Physical and Mechanical Properties of Hard Maple (*Acer saccharum*) and Yellow Poplar (*Liriodendron tulipifera*)

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Abstract

Maple and poplar are common names of species that grow in the eastern United States. Physical and mechanical properties were evaluated from small clear wood specimens of hard maple (*Acer saccharum*) and yellow poplar (*Liriodendron tulipifera*). Specific gravity, static bending strength and modulus of elasticity, compression parallel and perpendicular to grain, and Janka hardness were tested. The experiments were carried out on defect-free specimens extracted from boards supplied by members of the Staircase Manufacturers Association. The material was donated by companies located in the eastern United States. On the basis of the findings, it can be stated that mechanical properties for maple and yellow poplar have not changed substantially because the average values remain in a range that is very close to the values published in previous studies.

Hardwood 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, stairs and 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 in combining structural performance with aesthetic design.

Hard maple (in some cases also called sugar maple [*Acer saccharum*]) is a wide-ranging species that grows in the eastern United States (mainly the mid-Atlantic region) and the Great Lakes states of the upper Midwest. 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 (Wiemann 2010). Some uses include flooring, furniture, paneling, cabinets, millwork, stairs, handrails, doors, woodenware, and sporting goods (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 has parts that are 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, hardwoods have been identified as some of the species with the greatest economic impact due to their historically excellent performance. However, unlike other materials, the hardwoods used for kiln-dried appearance grade in stairs lack information on tests that confirm the design values necessary for the creation of products that meet the standards (Cooper 2014). Initial information about the mechanical properties of hardwoods comes from studies conducted nearly 100 years ago (Newlin and Wilson 1917, Markwardt and Wilson 1935). The most recent and accepted values for these properties are the ones published in the *Wood Handbook* (Kretschmann 2010). However, some of these data were generated in the early 1900s. For this reason, performing mechanical tests to verify

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Forest Prod. J. 70(3):326–334.
doi:10.13073/FPJ-D-20-00005

the properties of these species is important in maintaining current information that fulfills regulations and building codes.

The 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 test procedures are modulus of elasticity (MOE), modulus of rupture (MOR), maximum stress in compression parallel to grain, compression perpendicular to grain, shear strength parallel to grain, tension parallel to grain, hardness, and specific gravity (SG; Kretschmann 2010).

MOE and MOR are important properties used to determine the use of wood. MOE helps to describe stiffness and is a good overall indicator of wood strength (França et al. 2018). MOR, on the other hand, is a measure that indicates the bending strength of a board or structural member. MOR represents the maximum load that a wooden specimen can withstand in bending before rupture (Kretschmann 2010).

Mechanical testing is important when trying to understand the behavior of wood. Previous studies, such as those by Newlin and Wilson (1917), Markwardt and Wilson (1935), and Kretschmann (2010), have characterized physical properties, such as growth ring count (GRC), moisture content (MC), percentage of latewood (LW), SG, and the strength properties, such as MOE, bending strength (MOR), compression, and hardness, of hard maple and yellow poplar.

Variation in the values is associated with factors such as the modernization of the technology used to perform the tests, the temperature conditions or MC at the time of the test, the methods of data collection, the characteristics of some forests that change over time, and even the variability from each tree and 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 it invests large amounts of money carrying out continuous tests that later help to obtain the most accurate and reliable design values (Southern Forest Products Association 2013). As part of the contribution to maintaining the validity and reliability of these values, the Staircase Manufacturers Association, in conjunction with US Department of Agriculture Forest Service, Forest Products Laboratory, has funded tests to evaluate the mechanical properties of the most important species for the staircase industry.

Despite what is known about the physical and mechanical properties of these species, there is still uncertainty associated with the average values of the properties of hard maple and yellow poplar, and ongoing resource monitoring is needed to evaluate changes in these properties over time. This study will provide useful information to staircase manufacturers, allowing them to perform future calculations or adjustments to published strength values. This study will also provide information on the quality of the raw material and possibilities for its end use.

In this sense, 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 to determine the growth characteristics (GRC and LW), and test the physical properties (MC and SG) and mechanical properties of small clear wood specimens (static bending, compression parallel and perpendicular to grain, and Janka hardness) and then to compare the results from both species with the published values in earlier studies.

