applied at a rate of 0.003 inch/inch (0.00762 cm/cm) of nominal specimen length/min. The type of deformation was recorded for each specimen. Figure 3.5a exhibits the testing setup.

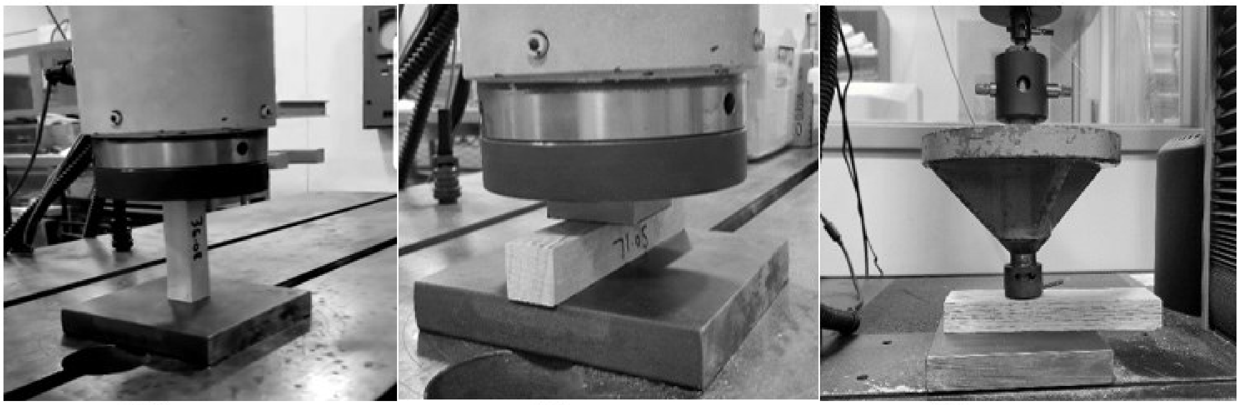

Figure 3.5 Compression parallel to the grain (a); compression perpendicular to the grain (b); and Janka ball side hardness (c).

Compression perpendicular to the grain

Dimensions for each test specimen were 1 × 1 × 6 $inch^3$ (2.54 × 2.54 × 15.24 cm^3). The load was applied through a bearing plate 2-inches (5.08 cm) wide, placed at the top of the specimen to be in contact with its radial surface. The speed rate of loading was 0.012 inches (0.305 mm) per minute. The setup for this test is shown in Figure 3.5b.

Janka side hardness

Hardness values of defect-free hard maple and yellow poplar samples were determined by embedding a steel 0.444 in (1.13 cm) diameter ball at a rate of 0.25 inch/min (0.6 cm/min). The ball penetrated their tangential and radial surfaces with a speed of 0.25 inches (6 mm) per min. The test continued until the ball penetrated to one half of the ball diameter as determined by the calibrated extensometer. The dimensions for each sample was as follows: 1 × 2 × 6 $inch^3$ (25.4 × 50.8 × 152.4 mm^3) (ASTM, 2014). The Janka test setup is shown in Figure 3.5c.

Results and Discussions

Table 3.1 exhibits a summary of the growth characteristics and physical properties of hard maple and yellow poplar specimens obtained from the conducted tests. The average moisture content of the hard maple boards varied between 8.6 and 15.3% with a mean value of 12.21% and a coefficient of variation of 14.36%. Moisture content of yellow poplar boards varied between 5.15 to 13.45% with an average value of 9.53% and a coefficient of variation of 18.89%. Rings per inch for hard maple varied between 1.07 and 65.63 with a mean of 19.39 and a coefficient of variation of 71.14%. For yellow poplar, rings per inch varied between 0.58 and 15.91 with a mean of 5.26 and a coefficient of variation of 51.88%.

