Mechanical Properties of Underutilized Hardwood Species and Potential for Use in Fabrication of Cross-Laminated Timber Industrial Mats

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Abstract

This research evaluated the mechanical and physical properties of three underutilized hardwood species according to visual lumber grades. Findings are discussed in relation to the requirements recommended such as density, modulus of rupture (MOR), and modulus of elasticity (MOE) for the manufacture of cross-laminated timber (CLT) industrial mats, which is a potential end use of low-valued hardwood species. Results showed that all species tested had an average MOE greater than that required for CLT lumber. Visual grading was an important component in strength determinations as evidenced by the correlation between MOE and MOR. All grades of red oak (*Quercus rubra* L.) had higher densities than those of southern yellow pine, which is the traditional wood used in manufacturing CLT industrial mats, with a density of 616 kg/m^3 at 12 percent moisture; the average density of the red oak tested was 770 kg/m^3 at 13.98 percent moisture. All grades of red oak also had MOE and MOR values that met the requirements for lumber used in the manufacture of CLT industrial mats. For sweetgum (*Liquidambar styraciflua* L.), all grades met the required values for MOE and MOR, but only Grades 3 and 4 met the required density. All grades of yellow poplar (*Liriodendron tulipifera* L.) met the required MOE and MOR, but none met the required density.

Cross-laminated timber (CLT) has gained recognition as a construction material that stands on par with other wood products in terms of mechanical performance, fire resistance, building costs, carbon footprint, construction lead times, and visual appeal (Adhikari et al. 2020). However, the utility of CLT extends beyond structural applications, as it finds a unique niche in the creation of industrial mats (Herberg 2018, Adhikari et al. 2020). Industrial mats, also called crane mats, access mats, or swamp mats, serve as versatile, prefabricated CLT platforms, strategically designed to safeguard the environmental integrity of job sites that require the deployment of heavy machinery. These mats are indispensable tools in a range of applications, facilitating the anchoring of heavy equipment and vehicles while enabling passage across diverse terrains. Their usage spans multiple industries, including pipeline installation, oil mining, electric power transmission lines, powerline installation, and other large-scale construction endeavors (Shmulsky et al. 2021). The fundamental requirements for industrial mats are their ease of manufacture and the ability to withstand substantial loads. These expansive, panelized wooden structures are placed on the ground, effectively distributing the weight of heavy machinery to minimize the ground pressure. This is crucial not only for safeguarding the surrounding flora and fauna but also for ensuring the longevity of the natural environment in work sites exposed to the impact of heavy machinery and personnel movement. They also save time and money by keeping machinery from getting stuck or

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damaged because of unstable soil. Upon project completion, these industrial mats are collected, cleaned, and stored for future use. The same mats can be used for about 2 years before a replacement is needed, whereas the old mats can be sized to produce mulch and also for sludge solidification, which can be used in the production of biochar, fostering sustainability and the restoration of construction sites to their original conditions (Mahamid et al. 2017, Herberg 2018, Owens et al. 2020, Shmulsky et al. 2021, Snow et al. 2022, Maco Corporation 2023, Blackwood 2024). In the United States, CLT production is manufactured largely using softwood species despite the competitive demand for softwood. The use of softwoods for CLT production has been studied extensively, whereas much less is known regarding the production of CLT using hardwood species. Hardwoods have the potential to improve CLT materials because of their naturally higher strength potential and increased durability properties compared with softwoods (Franke 2016, Espinoza and Buehlmann 2018).

The proliferation of hardwood tree species can be attributed to their remarkable adaptability, which has resulted in a large abundance of hardwood forests and thus available hardwood resources. Remarkably, hardwoods exhibit a removal rate of only 43.3 percent, leaving a more substantial proportion of hardwoods within the forest ecosystem, in contrast to softwoods, which experience a removal rate of 57.5 percent. This heightened abundance of hardwood resources within forest ecosystems presents a promising opportunity for its utilization for CLT industrial mats, a nonstructural industrial use (Adhikari et al. 2020). Despite the promising opportunity and competitive advantage presented by utilizing hardwood for CLT industrial mat production, there has been relatively limited research focusing on the utilization of hardwood species for this purpose at a fine-scale level.