Materials and Methods

Sample preparation

The material was obtained from the Northeast, upper Midwest, Southeast, mid-South, Appalachian, and Southeast United States. No species verification was performed because the objective of this study was to evaluate the material commercially utilized by the US wood industry. Kiln-dried, defect-free, straight-grained hard maple and yellow poplar boards with dimensions of 2.54 by 5 by 38 cm were donated by staircase manufacturers. Boards were kept in a controlled environment (21°C at 65 percent relative humidity) for several weeks before initial testing.

Prior to 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. GRC and percentage of LW were collected from each end of the boards. Manufacturer location, MC, and temperature were collected from 92 hard maple and 92 yellow poplar boards.

Specimens for SG ($SG_{12\%}$), static bending, Janka hardness, and compression (parallel and perpendicular to grain) tests were cut in accordance with the ''secondary method'' explained in Section 8.1 of ASTM D 143 (ASTM International 2014). The secondary method was selected by default because the boards were 2.54 cm thick. From each board, six samples were cut as follows: one SG, two for static bending (one radial and one tangential), one Janka hardness, and two compression (one parallel and one perpendicular; Fig. 1).

Each specimen was weighed and measured before testing. All machines were equipped with Bluehill 3 software (Instron, Norwood, Massachusetts) to control testing operations. The generated data were recorded directly into a Structured Query Language database. The MC of the test specimens was also measured during the SG procedure.

Growth characteristics

GRC was 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 LW was determined using a 2.54 by 2.54-cm dot grid by dividing the number of dots that fell on LW by the total number of dots in the grid. Both measurement techniques followed the standard grading rules of the Southern Pine Inspection Bureau (2014). Even though both species are diffuse porous, it was possible to delineate the transition from earlywood to LW. This boundary was made on the basis of the difference in colors. The earlywood region is where the vessels maintain their greatest water transport function during the first growth season, resulting in a lighter color compared to the LW region (Bond and Hamner 2002; see Fig. 2).

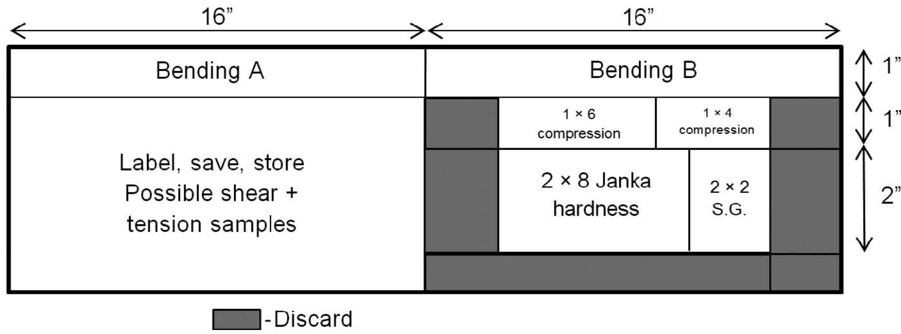


Figure 1.—Cutting scheme of small clear wood specimens from the boards. SG = specific gravity.

Board density, SG, and MC

Board density was determined using bulk weight and bulk volume. $SG_{12\%}$ followed the specifications of ASTM D 2395 (ASTM International 2017). MC was determined using a Model MMC 220 moisture meter (Wagner Meters, Rogue River, Oregon).

$SG_{12\%}$ values were determined on 2.54 by 5.08 by 5.08-cm test specimens. For calculation, dimensions of each specimen were collected before and after being oven-dried at 103°C ± 2°C. Ovendried weight of the specimens was recorded after the mass was stabilized (see Fig. 3).

Static bending test

The static bending, compression parallel and perpendicular to grain, and hardness tests were performed on a Model 5566 universal testing machine (Instron) following ASTM D 143 (ASTM International 2014).

Static bending tests were performed on specimens with dimensions of 2.54 by 2.54 by 40.64 cm^3. Load was applied at the center point with a test speed of 0.127 cm/min (Fig. 4a). The load span was 35.6 cm. As indicated in 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 the radial face and another group to be loaded in the tangential face (Fig. 4b). MOE was calculated as

$$\text{MOE} = \frac{\Delta \cdot P \cdot L^3}{4 \cdot \Delta \cdot f \cdot b \cdot h^3} \quad (1)$$

where MOE is the bending MOE (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). MOR was calculated as

$$\text{MOR} = \frac{3 \cdot P \cdot L}{2 \cdot b \cdot h^2} \quad (2)$$

where MOR is the bending MOR (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).

