Physical and Mechanical Properties of Hardwoods Cross-Laminated Timber

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Abstract

Cross-laminated timber (CLT), a type of engineered wood product, is becoming widespread in the construction sector, especially for large commercial buildings. The increased demand for CLT is due its perceived benefits over conventional building materials. To effectively utilize the numerous benefits of this modern building material, there is need to ascertain its reliability as a structural material without affecting its serviceability. Thus, the objectives of this study were to evaluate both the physical and mechanical properties of CLT and to compare the mechanical properties of CLT manufactured with hardwood of low-grade lumber and industrially made softwood CLT. Hardwood species used to manufacture CLT panels were red oak (*Quercus* spp.), yellow poplar (*Liriodendron* spp.), and sweetgum (*Liquidambar* spp.). Commercially manufactured southern pine CLT panels were used as control. The evaluation of density was done at a moisture content of 12 percent. All specimens were mechanically tested in accordance with ASTM D198 to determine the modulus of elasticity (MOE) and modulus of rupture (MOR). The range of values for both MOE and MOR found in this study are not significantly different from values reported in a previous study. Of the hardwood samples tested, 95 percent had MOE greater than minimum allowable MOE of 1.2×10^6 psi (8,274 MPa) specified for softwood CLT by the American National Standards Institute/The Engineered Wood Association performance-rated CLT. Thus, the average MOE values observed for all the CLT species can be used as a basis for design values in the construction industry for hardwood species.

Cross-laminated timber (CLT), a type of mass timber product used frequently in the construction of high-rise buildings, has recently gained popularity in the United States. In the United States, softwood lumber is the primary raw material in the fabrication of CLT. Hardwood is known to have more complex anatomical features compared with softwood. This affects the workability and drying time of hardwood. Hassler et al. (2022) also reported that softwoods are the primary species for satisfying dimensional, structural lumber markets, and that softwood lumber with the specific dimensions and grades needed for CLT manufacturing are readily available in the marketplace. These could be additional reasons why softwood lumber have been the primary raw material for CLT manufacturing in the United States, with the primary reason being lack of standards for hardwood CLT as structural materials.

Nonetheless, there is a growing interest in exploiting hardwood for CLT manufacturing to expand the wood products in the building sector. A notable reason that could be associated with this interest is the rising price of softwood lumber. The producer price index for softwood lumber has nearly doubled between 2019 and 2022 (Hassler et al. 2022). This, if not curtailed, could lead to a decline of supply of softwood raw material for CLT plants and thus a reduction in manufacturing capacity.

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According to the National Hardwood Lumber Association (NHLA; 2019), hardwood lumber graded as No. 2 common and below is generally considered low-grade material. Thomas and Buehlman (2017) reported that low-value hardwoods are used mostly in the manufacture of paper, pallet, railroad ties, and other industrial products. This indicated that the usage of low-value hardwood is only limited to nonstructural purposes. However, low-value hardwood can be further maximized by using it for structural purposes, which implies the manufacturing of CLT with underutilized hardwood. Muszynski et al. (2017) and Adhikari et al. (2020) stated that the manufacture of CLT from underutilized hardwood species may help to meet lumber supply for the industry.

CLT, whether fabricated from softwood or hardwood species, requires adequate strength tests to ascertain its integrity since it is considered a modern structural material. Structural evaluation begins with a notion of test, usually mechanical testing, for the determination of strength and stiffness values (Seale et al. 2021). Traditionally, mechanical testing is done by carrying out static bending tests on a piece of lumber or other (solid) structural wood products.

The static bending test technique, which has been available for a very long time, has proven to be accurate for predicting strength properties. This test is performed to evaluate the modulus of elasticity (MOE) and modulus of rupture (MOR). The softwood lumber industry is also known for its continuous investment into the testing of wood and wood products to obtain highly accurate and reliable design values for MOE and MOR. Hiziroglu (2016) defined MOE as the measure of stiffness (or resistance to deformation under stress).