Franke (2016) focused on evaluating the mechanical attributes of beech-based CLT. The investigation revealed that beech CLT exhibited a superior load-bearing capacity compared with CLT derived from spruce. In a related study Thomas and Buehlmann (2017) explored hardwood's utility in CLT construction. The study used low-grade yellow poplar (*Liriodendron tulipifera* L.) for CLT production, with the material graded according to US Forest Service log grading standards to assess quality and market value. The selected yellow poplar species exhibited a diminished grade, primarily attributed to heightened instances of severe defects and reduced clear areas in the logs. It is noteworthy that this grade of logs is not typically utilized in the production of graded lumber. However, the price and yield characteristics rendered it advantageous for CLT. The authors delved into the potential of enhancing yield through the utilization of this low-grade hardwood in CLT manufacturing. Their findings underscored that when specific attributes such as splits, checks, knots, and warp were acceptable in the laminated timber, wider and longer timbers could be produced. This approach not only contributed to cost reduction in finger jointing but also resulted in fewer longitudinal glue joints. These insights hold considerable significance for the feasibility and acceptance of low-grade hardwood species in CLT applications. In their assessment of utilizing low-grade yellow poplar as the primary resource for CLT panel fabrication, Azambuja et al. (2021) observed that, in situations where the outer layer of the timber exhibited an absence of strength-reducing defects such as knots, yellow poplar emerges as a highly viable choice for satisfying the requirements of bridge construction. This observation implies that yellow poplar stands as a promising candidate among wood species suitable for industrial mats.

It is important to recognize that most hardwoods undergo prolific growth due to their adaptability, ultimately leading to an overabundance of hardwood trees in relation to industry demand (Osamah 2016, Espinoza and Buehlmann 2018, Howard and Liang 2019, Senalik and Farber 2021). This abundance, coupled with the exceptional mechanical properties inherent to hardwoods, positions them as a prime choice for the construction of long-span and high-stress wooden structures. Consequently, CLT emerges as a viable and strategic option to enhance the value and utilization of the ample hardwood species available (Franke 2016). However, some of the barriers that remain in adopting hardwood CLT include raw material cost, manufacturing processes, hardwood lumber supply chain, machining of hardwood CLT panels, adhesion of hardwood lumber, sustainability of hardwood timber, and grading standards (Adhikari et al. 2020). It is noteworthy to point out that few studies have assessed the properties of low-valued hardwood species in the southern United States for manufacturing hardwood CLT industrial mats as well as assessing their performance on the basis of their grades (Franke 2016, Aldhikari et al. 2020, Azumbaja et al. 2021).

The establishment of large-scale production for hardwood CLT can become a realistic prospect when manufacturers are equipped with relevant data and exhibit willingness to embrace hardwood materials. Central to this endeavor is comprehending the existing manufacturing framework and discerning avenues through which hardwood can be effectively incorporated into CLT production. This necessitates understanding the integration of hardwood materials into current manufacturing processes, identifying the requisites for optimizing hardwood utilization in CLT manufacturing, and integrating hardwood-related data into CLT design standards. These initial stages are pivotal for advancing and endorsing hardwood CLT products. In this context, our study assessed the physical and mechanical properties of three underutilized hardwood species: red oak (*Quercus rubra* L.), yellow poplar, and sweetgum (*Liquidambar styraciflua* L.), using American National Standards Institute (ANSI)/APA—The Engineered Wood Association (APA) PRG 320 as a standard. This provides the requirements for the manufacture of CLT meant for construction using softwood species. The standard specification for timber mat production designed by the North American Matting Association (NAMA), which accepts the use of hardwood species, implied that mats meant for nonstructural use do not necessarily need to have specified mechanical properties except for situations where the mats are intended to be used for overhead rigging, for heavier loads, and in soft or sensitive soils (North American Matting Association [NAMA] 2023).

However, the scope of the study is limited to testing the physical and mechanical properties of hardwood species intended for CLT mats, comparison with southern yellow pine, a softwood species, and the traditional species used in accordance with ANSI/APA PRG 320 to weigh their potentiality to fit. In addition, this study can serve as a baseline to close the gap of hardwood graders in the United States for structural hardwood lumber. This evaluation is directed toward ascertaining their suitability for application in the fabrication of CLT industrial mats. By providing pertinent data on these wood species, our research endeavors to furnish wood industry stakeholders with essential information that supports the adoption of these tested hardwood species.