Compression parallel to grain

Specimen dimensions for the compression parallel to grain test were 2.54 by 2.54 by 10.16 cm^3. The load was

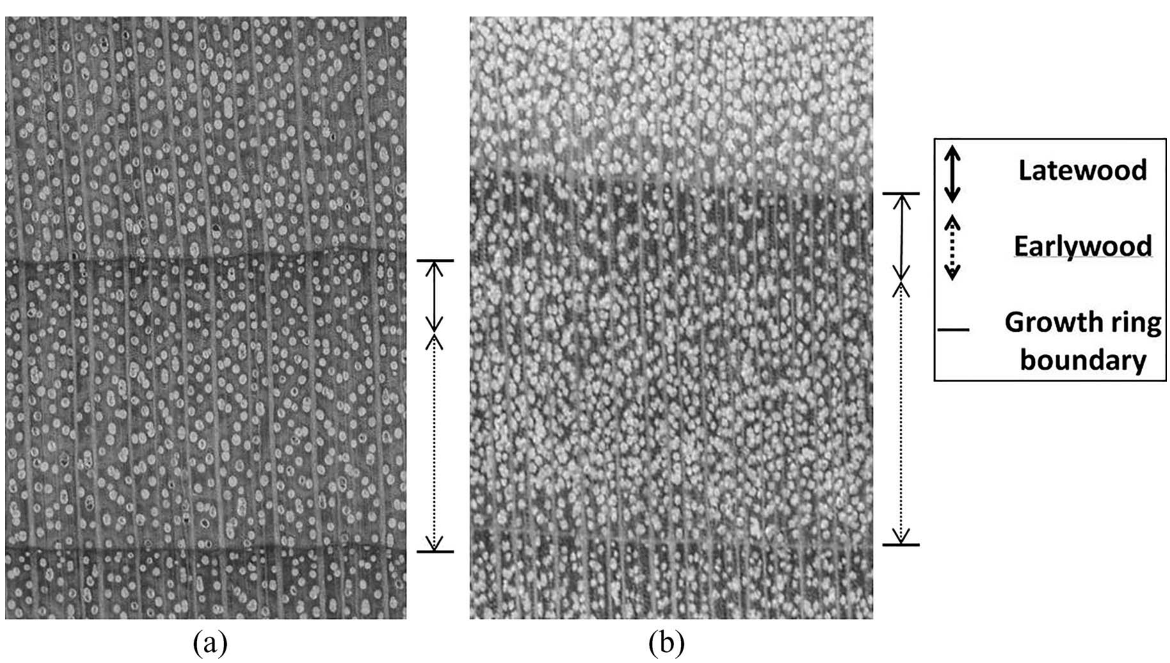


Figure 2.—Transition from earlywood/latewood in (a) hard maple and (b) yellow poplar. Source: The Wood Database (2019a, 2019b).

Figure 3.—Yellow poplar ovendried samples.

applied at a rate of 0.00762 cm/cm of nominal specimen length per minute. The type of deformation was recorded for each specimen. Figure 5a shows the testing setup.

Compression perpendicular to grain

Dimensions for each test specimen were 2.54 by 2.54 by 15.24 cm^3. The load was applied through a bearing plate 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 0.305 mm/min. The setup for this test is shown in Figure 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 steel ball at a rate of 0.6 cm/min. The ball penetrated the tangential and radial surfaces with a speed of 6 mm/min. The test continued until the ball penetrated to one-half of the ball's diameter as determined by the calibrated extensometer. The dimensions for each sample were 25.4 by 50.8 by 152.4 mm^3 (ASTM International 2014). The Janka test setup is shown in Figure 5c.