Franca et al. (2018) stated that MOE is a good overall indicator of wood strength. MOR, known as ultimate strength, measures the maximum bending stress a sample can withstand before failing. These properties of wood are not constant because of the complexity of the anatomy of wood. Uzcategui et al. (2020) identified several factors that could affect the mechanical and physical properties of wood, including moisture availability, geographic location, soil, silvicultural practices, and harvesting methods.

Currently, there are no established standards for hardwood CLT as structural materials. However, a few studies have been carried out on species like red oak (*Quercus* spp.) and yellow poplar (*Liriodendron* spp.) of the Appalachian region to determine their mechanical properties. Azambuja et al. (2023) evaluated the possibility of making full-scale CLT panels from yellow poplar by following visual structural-grade layup methods. The results of this study indicated that low-grade yellow poplar exceeded minimum requirements specified for softwood CLT. Hassler et al. (2024) evaluated the use of low-grade red oak as a raw material for CLT panel production. The results of the study showed that red oak boards met the minimum requirements and can thus be used as a value-added opportunity for hardwood CLT as a structural material.

Despite these studies, there is still limited information about other different species of hardwood CLT, for instance CLT from sweetgum. Furthermore, these studies were constrained to the species of the Appalachian region. The performance of more mechanical testing on species from other regions will thus be helpful in the development of a standard for hardwood CLT for structural usage.

The objectives of this study were to investigate the physical and mechanical properties of hardwood CLT panels made using red oak, sweetgum, and yellow poplar lumber from the U.S. Southeast region by (1) evaluating the density, (2) determining the MOE and MOR, and (3) comparing results with industrially fabricated southern pine (*Pinus* spp.) panels.

Materials and Methods

Material selection

Harwood lumber of the species red oak, sweetgum, and yellow poplar was procured from two sawmills in Mississippi. These species were strategically chosen since they belong to three different density classes. There were 382 lumber pieces used in this study of the dimensions 2 by 6. The lengths of the lumber pieces were 7 ft (2.1 m; used for the surface layers) and 8 ft (2.4 m; used for core layers). The 8-ft pieces were cut into 4 ft (1.2 m) after planing. The size of the produced panels was 4 ft (1.2 m) by 7 ft (2.1 m).

Hardwood lumber preparation

Lumber obtained for this study had a moisture content (MC) above the fiber saturation point. For further processing, the Engineered Wood Association (APA) performance-rated CLT (ANSI/APA 2020) standard for CLT production requires that the lumber is dried to a MC of 12 percent ± 3 percent. This range, however, is specifically for softwood lumber; there are no requirements for hardwood lumber.

The samples were air dried to approximately 12 percent MC at different relative humidities. During this time, the relative humidity varied because of fluctuation of the environmental conditions at the storage site. Air drying was selected rather than kiln drying because it saves energy costs (Forest Products Laboratory 2021), thus making it more economical; it also helps to avoid drying defects such as cracking throughout the drying process. A pinless moisture meter, Wagner Meter MMC 220, was used periodically to read the MC. The desired MC was achieved after 18 months of outdoor storage.

Strength grading

Before manufacturing CLT panels, all lumber was graded on the basis of strength by a certified grader from Timber Products Inspection, a grading agency specializing in hardwood lumber certification. The grading procedure followed the Northeastern Lumber Association Manufacturers (NELMA 2021) strength rules based on knot sizes, knot positions, number of knots, and slope of grain on lumber faces. The grading standard provides guidelines for red oak and yellow poplar species; however, sweetgum, which is currently not presented in the standard, was graded following same set of rules for grading red oak and yellow poplar species. More detail about the grading procedures is reported in the study by Ogunruku et al. (2024). Upon inspection, grades were assigned to lumber using numbers ranging from 1 to 4, with 1 being the strongest and 4 being the weakest. Table 1 shows the summary of lumber pieces used for this study.

CLT manufacturing

According to the CLT Handbook, the typical manufacturing process of CLT includes the following steps: lumber selection, lumber grouping and planing, adhesive application, panel layup and pressing, surfacing, machining, and packaging (Karacabeyli

Table 1.—Lumber pieces for cross-laminated timber manufacturing.