Table 3.1 Moisture content (MC), rings per inch, percentage of latewood and specific gravity values, for hard maple and yellow poplar

Species	N	Properties	Mean	Min	Max	SD	CV (%)
Hard maple	90	M.C (%)	12.21	8.6	15.3	1.75	14.36
	92	Rings per inch	19.39	1.07	65.63	13.79	71.14
	92	% Latewood	49.22	12.5	73.5	21.22	43.11
	92	Board density	703	416	797	45	6.43
	91	$SG_{12\%}$	0.65	0.57	0.79	0.03	4.97
Yellow poplar	92	M.C (%)	9.53	5.15	13.45	1.80	18.89
	90	Rings per inch	5.26	0.58	15.91	2.73	51.88
	92	% Latewood	31.19	7.81	62.5	11.07	35.49
	92	Board density	508	394	659	53	10.43
	89	$SG_{12\%}$	0.46	0.36	0.60	0.05	11.14

SD: Standard deviation; CV: coefficient of variation

The average percentage of latewood of the hard maple varied between 12.5 and 73.5% with a mean value of 49.22%. Density for hard maple boards varied between 416 and 797 $kg \cdot m^{-3}$ with a mean of 703 $kg \cdot m^{-3}$ and coefficient of variation of 6.43%. The mean specific gravity of the hard maple was found to be 0.65, with a coefficient of variation of 4.97%. Minimum and maximum values were 0.57 and 0.79 respectively.

Percentage of latewood of yellow poplar varied between 7.81 and 62.5% with a mean of 31.19% and coefficient of variation 35.49%. Board density varied between 394 and 659 kg·m^{-3} with a mean of 508 kg·m^{-3} and coefficient of variation of 10.43%. The specific gravity mean was found to be 0.46, with a minimum of 0.36 and a maximum of 0.60 and a coefficient of variation of 11.14%.

MOE and MOR average values for hard maple are higher than yellow poplar values. In Table 3.2, average values as well as the range of variation and coefficient of variation obtained from testing in the radial and tangential direction are listed. Hard maple average values for MOE and MOR were 12,417 MPa and 123.6 MPa respectively.

Yellow poplar average value for MOE was 9,611 MPa while for MOR was 83.4 MPa. In general, for both species, MOE and MOR results in tangential direction are slightly higher than the ones obtained in radial direction.

Table 3.2 Static bending modulus of elasticity (MOE) and modulus of rupture (MOR) values, in radial and tangential directions, for hard maple and yellow poplar.

Species	**N**	**Static Bending (MPa)**					
		Direction	**Variable**	**Mean**	**Min**	**Max**	**CV (%)**
Hard maple	92	Radial	MOE	12,162	7,384	15,720	13.51
			MOR	128.6	78.9	167.2	12.19
	92	Tangential	MOE	12,679	7,267	15,796	11.60
			MOR	118.6	67.3	165.4	14.83
	184	Average	MOE	12,417	7,267	15,796	12.69
			MOR	123.6	67.3	167.2	14.03
Yellow poplar	92	Radial	MOE	9,349	7,074	11,514	10.96
			MOR	82.7	54.5	108.6	14.00
	91	Tangential	MOE	9,880	7,612	12,259	10.91
			MOR	83.9	49.4	108.6	14.06
	183	Average	MOE	9,611	7,067	12,259	11.26
			MOR	83.4	49.4	108.6	14.02

Compression parallel and compression perpendicular results for hard maple and yellow poplar are listed in Table 3.3. For both species, tested samples in compression parallel to the grain are higher than the ones obtained from tests perpendicular to the grain. This is due to fibers orientation. Hard maple's compression parallel values ranged from 45.2 to 83.1 MPa, with a mean value of 61.7 MPa and coefficient of variation of 10.78%. Yellow poplar's compression parallel values ranged from 30.4 to 56.3 MPa, with a mean value of 43.7 MPa and coefficient of variation of 12.17%.

For compression perpendicular, hard maple values ranged from 15.5 to 32.7 MPa, with a mean value of 21.0 MPa and coefficient of variation of 13.71%. For yellow poplar, compression perpendicular values ranged from 5.1 to 18.5 MPa, with a mean value of 9.9 MPa and coefficient of variation of 26.13%.