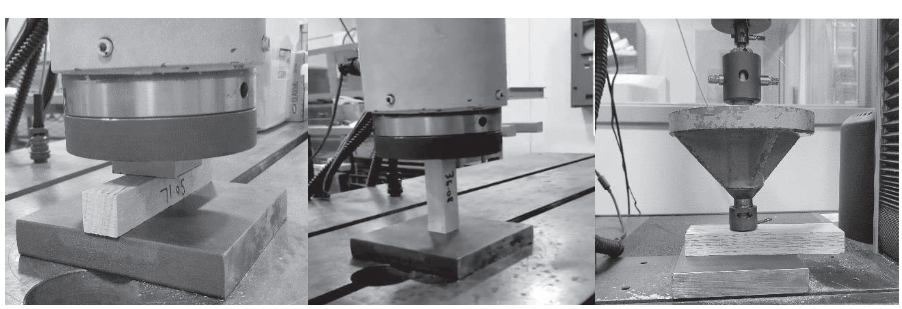
Results and Discussion

Table 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 MC of hard maple boards ranged from 8.6 to 15.3 percent with a mean of 12.21 percent and a coefficient of variation of 14.36 percent, whereas the MC yellow poplar boards ranged from 5.2 to 13.5 percent with an average value of 9.53 percent and a coefficient of variation of 23.46 percent. GRC for hard maple ranged from 1.07 to 65.63 with a mean of 19.39 and a coefficient of variation of 71.14 percent. For yellow poplar, GRC ranged from 0.58 to 15.91 with a mean of 5.26 and a coefficient of variation of 51.88 percent.

The average percentage of LW of hard maple ranged from 12.5 to 73.5 percent with a mean of 49.22 percent. Density for hard maple boards ranged from 416 to 797 kg/m^3 with a mean of 703 kg/m^3 and a coefficient of variation

(a) (b)

Figure 4.—Bending test: (a) test setup and (b) radial and tangential bending specimens.



(a) (b) (c)

Figure 5.—Minor properties test: (a) compression perpendicular to grain, (b) compression parallel to grain, and (c) Janka ball side hardness.

Table 1.—Moisture content (MC), growth ring count (GRC), percentage of latewood (LW), and specific gravity (SG) values for hard maple and yellow poplar.

Species	*N*	Properties	Mean	Min	Max	SD	CV[a] (%)
Hard maple	90	MC (%)	12.21	8.6	15.3	1.75	14.36
	92	GRC	19.39	1.07	65.63	13.79	71.14
	92	LW (%)	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	MC (%)	9.53	5.2	13.5	1.80	18.89
	90	GRC	5.26	0.58	15.91	2.73	51.88
	92	LW	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

[a] CV = coefficient of variation.

of 6.43 percent. The mean SG of hard maple was found to be 0.65 with a coefficient of variation of 4.97 percent. Minimum and maximum values were 0.57 and 0.79, respectively.

Percentage of LW of yellow poplar ranged from 7.81 to 62.5 percent with a mean of 31.19 percent and a coefficient of variation of 35.49 percent. Board density ranged from 394 to 659 kg/m^3 with a mean of 508 kg/m^3 and a coefficient of variation of 10.43 percent. The SG 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 percent.

MOE and MOR average values for hard maple are higher than those for yellow poplar. In Table 2, average values as well as the range of variation and coefficient of variation obtained from testing in the radial and tangential directions are listed. Hard maple average values for MOE and MOR were 12,417 and 123.6 MPa, respectively. Yellow poplar average values for MOE and MOR were 9,611 and 83.4 MPa, respectively. In general, for both species, MOE and MOR results in the tangential direction are slightly higher than the ones obtained in the radial direction.

Compression parallel and perpendicular to grain results for hard maple and yellow poplar are listed in Table 3. For both species, tested samples in compression parallel to grain are higher than the ones obtained from tests perpendicular to grain. Hard maple's compression parallel to grain values ranged from 45.2 to 83.1 MPa with a mean of 61.7 MPa and a coefficient of variation of 10.78 percent. Yellow poplar's compression parallel to grain values ranged from 30.4 to 56.3 MPa with a mean of 43.7 MPa and a coefficient of variation of 12.17 percent.

For compression perpendicular to grain, hard maple values ranged from 15.5 to 32.7 MPa with a mean of 21.0 MPa and a coefficient of variation of 13.71 percent. For

Table 2.—Static bending modulus of elasticity (MOE) and modulus of rupture (MOR) values in radial and tangential directions for hard maple and yellow poplar.

		Static bending (MPa)					
Species	*N*	Direction	Variable	Mean	Min	Max	CV[a] (%)
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

[a] CV = coefficient of variation.

Table 3.—Compression parallel and perpendicular to grain values for hard maple and yellow poplar.

		Compression (MPa)				
Species	Direction	*N*	Mean	Min	Max	CV[a] (%)
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

[a] CV = coefficient of variation.