Grade	Red oak		Sweetgum		Yellow poplar		Total
	Core	Faces	Core	Faces	Core	Faces	
2	0	79	0	75	8	76	238
3	38	0	10	0	28	0	76
4	18	0	30	0	20	0	68
Total	135		115		132		382

and Douglas 2013). These processes were followed stepwise during the manufacturing of the panels. A two-face planing operation was performed to achieve equal thickness on lumber faces. This also ensured that the lumber surfaces were prepared for the gluing procedure, which was done before gluing the samples. The adhesive used was Loctite UR 5151, a hot-melt adhesive based on polyurethane technology. It is a one-component adhesive that cures with moisture. This adhesive was selected because it is recommended by the manufacturer for hardwood species.

The glue was applied at a spread rate of 0.03 lb/ft^2 (165 g/m^2) to each face of the laminates being bonded together. This gave a three-ply panel with two glue lines. The panels were then cold pressed using a heavy-duty hydraulic press for 80 to 90 minutes and a pressure of about 0.7 MPa (100 psi). Additional conditions of the pressing procedure were a relative humidity of 65 percent and a temperature of 47°C (117°F). Even though panels were cold pressed, low temperature was used to melt the glue. For each hardwood species, four panels were produced, resulting in 12 panels. Figure 1 shows the manufacturing conditions of the panels.

The control sample used in this study was industrially manufactured CLT from southern pine species. The panels used were three ply manufactured to the dimensions of 7 ft (2.1 m) by 9 ft (2.7 m). The glue used for the southern pine CLT is a moisture-cure adhesive based on polyurethane technology and the spread rate was 0.03 lb/ft^2 (165 g/m^2).

Testing specimens

All 12 hardwood panels were trimmed to equal dimensions that were required for testing. Each panel was cut into 8 strips, resulting in 96 strips (32 strips per species). From the southern pine control panels, 30 strips were obtained. Thus 126 strips were tested, and a summary is provided in Table 2.

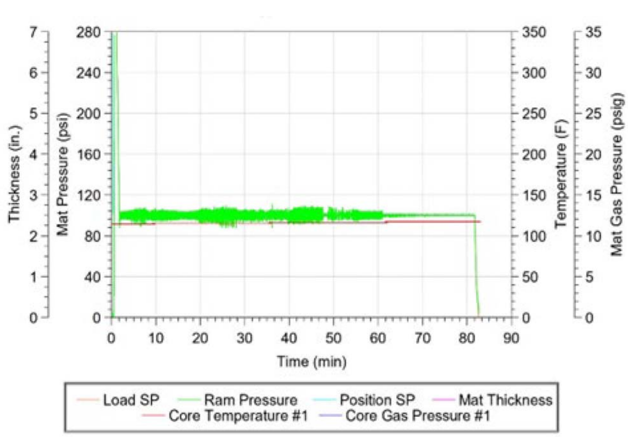

Figure 1.—Cross-laminated timber manufacturing conditions.

Table 2.—Summary of cross-laminated timber strips tested.

Species	Length m (ft)	Thickness mm (in.)	Width mm (in.)	Quantity
Red oak	2.1 (7)	102 (4)	152 (6)	32
Yellow poplar	2.1 (7)	102 (4)	152 (6)	32
Sweetgum	2.1 (7)	102 (4)	152 (6)	32
Southern pine	2.1 (7)	102 (4)	152 (6)	30
Total				126

Density

Density measurement of all samples was conducted at approximately 12 percent MC. The density of samples was calculated using the equation of ASTM D4052-15 (ASTM 2015) standard shown in Equation 1.

$$\rho = m/V \quad (1)$$

where ρ = density (kg m^{-3}), m = mass (kg), V = volume (m^3).