Table 3.3 Compression parallel and perpendicular values, for hard maple and yellow poplar.

Species	Direction	Compression (MPa)				
		N	**Mean**	**Min**	**Max**	**CV (%)**
Hard maple	Parallel	91	61.7	45.2	83.1	10.78
	Perpendicular	91	21.0	15.5	32.7	13.71
Yellow poplar	Parallel	93	43.7	30.4	56.3	12.17
	Perpendicular	93	9.9	5.1	18.5	26.13

Janka hardness results for hard maple and yellow poplar are listed in Table 3.4. For hard maple, Janka hardness values in the radial direction ranged from 4.5 to 10.5 kN, with a mean value of 6.3 kN and coefficient of variation of 14.33%. In the tangential direction, hard maple hardness values ranged from 4.8 to 10.5 kN with a mean of 7.0 and coefficient of variation of 12.53%. The average hardness for hard maple varied between 4.5 kN and 10.5 kN with a mean of 6.7 kN and coefficient of variation of 14.49%.

For yellow poplar, Janka hardness values in the radial direction ranged from 1.6 to 5.4 kN, with a mean value of 2.9 kN and coefficient of variation of 26.75%. In the tangential direction, yellow poplar values ranged from 1.8 to 6.2 kN, with a mean value of 3.2 kN and coefficient of variation of 26.58. The average hardness for yellow poplar varied between 1.6 and 6.2 with a mean of 3.1 kN and coefficient of variation of 27.16%.

Table 3.4 Janka hardness values, in radial and tangential directions, for hard maple and yellow poplar.

Species	Direction	Janka hardness (kN)				
		N	Mean	Min	Max	CV (%)
Hard maple	Radial	186	6.3	4.5	10.5	14.33
	Tangential	182	7.0	4.8	10.5	12.53
	Average	368	6.7	4.5	10.5	14.49
Yellow poplar	Radial	184	2.9	1.6	5.4	26.75
	Tangential	184	3.2	1.8	6.2	26.58
	Average	368	3.1	1.6	6.2	27.16

Comparisons with previous publications

Comparisons between mechanical property values obtained from different studies and the current study were done to identify the possible variations in the physical and mechanical properties of hard maple and yellow poplar. Some property values were absent in the literature, thus comparisons in some cases were limited to the information available. The comparisons between the present study with previous authors for rings per inch and percentage of latewood for hard maple and yellow poplar are shown in Table 3.5.

Table 3.5 Comparison of rings per inch and percentage of latewood between the present study with previous authors for hard maple and yellow poplar

Hard maple				
	Rings per inch (RPI)		% Latewood	
Literature	Mean	Range	Mean	Range
Newlin and Wilson (1917)	21	-	49	-
Markwardt *et al.* (1935)	18	-	-	-
Duchesne *et al.* (2016)	45.7	22.86 - 83.82	-	-
Yelle *et al.* (2016)	10.2	4.2 - 16.2	-	-
Present study	19.39	1.07 – 65.63	49.22	12.5 - 73.5
Yellow poplar				
Newlin and Wilson (1917)	14	-	-	-
Markwardt *et al.* (1935)	14	-	-	-
Present study	5.26	0.58 – 15.91	31.17	7.81 - 62.5

For hard maple, Newlin *et al.* (1917) found an average of 21 RPI. Markwardt *et al.* (1935) determined an average of 18 RPI. Duchesne *et al.* (2016) studied mechanical properties and discolored heartwood proportion in sugar maple from New Brunswick, Canada. The study found an average of 45.7 rings per inch with a range between 22.9 and 83.8. Yelle *et al.* (2016) found an average of 10.2 rings per inch with a range between 4.2 and 16.2. For yellow poplar, Newlin *et al.* (1917) and Markwardt *et al.* (1935) found an average of 14 RPI.