Table 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[a] (%)
Hard maple	Radial	184	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

[a] CV = coefficient of variation.

yellow poplar, compression perpendicular values ranged from 5.1 to 18.5 MPa with a mean of 9.9 MPa and a coefficient of variation of 26.13 percent.

Janka hardness results for hard maple and yellow poplar are listed in Table 4. For hard maple, Janka hardness values in the radial direction ranged from 4.5 to 10.5 kN with a mean of 6.3 kN and a coefficient of variation of 14.33 percent. In the tangential direction, hard maple hardness values ranged from 4.8 to 10.5 kN with a mean of 7.0 and a coefficient of variation of 12.53 percent. The average hardness for hard maple ranged from 4.5 to 10.5 kN with a mean of 6.7 kN and a coefficient of variation of 14.49 percent.

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

Comparisons with previous studies

Table 5 shows a summary of sample sizes and methods used in previous studies. Comparisons of the properties' values obtained from different studies and the current study were done to identify possible variations in the physical and mechanical properties of hard maple and yellow poplar. Some of these values were absent in the literature; thus, comparisons in some cases were limited to the information available. A comparison of the present study with previous studies for GRC and LW for hard maple and yellow poplar is shown in Table 6.

A study was conducted by Newlin and Wilson (1917) to determine the physical and mechanical properties of wood species grown in the United States. This study observed an average of 21 GRC for hard maple and 14 GRC for yellow poplar. Markwardt and Wilson (1935) found an average of 18 GRC. Duchesne et al. (2016) studied mechanical properties and discolored heartwood proportions in hard maple from New Brunswick, Canada. The study found an average of 45.7 GRC with a range of 22.9 to 83.8. Yelle and

Table 5.—Summary information of literature cited for specific gravity and mechanical properties: sample size, moisture content (MC), and method used.

Literature	Specific gravity			Mechanical properties		
	N	MC (%)	Method	*N*	MC (%)	Standard
Hard maple						
Newlin and Wilson (1917)	22[a]	Green[b]	Clear samples	22[a]	Green[b]	Clear samples
Markwardt and Wilson (1935)	22[a]	Green[b]	Clear samples	5[a]	Green[b]	ASTM D 143
Zhang et al. (2006)	—	8	Unknown	—	—	—
Kretschmann (2010)	—	12	Unknown	—	12	ASTM D 143
Duchesne et al. (2016)	122[a]	12	ASTM D 143			
Yelle and Stirgus (2016)	30	12	ASTM D 143	30	12	ASTM D 143
Duchesne et al. (2016)	—	—	—	92	12	ASTM D 143
Hindman (2017)	—	—	—	90	12	Schmidt and MacKay (1997)
Fu et al. (2018)	8	12	X-ray	—	—	—
Fortin-Smith et al. (2018)	—	—	—	54		ASTM D 6110-10
Yellow poplar						
Newlin and Wilson (1917)	22[a]	Green[b]	Clear samples	22[a]	Green[b]	Clear samples
Markwardt and Wilson (1935)	22[a]	Green[b]	Clear samples	11[a]	Green[b]	ASTM D 143
Faust et al. (1990)	—	—	—	240	12	ASTM D 143
Stern (1944)	—	—	—	480	9	ASTM D 143
Green et al. (2006)	—	—	—	10	12	ASTM D 143
Kretschmann and Green (2008)	—	—	—	160	12	ASTM D 143
Kretschmann (2010)	—	12	Unknown	—	12	ASTM D 143
Ulker et al. (2018)	—	—	—	80	12	Ulker and Hiziroglu (2017)

[a] Number of trees tested.
[b] Above fiber saturation point.

Table 6.—Comparison of the present study with previous studies for growth ring count (GRC) and percentage of latewood (LW) for hard maple and yellow poplar.

Literature	GRC, mean (range)	%LW, mean (range)
Hard maple		
Newlin and Wilson (1917)	21 (—)	49 (—)
Markwardt and Wilson (1935)	18 (—)	—
Duchesne et al. (2016)	45.7 (22.86–83.82)	—
Yelle and Stirgus (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 and Wilson (1935)	14 (—)	—
Present study	5.26 (0.58–15.91)	31.17 (7.81–62.5)

Stirgus (2016) found an average of 10.2 GRC with a range of 4.2 to 16.2.