Bending test

Static bending tests were performed on samples using an Instron machine with a 600-kN (135,000-lbf) bending capacity. The machine was set up to a third-point loading system according to ASTM D198-15 (ASTM 2022) at a span-to-depth ratio of 17:1. A deflectometer was attached to the midpoint of the samples to measure the deflection. The MOE and MOR values for each test specimen were logged by the computer connected to the Instron testing machine.

Statistical analysis

The statistical analysis, which included mean (a measure of central tendency), minimum, maximum, and coefficient of variation (CV), was carried out on the physical and mechanical properties of all samples using Microsoft Excel. A one-way analysis of variance (ANOVA) was also done to determine whether there were significant differences between the physical property and the mechanical properties among all species tested. The mean comparisons were then checked with t tests using SAS 9.4 software.

Results and Discussion

Density

The summarized result of density obtained for each species in this study is presented in Table 3. The red oak samples were observed to have the highest density of all the samples tested in this study. The density values of red oak ranged from 709 to 800 kg·m^{-3} (44 to 50 lb·ft^{-3}), with a mean value of 748 kg·m^{-3} (46.7 lb·ft^{-3}). The density test of the red oak strips resulted in a 2.64 percent CV. In comparison with CVs obtained for samples from the other species that were tested in the same manner, red oak had the least variation. The mean density of red oak CLT was also compared with the density of lumber reported in the Wood Handbook (Forest Products Laboratory 2021). The report presented density as a function of MC and specific gravity (sg). At 12 percent MC and 0.63 sg, extrapolation yielded 705 kg·m^{-3}(44 lb·ft^{-3}). This is slightly lower than the mean value found for red oak CLT in this study.

Table 3.—Summary of cross-laminated timber physical and mechanical properties.

Species	Density ($kg \cdot m^{-3}$)	Modulus of elasticity (MPa)	Modulus of rupture (MPa)
Red oak			
Mean	748	13,238	52.77
Minimum	709	10,948	30.07
Maximum	800	16,335	64.35
CV (%)[a]	2.64	10.50	15.97
Sweetgum			
Mean	592	10,317	36.13
Minimum	554	6,746	9.33
Maximum	639	14,166	51.68
CV (%)	3.40	15.03	34.57
Yellow poplar			
Mean	515	10,708	45.02
Minimum	479	8,893	26.30
Maximum	556	12,830	58.34
CV (%)	4.06	8.93	19.29
Southern pine			
Mean	562	9,406	36.21
Minimum	502	5,107	22.37
Maximum	610	12,144	46.37
CV (%)	4.51	17.81	17.33

[a] CV = coefficient of variation.

The samples from sweetgum had densities ranging from 554 to 639 $kg \cdot m^{-3}$ (34.5 to 40 $lb \cdot ft^{-3}$), with an average value of 592 $kg \cdot m^{-3}$ (37 $lb \cdot ft^{-3}$). The CV obtained for the sweetgum density test was 3.40 percent, which was slightly higher than that of red oak. The comparison of sweetgum mean density was also done. At 12 MC and 0.52 sg, the Wood Handbook (Forest Products Laboratory 2021) reported density to be 582 $kg \cdot m^{-3}$. (36.3 $lb \cdot ft^{-3}$).

The yellow poplar samples were the least dense among all four species tested. Yellow poplar had a mean, minimum, and maximum value of 515 $kg \cdot m^{-3}$ (32 $lb \cdot ft^{-3}$), 479 $kg \cdot m^{-3}$ (30 $lb \cdot ft^{-3}$), and 556 $kg \cdot m^{-3}$ (34.7 $lb \cdot ft^{-3}$) respectively. By comparison with other tested samples, these values were the lowest for each of the categories. The CV of yellow poplar was 4.06 percent. The mean density of this study was higher than the reported value of the Wood Handbook (Forest Products Laboratory 2021) as 470 $kg \cdot m^{-3}$ (29.3 $lb \cdot ft^{-3}$).