Materials and Methods

Lumber of three hardwood species (red oak, sweetgum, and yellow poplar), donated by Copiah Lumber (Crystal Springs, MS) and Superior Mat Co. (Collins, MS), were cut at Mississippi State Univ. (Dept. of Sustainable Bioproducts) into 7-ft- and 8-ft-long boards with an average thickness and width of 1.375 and 7.5 in, respectively. Boards were then air-dried outdoors under the shade for about 14 months. Since this study was designed to assess the potential use of these species in the manufacturing of CLT, the moisture content (MC) requirement of 12 $\pm$ 3 percent at the time of CLT manufacturing was followed, as stated in the standard for performance-rated cross-laminated timber (APA 2019). The MC of all samples was constantly measured until the desired MC was reached using a Wagner meter MMC220 (Wagner Meters 2023) moisture meter. For each of the species tested, the moisture meter was calibrated to the specific gravity for that species as follows: 0.65 for red oak, 0.55 for sweetgum, and 0.45 for yellow poplar (InsideWood 2004).

Classification of boards

Samples from each species were graded by a certified grader according to the Northeastern Lumber Manufacturers Association standard grading rules (NELMA 2021). For sweetgum, grading was done using the same set of rules for grading yellow poplar and red oak as there are currently no grading standards or guidelines for this species (NELMA 2021). The total number of replicate specimens evaluated after all boards were classified is given in Table 1.

Density

The density of all samples evaluated in this research was determined using Equation 1 (ASTM D2395 2022).

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} \tag{1}$$

Static bending tests

Bending tests were performed to evaluate the mechanical properties using an Instron hydraulic universal testing machine (UTM-HYD, serial no. KN60001605, model 600KN) with a capacity of 135,000 lbf. The machine was set for a four-point loading system following the ASTM D198-22 standard method (ASTM 2022) with a span ratio of 7.75 or 6.55 ft for testing the 8- and 7-ft specimens, respectively. An extensometer was attached to the machine, which was sufficiently rigid and at the midpoint of the samples as shown in Figure 1 so that level of deformation/deflection to determine modulus of elasticity (MOE) and maximum load before failure modulus of rupture (MOR) could be measured. The loads were applied at the center for all lumber tested.

Table 1.—Total number of replicate specimens used to evaluate density, modulus of elasticity, and modulus of rupture within each grade.

Grade	Red oak	Yellow poplar	Sweetgum
1	6	115	85
2	64	143	181
3	63	27	50
4	129	36	77
Total	262	321	393

Statistical analysis

A descriptive statistical analysis, including the mean, coefficient of variation (COV), minimum, and maximum was carried out to summarize the physical and mechanical properties of all the species across the grades. For each wood species, density, MOE, and MOR are presented according to classification grade and COV was determined on the basis of the ratio of the standard deviation to the mean. Coefficient of determination (R^2) was calculated to examine the strength of association among density, MOE, and MOR for each species across the different classification grades. This can be used as proxy for quantifying the percentage of variability that can be explained between two properties in relation to grade. A regression analysis was adopted for this assessment ($P \leq 0.05$). To predict the normality in the relationship between MOE and MOR, a heteroscedasticity test was selected using the Durbin-Watson statistics for autocorrelation (DW = 2; SAS 2023).

Results and Discussion

Moisture content

Before testing, the MCs of all samples were determined to be within the MC requirement for lumber used in the fabrication of CLT according to the APA (2019) standard and NAMA (2023) for seasoned wood (Table 2). This MC is higher than normally required for hardwood manufacturers as hardwood mills generally require a lower MC (i.e., 6% to 8%) depending on end use (e.g., furniture and cabinets; Simpson 1999). This means that hardwood industries with interest in the manufacturing of hardwood CLT will have to adjust their kiln system to achieve a higher MC, which to some extent could reduce costs associated with kiln-drying (Hassler et al. 2023).