From the Table 3.5, the average rings per inch obtained in the present study are similar to the ones obtained by Newlin *et al.* (1917) and Markwardt *et al.* (1935). For yellow poplar on the other hand, results show lower average of RPI.

The comparison between the present study with other authors for specific gravity of hard maple and yellow poplar is shown in Table 3.6. The results found in this study are similar to the results found by other authors.

Table 3.6 Comparison between the present study with other authors for specific gravity for hard maple and yellow poplar

Literature	**Hard maple**		**Literature**	**Yellow poplar**	
	Mean	**Range**		**Mean**	**Range**
Newlin and Wilson (1917)	0.62	-	Newlin *et al*. (1917)	0.41	-
Markwardt *et al.* (1935)	0.68	-	Markwardt *et al*. (1935)	0.40	-
Zhang *et al.* (2006)	0.70	-	Stern (1944)	0.43	0.41 - 0.44
Kretschmann (2010)	0.63	-	Kretschmann *et al*. (2008)	0.51	0.42 - 0.64
Duchesne *et al.* (2016)	0.60	0.52 - 0.65	Kretschmann (2010)	0.42	-
Yelle *et al.* (2016)	0.67	0.64 - 0.70	Present study	0.46	0.36 - 0.60
Hindman (2017)	0.66	0.51 - 0.81	-	-	-
Fu *et al.* (2018)	0.69	0.68 - 0.71	-	-	-
Present study	0.70	0.42 - 0.80	-	-	-

(-) information not available.

For hard maple, wood samples tested by Newlin *et al.* (1917) showed an average SG of 0.62. Markwardt *et al.* (1935) found that SG for hard maple was 0.68. In a study conducted by Fu *et al.,* (2018) to determine the properties of sugar maple, they reported a specific gravity average value of 0.69 with a range between 0.68 and 0.71. Hindman (2017) described an average specific gravity of 0.66 with 0.51 as minimum and 0.81 as maximum. In a study conducted by Zhang *et al.* (2006), the authors found an average specific gravity of 0.70. Yelle *et al.* (2016) found an average specific gravity of 0.67 with a range varying from 0.64 to 0.70. Kretschmann (2010) listed an average SG of 0.63 for hard maple.

For yellow poplar, Newlin *et al.* (1917) found an average value of 0.41 for SG. Markwardt *et al.* (1935) found that SG was 0.40. Stern (1944) evaluated specific gravity of yellow poplar from Virginia. From small specimens, the author found that the average specific gravity was 0.43 varying from 0.41 to 0.44. Kretschmann *et al.* (2008) determined an average specific gravity of 0.51 with a range between 0.42 and 0.64. Kretschmann, (2010) reported an average of 0.42.

The comparison between the present study with previous authors for bending MOE and MOR for hard maple and yellow poplar are shown in Table 3.7. Even though MOE for yellow poplar was found to be slightly lower in general, the MOE average value found in this study for hard maple and yellow poplar are similar to the results found by other authors.

For hard maple, the MOR average value was found to be slightly higher when compared to the other authors' results. For yellow poplar, MOR was found to be similar to the results obtained by Newlin *et al.* (1917) and higher to the results obtained by the other listed authors.

Table 3.7 Comparison between the present study with previous authors for bending MOE and MOR for hard maple and yellow poplar

Literature	Hard maple			
	MOE (MPa)	**Range**	**MOR (MPa)**	**Range**
Newlin *et al.* (1917)	12,548	-	108.9	-
Markwardt *et al.* (1935)	12,617	-	108.9	-
Zhang *et al.* (2006)	12,600	10,500 - 14,700	-	-
Kretschmann (2010)	12,617	-	108.9	-
Duchesne *et al.* (2016)	10,684	5,434 - 15,008	113.2	65.4 - 144.6
Present study	12,417	7,267 - 15,796	123.6	67 - 167.2
	Yellow Poplar			
Newlin *et al.* (1917)	11,100		81.35	-
Markwardt *et al.* (1935)	10,342		63.43	-
Faust *et al.* (1990)	11,032	11,030 - 11,033	41.56	33.7 - 49.4
Stern (1944)	10,928	11,611 – 12,480	-	-
Kretschmann (2010)	10,893		69.63	-
Carmona (2019)	9,611	7,067 - 12,259	83.4	49.4 - 108.6

(-) information not available.