Of the various species that were tested, southern pine samples had the highest CV on the basis of the density test, with a value of 4.51 percent. The lowest density value obtained was 502 kg m^{-3} (31 $lb \cdot ft^{-3}$), the highest was 610 kg m^{-3} (38 $lb \cdot ft^{-3}$), and an average mean value of 562 $kg \cdot m^{-3}$ (35 $lb \cdot ft^{-3}$) was observed. The overall density values for all samples tested are presented in Figure 2.

For the density, there were significant differences among all hardwood species and control panels. Red oak panels were statistically higher than the other species studied, followed by sweetgum, yellow poplar, and southern pine. The density ANOVA result is presented in Table 4 and the mean comparison result is shown in Figure 3.

Mechanical properties

Table 3 shows the result from third-point bending tests for each species of CLT specimen. For the MOE of red oak

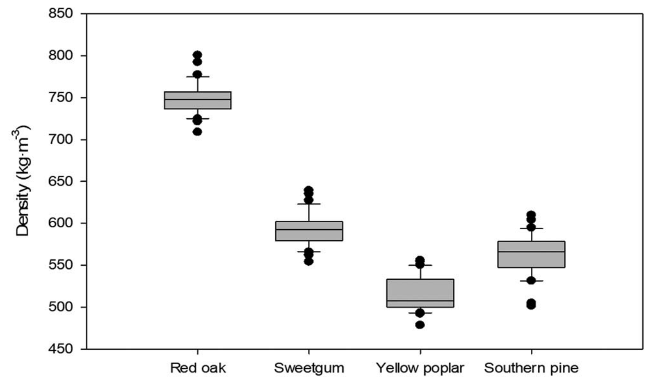

Figure 2.—Box-plot graphic of cross-laminated timber density results.

specimens, the mean value was 13,238 MPa (1.92 $\times$ 10^6 psi), with minimum and maximum values of 10,948 MPa (1.58 $\times$ 10^6 psi) and 16,335 MPa (2.37 $\times$ 10^6 psi), respectively. The MOR for red oak ranged from 30.07 to 64.35 MPa (4,361 to 9,333 psi), with a mean value of 52.77 MPa (7,653psi). The CVs for MOE and MOR were 10.5 percent and 15.97 percent respectively.

Among the sweetgum samples, the MOE varied from 6,746 to 14,166 MPa (978,424 to 2.05 $\times$ 10^6 psi), with a mean value of 10,317 MPa (1.5 $\times$ 10^6 psi) and a CV of 15.03 percent. The MOR of sweetgum ranged from 9.33 to 51.68 MPa (1,353 to 7,495 psi). The average MOR of this species was 36.13 MPa (5,240 psi). Sweetgum had the lowest minimum MOR value among all species that were tested. This species had the highest range of MOR values among all four species, which also led to the highest CV among all four species, with a value of 34.57 percent. The high value of CV obtained for the MOR could be due to a few outliers having extremely low values, thus affecting the curve describing the samples from sweetgum species.

The mean, minimum, and maximum values for the MOE of yellow poplar samples were 10,708, 8,893, and 12,830 MPa (1.55 $\times$ 10^6, 1.28 $\times$ 10^6, 1.92 $\times$ 10^6 psi) respectively. The MOE CV was found to be 8.93 percent. For the MOR, the mean, minimum, maximum, and CV values were 45.02, 26.3, 58.34 MPa (6,530, 3,814, 8,461 psi), and 19.29 percent respectively.

Among the southern pine strips, the mean value of the MOE was 9,406 MPa (1.36 $\times$ 10^6 psi), with minimum and maximum values of 5,107 (740,707 psi) and 12,144 MPa (1.76 $\times$ 10^6 psi) respectively. The MOR for southern pine ranged from 22.37 to 46.37 MPa (3,190 to 6,671 psi), with a mean value of 36.21 MPa (5,250 psi). The CV for red oak for MOE and MOR were 17.81 percent and 17.33 percent respectively. The MOE CV value for southern pine was the highest among the four species tested. The results of the

Table 4.—Density one-way analysis of variance result for cross-laminated timber samples tested.