From Table 6, it can be seen that the average GRC obtained in the present study is similar to that obtained by Newlin and Wilson (1917) and Markwardt and Wilson (1935). For yellow poplar, on the other hand, results show lower average GRC.

A comparison of the present study and other studies for SG of hard maple and yellow poplar is shown in Table 7. The results of this study are similar to those of other studies.

For hard maple, wood samples tested by Newlin and Wilson (1917) showed an average SG of 0.62. Markwardt and Wilson (1935) found that SG for hard maple was 0.68. A study conducted by Fu et al. (2018) to determine the properties of hard maple reported an average SG value of 0.69 with a range of 0.68 to 0.71. Hindman (2017) described an average SG of 0.66 with 0.51 as a minimum and 0.81 as a maximum. In a study conducted by Zhang et al. (2006), the authors found an average SG of 0.70. Yelle and Stirgus (2016) found an average SG 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 and Wilson (1917) found an average value of 0.41 for SG, and Markwardt and Wilson (1935) found a value of 0.40. Stern (1944) evaluated the SG of yellow poplar from Virginia. For small specimens, the author found that the average SG was 0.43, varying from 0.41 to 0.44. Kretschmann and Green (2008) determined an average SG of 0.51 with a range of 0.42 to 0.64. Kretschmann (2010) reported an average of 0.42.

A comparison of the present study with previous studies for bending MOE and MOR for hard maple and yellow poplar is shown in Table 8. Even though MOE for yellow poplar was found to be slightly lower in general, the average MOE values found in this study for hard maple and yellow poplar are similar to the results found by other studies.

For hard maple, the average MOR value was found to be slightly higher when compared with other studies. For yellow poplar, MOR was found to be similar to the results obtained by Newlin and Wilson (1917) and higher than the results obtained by the other studies.

For hard maple, Newlin and Wilson (1917) reported average MOE and MOR values of 12,548 and 108.9 MPa, respectively. Markwardt and Wilson (1935) found MOE and MOR values for hard maple of 12,617 and 108.9 MPa, respectively. Duchesne et al. (2016) found the mechanical

Table 7.—Comparison of the present study with other studies for specific gravity for hard maple and yellow poplar.

Literature	Mean (range)
Hard maple	
Newlin and Wilson (1917)	0.62 (—)
Markwardt and Wilson (1935)	0.68 (—)
Zhang et al. (2006)	0.70 (—)
Kretschmann (2010)	0.63 (—)
Duchesne et al. (2016)	0.60 (0.52–0.65)
Yelle and Stirgus (2016)	0.67 (0.64–0.70)
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)
Yellow poplar	
Newlin and Wilson (1917)	0.41
Markwardt and Wilson (1935)	0.40
Stern (1944)	0.43 (0.41–0.44)
Kretschmann and Green (2008)	0.51 (0.42–0.64)
Kretschmann (2010)	0.42 (—)
Present study	0.46 (0.36–0.60)

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 of 65.4 to 144.6 MPa. Zhang et al. (2006) reported an average MOE of 12,600 MPa with a range of 10,500 to 14,700 MPa. Kretschmann (2010) listed the average values for hard maple as 12,617 MPa for MOE and 108.9 MPa for MOR.

Yellow poplar static bending values described by Newlin and Wilson (1917) were 11,100 MPa for MOE and 81.35 MPa for MOR. Markwardt and Wilson (1935) determined average MOE and MOR values for yellow poplar of 10,342 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 an average MOE value of 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 of 11,611 to 12,480 MPa. Kretschmann (2010) listed average MOE and MOR values of 10,893 and 69.63 MPa, respectively.

A comparison of the present study with other studies for compression parallel and perpendicular to grain for hard maple and yellow poplar is shown in Table 9. The results of the present study are in accordance with previous studies.

Newlin and Wilson (1917), studying hard maple compression properties, found average values of 59 and 11.16 MPa for compression parallel and perpendicular to grain, respectively. Markwardt and Wilson (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 and 14.5 MPa, respectively. Kretschmann (2010) listed the average for compression parallel to grain as 54 and 10.13 MPa for compression parallel and perpendicular to grain, respectively.