Newlin *et al.* (1917) describing hard maple properties reported the MOE average value was 12,548 MPa while MOR was 108.9 MPa. Markwardt *et al.* (1935) determined the MOE and MOR for hard maple were found to be 12,617 MPa and 108.9 MPa respectively. Duchesne *et al.* (2016) found the mechanical properties of small clear wood of sugar maple varying from 5,434 to 15,008 MPa for MOE with an average of 10,684 MPa and an average of 113.2 for MOR with a range between 65.4 and 144.6 MPa. Zhang *et al.* (2006) reported an average MOE of 12,600 MPa varying from 10,500 to 14,700 MPa. Kretschmann (2010) listed the average values for hard maple were 12,617 MPa for MOE and 108.9 MPa for MOR.

Yellow poplar static bending values described by Newlin *et al.* (1917) were 11,100 MPa for MOE and 81.35 MPa for MOR. Markwardt *et al.* (1935) determined for yellow poplar MOE and MOR average values of 10,342 MPa and 63.43 MPa respectively. Faust *et al.* (1990) studied the strength and stiffness properties of yellow-poplar structural lumber. In the study, the authors found that MOE average was 11,032 MPa. For MOR the authors reported an average value of

41.56 MPa varying from 33.7 to 49.4. Stern (1944) found an average MOE of 10,928 MPa with a range between 11,611 and 12,480 MPa. Kretschmann (2010) listed the average of 10,893 MPa and 69.63 MPa for MOE and MOR respectively.

The comparison between the present study with other authors for compression parallel and perpendicular for hard maple and yellow poplar are shown in Table 3.8. The results found in the present study are similar to results published in previous studies.

Table 3.8 Comparison between the present study with other authors for compression parallel and perpendicular to the grain for hard maple and yellow poplar

Hard maple			**Yellow poplar**		
Literature	**Compression**		**Literature**	**Compression**	
	Parallel (MPa)	**Perpendicular (MPa)**		**Parallel (MPa)**	**Perpendicular (MPa)**
Newlin *et al*. (1917)	59	11.16	Newlin *et al.* (1917)	51.6	5.1
Markwardt *et al*. (1935)	54	12.47	Markwardt *et al*. (1935)	36.5	3.9
Fortin-Smith *et al*. (2018)	77.4	14.5	Faust *et al.* (1990)	40.2	-
Kretschmann (2010)	54	10.13	Stern (1944)	43.6	8.6
Present study	62	21	Kretschmann *et al.* (2008)	42.1	5.7
			Kretschmann (2010)	38.2	3.4
			Present study	43.7	9.9

(-) information not available.

Newlin *et al*. (1917) studying hard maple compression properties found an average value of 59 MPa and 11.16 MPa for compression parallel and perpendicular respectively. Markwardt *et al.* (1935) reported for hard maple an average value of 54 MPa for compression parallel to grain and 12.47 MPa for compression perpendicular to grain. Fortin-Smith *et al.* (2018) found an average of 77.4 MPa and 14.5 MPa respectively. MPa. Kretschmann (2010) listed the average for compression parallel to the grain was 54 MPa and 10.13 MPa for compression perpendicular to the grain.

For yellow poplar, Newlin *et al.* (1917) found 51.6 MPa for compression parallel to the grain and 5.1 MPa for compression perpendicular to the grain. Markwardt *et al.* (1935) reported an average value of 36.5 MPa and 3.9 MPa respectively. Kretschmann (2010) reported the average value for compression parallel to the grain was 38.2 MPa and 3.4 MPa for compression perpendicular to the grain. Stern (1944) found an average compression parallel of 43.6 MPa and 8.6 MPa for compression perpendicular to the grain. Faust *et al.* (1990) reported an average value of 40.2 for compression parallel to grain.