	df	Sum of squares	Mean square	F value	Probability $> F$
Species	3	975,451.46226	325,150.48742	696.37241	$<$0.0001
Error	122	56,964.28973	466.92041		
Total	125	1,032,415.75199			

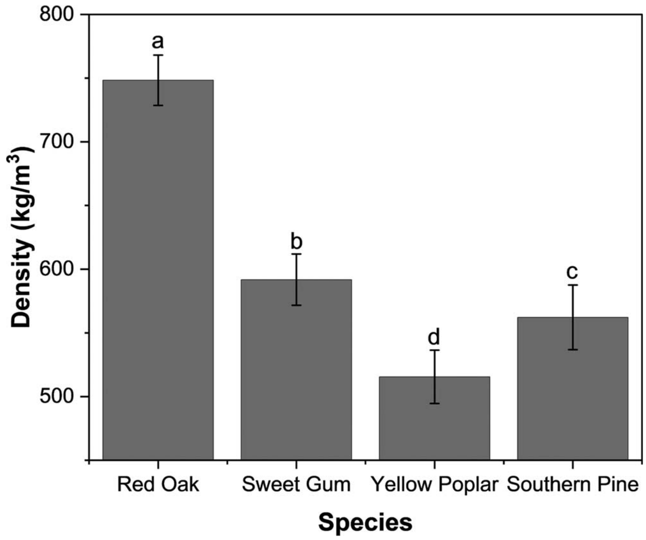

Figure 3.—Cross-laminated timber samples density mean comparison.

properties examined for all CLT species are summarized in Table 3 and the overall MOE and MOR values for all samples tested are presented in Figures 4 and 5 respectively.

There were significant differences among MOE results. The mean value of red oak samples was significantly higher than those from other tested species. There was no statistically significant difference between sweet gum and yellow poplar samples. There were also significant differences between hardwood species in comparison with southern pine samples, where southern pine presented statistically lower MOE values than hardwood species. The MOE ANOVA result is presented in Table 5 and the mean comparison result is shown in Figure 6.

The analysis of MOR indicated significant differences. There were significant differences among all hardwood species tested. Also, in the comparison of hardwood species and southern pine samples, there were significant differences between both red oak and yellow poplar in comparison with southern pine. However, no significant difference was found between sweetgum and southern pine. The MOR ANOVA result is

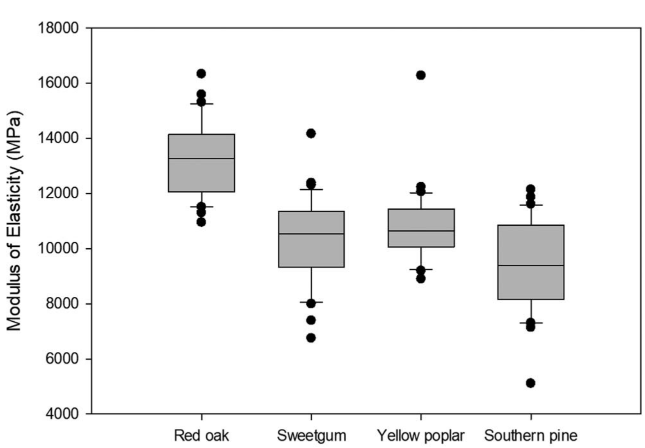

Figure 4.—Box-plot graphic of cross-laminated timber modulus of elasticity results.

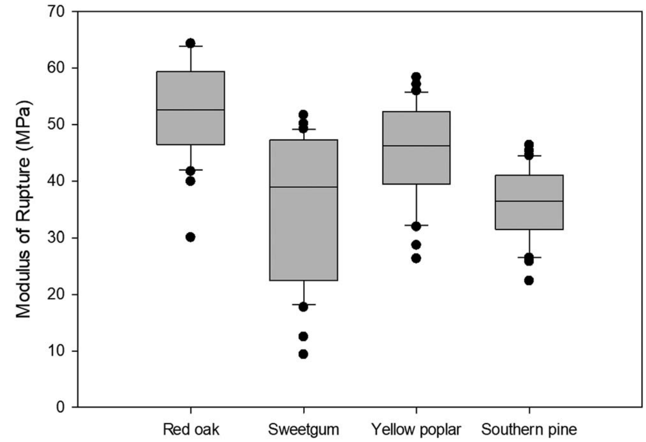

Figure 5.—Box-plot graphic of cross-laminated timber modulus of rupture results.

presented in Table 6 and the mean comparison result is shown in Figure 7.