For yellow poplar, Newlin and Wilson (1917) found values of 51.6 MPa for compression parallel to grain and 5.1 MPa for compression perpendicular to grain. Markwardt and Wilson (1935) reported average values of 36.5 and 3.9 MPa, respectively. Kretschmann (2010) reported average values of 38.2 and 3.4 MPa for compression parallel to grain

Table 8.—Comparison of the present study with previous studies for bending modulus of elasticity (MOE) and modulus of rupture (MOR) for hard maple and yellow poplar.

Literature	MOE (MPa)	Range	MOR (MPa)	Range
Hard maple				
Newlin and Wilson (1917)	12,548	—	108.9	—
Markwardt and Wilson (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 and Wilson (1917)	11,100		81.35	—
Markwardt and Wilson (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	—
Present study	9,611	7,067–12,259	83.4	49.4–108.6

and compression perpendicular to grain, respectively. Stern (1944) found average values of 43.6 and 8.6 MPa for compression perpendicular to the grain and compression parallel to grain, respectively. 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 those reported for yellow poplar. It is also noticeable that values of compression parallel to grain are higher than those obtained in the other direction for both species. From the literature review, for hard maple, values for compression parallel to grain are similar those obtained in the present study. However, values for compression perpendicular to grain were found to be higher than those of other studies.

For yellow poplar, compression parallel to grain was found to be within the range of values listed in the other studies. The current results are very similar to those obtained by Stern (1944), Faust et al. (1990), and Kretschmann and Green (2008). For compression perpendicular to grain, the results are similar to those of Stern (1944) and higher than those of the other studies. These findings show that over time, there was no significant change for compression parallel to grain for both species tested.

Table 9.—Comparison of the present study with other studies for compression parallel and perpendicular to grain for hard maple and yellow poplar.

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

A comparison of the present study with other studies for Janka hardness for hard maple and yellow poplar is shown in Table 10. The results found in the present study are similar to those found in the other studies. For hard maple, Newlin and Wilson (1917) reported an average Janka hardness of 6.3 kN. Markwardt and Wilson (1935) found an average value of 6.4 kN. Kretschmann reported values similar to those of the two previous studies.

Newlin and Wilson (1917), studying yellow poplar Janka hardness, found an average value of 2.0 kN. The same value was reported by Markwardt and Wilson (1935). Ulker et al. (2018) evaluated the properties of thermally treated yellow poplar. The authors reported an average hardness value of 5.7 kN with a range of 5.1 to 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 of 1.36 to 4.55 kN. Kretschmann (2010) reported an average hardness 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 updated information on the characteristics of the mechanical properties of hard maple and yellow poplar lumber and to compare the findings of the current study with those of past

Table 10.—Comparison of the present study with other studies for Janka hardness for hard maple and yellow poplar.

Literature	Mean (range), kN
Hard maple	
Newlin and Wilson (1917)	6.3 (—)
Markwardt and Wilson (1935)	6.4 (—)
Kretschmann (2010)	6.4 (—)
Present study	6.7 (4.5–10.5)
Yellow poplar	
Newlin and Wilson (1917)	2.00 (—)
Markwardt and Wilson (1935)	2.00 (—)
Stern (1944)	4.08
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)

studies. It is economically important for the hardwood industry to confirm the accuracy and reliability of mechanical property values to develop design values that are up to date with building codes and regulations.

The staircase industry will be able to use this information to calculate the strength of wood members and establish safe working stresses of the studied species. These findings reinforce the need for ongoing sampling of raw material to assess possible resource changes over time. More specifically, the results of this study show the following:

- The mechanical properties of hard maple and yellow poplar have not changed substantially because the average values remain in a range that is very close to those of previous studies.
- GRC decreased for yellow poplar when compared with past studies. GRC for hard maple remained similar to that of previous studies.
- The percentage of LW for hard maple was found to be very similar to that reported in the literature review.
- The values found in the literature can still be used for engineering purposes.
- MOE and MOR values for hard maple and yellow poplar were found to be similar to those of previous studies.
- For hard maple, compression parallel to grain values found in the literature review showed similar values when compared with the present study. However, the values for compression perpendicular to grain were found to be slightly higher.
- For yellow poplar, compression strength values are similar to those used for comparison.
- SG and hardness values are similar to those found in previous studies.

Acknowledgments

This research was funded by a grant from the USDA Forest Service. This publication is a contribution and is approved as journal article SB 982 of the Forest and Wildlife Research Center, Mississippi State University. The authors are also thankful for the technical assistance provided by Franklin Quin and Edward Entsminger to carry out the above work.

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