Overall, hard maple compression values in both directions are higher than the values reported for yellow poplar. It is also noticeable that values of compression parallel to the grain is higher than the ones obtained in the other direction for both species. From the literature review, for hard maple it was found that compression parallel to the grain results are similar to the values obtained in the present study. However, results in compression perpendicular to the grain were found higher than other authors' values.

For yellow poplar, compression parallel to the grain was found to be within the range of the other authors' listed values. The current results are very similar to the ones obtained by Stern (1944) Kretschmann *et al.* (2008) and Faust *et al.* (1990). For compression perpendicular to the grain, the results are similar to the ones published by Stern (1944) and higher than the other authors' results.

The comparison between the present study with other authors for Janka hardness for hard maple and yellow poplar are shown in Table 3.9. The results found in the present study are according to the ones found in the literature. For hard maple, Newlin *et al.* (1917) reported an average Janka hardness of 6.3 kN. Markwardt *et al.* (1935) found an average value of 6.4 kN. Kretschmann reported similar values as the two previous authors.

Table 3.9 Comparison between the present study with other authors for Janka hardness for hard maple and yellow poplar

Hard maple			Yellow poplar		
Literature	**Mean (kN)**	**Range**	**Literature**	**Mean (kN)**	**Range**
Newlin *et al.* (1917)	6.3	-	Newlin *et al.* (1917)	2.00	-
Markwardt *et al.* (1935)	6.4	-	Markwardt *et al.* (1935)	2.00	-
Kretschmann (2010)	6.4	-	Stern (1944)	4.08	
Present study	6.7	4.5 - 10.5	Green *et al.* (2006)	2.44	1.36 - 4.55
			Kretschmann (2010)	2.40	-
			Ulker *et al.* (2018)	5.7	5.1 - 6.3
			Present study	3.1	1.6 - 6.2

(-) information not available.

Newlin *et al.* (1917) studying yellow poplar Janka hardness, found an average value of 2.0 kN. Markwardt *et al.* (1935) reported the same value. Ulker *et al.* (2018) evaluated the properties of thermally treated yellow poplar. In the study, the authors reported an average hardness value of 5.7 kN with a range between 5.1 and 6.3 kN. Green *et al.* (2006) determined the Janka hardness using nonstandard specimens. The authors found an average hardness of 2.44 kN with a range between 1.36 to 4.55 kN. Kretschmann, (2010) reported an average of 2.40 kN for yellow poplar. Stern (1944) found an average side hardness of 4.08 kN.

Conclusions

Through this research, it was possible to obtain more information on the characteristics of mechanical properties of hard maple and yellow poplar lumber by comparing the current results with past publications. It is economically important for the hardwood industry to confirm the accuracy and reliability of mechanical properties values to develop design values that are up to date with the building codes and regulations. The results of this study show that:

1. The mechanical properties for hard maple and yellow poplar have not changed substantially because the average values remain in a range that is very close to the ones published previously.
2. The values found in the *Wood Handbook* can still be used for engineering purposes.
3. The number of RPI decreased for yellow poplar when compared with past studies.
4. RPI for hard maple remained similar to previous publications.
5. Percentage of latewood for hard maple was found to be very similar to the value reported in the literature review.
6. MOE and MOR values for hard maple and yellow poplar were found to be similar to the ones of previous studies.
7. For hard maple, compression parallel to the grain values found in the literature review were similar to the values obtained in the present study.
8. For hard maple, results from the present study for compression perpendicular to the grain were found to be slightly higher when compared with other authors' results.
9. For yellow poplar, compression strength values were found to be similar to the ones used for comparison.
10. Specific gravity and hardness values were found to be similar to the ones found by the listed authors.

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