Comparison with previous publications

A comparison of MOE values of all four species was performed between this study and previous studies to observe the variation among materials. The red oak MOE values in this study were compared with those in Hassler et al. (2024), which evaluated low-grade red oak as raw material for CLT production. The authors reported the mean, minimum, and maximum as 13,031 MPa (1.9 $\times$ 10^6 psi), 8,756 MPa (1.27 $\times$ 10^6 psi), and 19,925 MPa (2.89 $\times$ 10^6 psi) respectively. The mean values of red oak CLT in this study and the authors' study were comparable; however, this study exhibited higher minimum and maximum values. This slight variation could be because of the source of the raw materials, as Hassler et al. (2024) samples were from the Appalachian region, whereas red oak for this study were obtained from the Southeast region of the United States.

In the study conducted by Shmulsky and Shi (2008) to develop industrial laminated planks from sweetgum lumber, the authors reported the mean, minimum, and maximum MOE values of sweetgum CLT as 10,687 MPa (1.55 $\times$ 10^6 psi), 8,895 MPa (1.3 $\times$ 10^6 psi), and 12,759 MPa (1.85 $\times$ 10^6 psi) respectively. The mean value of sweetgum MOE in this study was similar to the cited authors' findings. The minimum value of MOE in this study was lower than the one found by the authors, but the maximum value of MOE in this study was higher. This indicates that there was a greater range of MOE values obtained for sweetgum used in this study. This variation associated with sweetgum could be because of kiln drying treatment used for the study of Shmulsky and Shi (2008).

Table 5.—Modulus of elasticity one-way analysis of variance result for cross-laminated timber samples tested.

	df	Sum of squares	Mean square	*F* value	Probability > *F*
Species	3	2.52487E8	8.41622E7	37.96857	<0.0001
Error	122	2.70429E8	2,216,629.08404		
Total	125	5.22915E8			

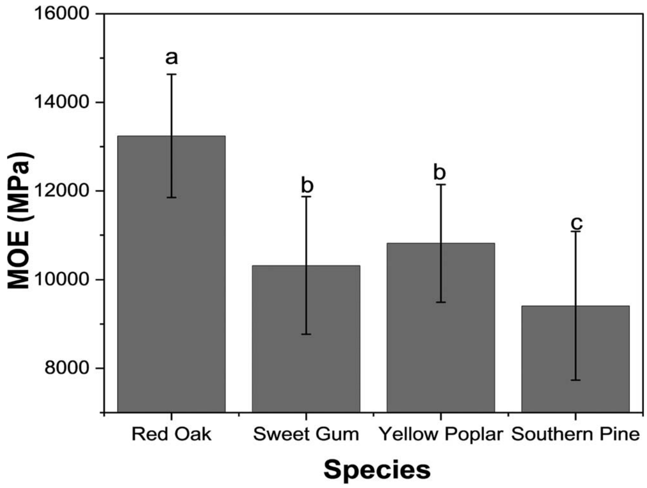

Figure 6.—Cross-laminated timber samples modulus of elasticity (MOE) mean comparison.

A study conducted by Azambuja et al. (2021) evaluated low-grade yellow poplar as raw material for CLT production. The reported mean and minimum MOE values of yellow poplar CLT were 11,445 and 5,308 MPa (1.66×10^6, 769,860 psi) respectively for a No. 2A grade specimens according to the NHLA grading rule. The mean value of yellow poplar MOE in this study was slightly lower than that reported by Azambuja et al. (2021), and the minimum value for this study was higher than that obtained by the authors. This shows a greater variation among the MOE values of the individual lumber tested by Azambuja et al. (2021), which could be explained by the higher number of samples used in that study, a total of 513 samples for that grading category. It can also be argued that producing CLT from these samples enhanced the overall mechanical properties of individual lumber when glued together.