Comparison of physical and mechanical properties of each species tested by grade

Average density values for all species according to grade are shown in Figure 2 and Table 2. Red oak showed the highest density of the species tested, regardless of grade, with an average density of 770 kg/m^3 for all samples tested ($n = 262$), and COV of 5.18 percent. For sweetgum, the average density of all samples ($n = 393$) was 607 kg/m^3 with COV of 7.45 percent. Yellow poplar showed the lowest mean density of all samples tested ($n = 321$) at 519 kg/m^3 and COV 7.49 percent. According to a post hoc Tukey test at $P = 0.05$, only red oak Grade 3 differed significantly in density from other grades, yellow poplar showed no significant difference in density between any of the grades, and the density of sweetgum Grade 4 was significantly different; this is shown with letters in Figure 2.

Figure 1.—Bending machine set up with the extensometer attached to the sample.

In a study performed using small clear red oak samples of unspecified grade, Uzcategui et al. (2020a) showed that sample density varied between 571 kg/m^3 and 853 kg/m^3, with an average density of 699 kg/m^3. Density result for red oak according to the *Wood Handbook*, which uses an average MC for that wood species of 13.98 percent and a specific gravity of 0.65, was 741 kg/m^3 (Glass and Zelinka 2021). This is different from the result obtained by Uzcategui et al. (2020a) and slightly lower than the result obtained for red oak from this study (i.e., 770 kg/m^3). Possible reasons for differences in density values may be related to lumber size, MC, or specific gravity (Glass and Zelinka 2021).

Uzcategui et al. (2020b) determined the mean density of small clear yellow poplar samples to be 508 kg/m^3, whereas the *Wood Handbook* (Glass and Zelinka 2021) lists the density of yellow poplar at the MC and specific gravity used in this study as 513 kg/m^3. These values agree with the average density values recorded during this study (i.e., 514 kg/m^3). The density of sweetgum, as determined using specific gravity and MC values from the *Wood Handbook* (Glass and Zelinka 2021), was 640 kg/m^3, whereas the average density recorded in this study was 604 kg/m^3.

Average static bending MOE values associated with lumber grade are shown in Figure 3 and Table 2 for all species evaluated. These results show that red oak specimens within Grades 1 to 3 show the highest MOE values. Specimens of Grade 4 red oak match with sweetgum lumber Grades 1 or 2 or Grade 1 yellow poplar. Sweetgum lumber within Grades 3 and 4 was similar to yellow poplar lumber Grades 3 and 4. Average MOE for all red oak specimens tested (n = 262) was 11,509 MPa, with COV of 18.15 percent. Sweetgum (n = 393) and yellow poplar (n = 321) specimens showed similar average MOE values of 9,627 MPa and 9,621 MPa, respectively and COV of 20.4 percent and 15.83 percent, respectively. The variability in the values from the mean shows low to moderate risk across all species since all the COV values have shown that the disparity of the data from the mean was low. The post hoc Tukey test showed that the MOE of Grade 4 of red oak was significantly different, whereas the MOE of Grade 1 yellow poplar was significantly different and sweetgum formed two distinct sets of differences, with Grades 1 and 2 forming a set and Grades 3 and 4 forming a different set, all at P = 0.05 (note: the letters in Fig. 3 show these differences).

While referencing the ANSI/APA PRG-320 (2019) standard, Azambuja et al. (2021) noted that the minimum MOE for lumber to be used in the manufacturing of CLT is 8,274

Table 2.—Summary of properties of samples/species evaluated.

Species	Parameters	Moisture content (%)	Density (kg/m^3)	Modulus of elasticity (MPa)	Modulus of rupture (MPa)
Red oak	Minimum	12.97	657	6,763	30.50
	Maximum.	15.75	851	13,136	94.77
	Average	13.98	770	11,509	50.85
	COV[a] (%)	3.54	5.18	18.15	24.81
Sweetgum	Minimum	12.98	512	5,423	10.93
	Maximum	15.22	746	14,087	84.78
	Average	13.68	607	9,627	50.13
	COV (%)	3.35	7.45	20.4	36.93
Yellow poplar	Minimum	11.92	408	5,458	15.47
	Maximum	14.54	608	13,168	83.26
	Average	13.21	519	9,621	47.45
	COV (%)	3.86	7.49	15.83	37.78

[a] COV = coefficient of variation.