The values of MOE obtained for southern pine in this study were compared with the study conducted by Correa et al. (2023) to determine the mechanical properties and design values of three-ply commercial southern pine CLT. The mean, minimum, and maximum MOE values of southern pine CLT were 8,142 MPa (1.18×10^6 psi), 5,755 MPa (834692 psi), and 10,469 MPa (1.52×10^6 psi) respectively. The MOE values reported by the authors were based on the MOE_{gross}, which assumes specimens behave as a continuous material rather than on shear analogy method. The minimum of southern pine CLT in this study was found to be lower than the mean found by the authors; however, this study had slightly higher values for both mean and maximum MOE values compared with the ones reported by Correa et al. (2023). This could be because the values obtained on the basis of gross moment of inertia are lower compared with constituent lumber as reported by the authors, thus making the MOE_{gross} values more conservative than reported by this study.

Table 6.—Modulus of rupture one-way analysis of variance result for cross-laminated timber samples tested.

	df	Sum of squares	Mean square	F value	Probability > F
Species	3	6,065.07879	2,021.69293	23.43744	<0.0001
Error	122	10,523.61135	86.25911		
Total	125	16,588.69014			

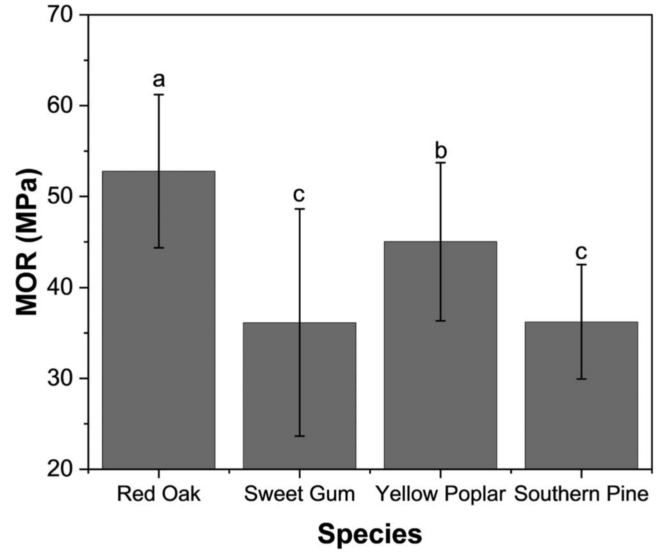

Figure 7.—Cross-laminated timber samples modulus of rupture (MOR) mean comparison.

Conclusions

This research examined the physical and mechanical properties of three species of low-valued hardwood CLT in comparison with industrially manufactured softwood CLT. For the physical property examined, which was density, the highest average density value found was on panels made with red oak, followed by sweetgum, southern pine, and yellow poplar.

The average MOE values of all hardwood species were higher than the MOE of southern pine, where red oak presented the statistically significantly highest MOE; no statistical differences were found between sweetgum and yellow poplar. Of the 96 hardwood samples subjected to static bending test, 92 samples (about 96%) exceeded the minimum MOE requirement specified by the American National Standards Institute/APA PRG 320 (ANSI/APA 2020) for softwood CLT. The only four samples not satisfying the requirement were sweetgum species. For the softwood CLT, 22 of the 30 samples, approximately 73 percent, performed above the specified minimum requirement. Also, the MOE values for hardwood CLT samples in this study were found to be comparable with those in previous studies, signifying that the average values were closely related despite samples used in previous studies being from different regions within the United States.

Given these results, it is evident that low-value hardwood lumber from red oak, yellow poplar, and sweetgum species can be used as structural members even in large commercial buildings when they are layered up to manufacture CLT. In addition, the mechanical values obtained from this study, in combination with results from other studies, can be used as a basis for developing design codes for hardwood CLT for the tested hardwood species.

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