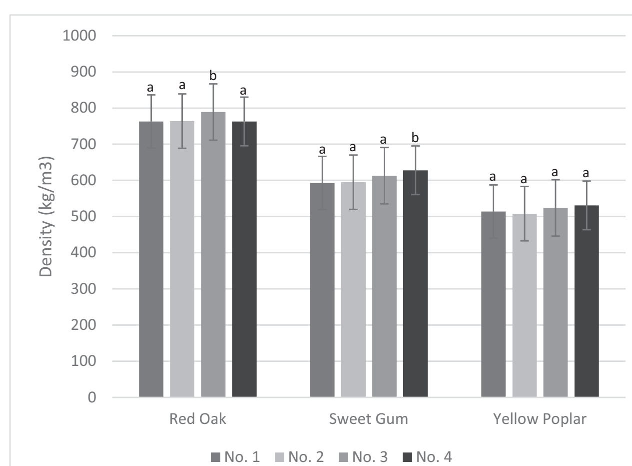

Figure 2.—Average density of each species by grade. Grades with the same letter for each species are not significantly different at P = *0.05.*

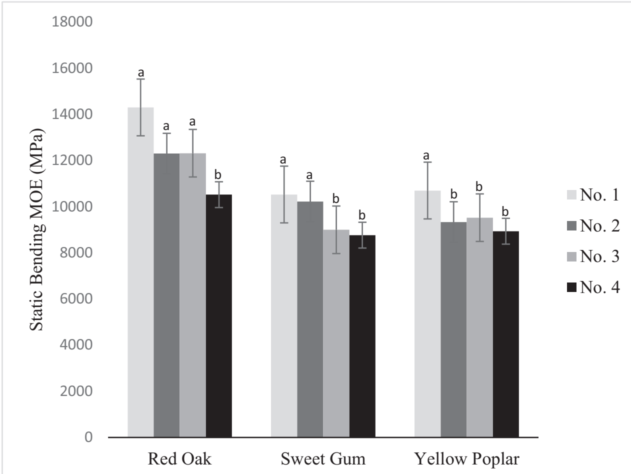

Figure 3.—Average modulus of elasticity (MOE) for each species by grade. Grades with the same letter for each species are not significantly different at P = *0.05.*

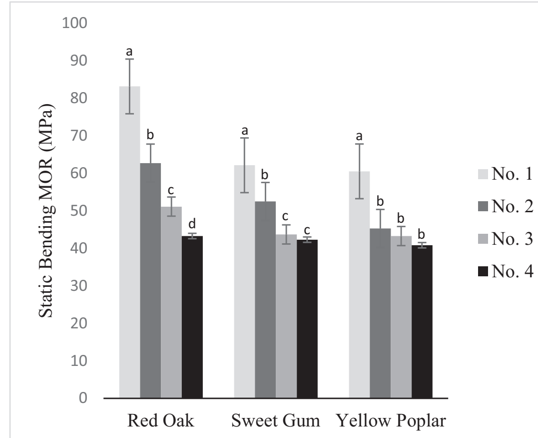

Figure 4.—Average modulus of rupture (MOR) for each wood species by grade. Grades with the same letter for each species are not significantly different at P = *0.05.*

MPa. This implies that all grades of lumber from each of the three species tested in this study demonstrate a minimum MOE that meets the requirements for the fabrication of CLT.

The average static bending MOR for all species tested according to grade is shown in Figure 4 and Table 2. According to these results, Grade 1 red oak had a significantly higher MOR value compared with all grades of the other species tested. The average MOR for all red oak specimens tested ($n = 262$) was 50.85 MPa with COV of 24.81 percent. Average MOR for all sweetgum samples ($n = 393$) was similar to red oak at 50.13 MPa and COV 36.93 percent. Yellow poplar showed the lowest average MOR with a value of 47.45 MPa for all specimens tested ($n = 321$) and COV of 37.78 percent. Using the post hoc Tukey test at $P =$ 0.05, red oak shows a significant difference among all grades for MOR, whereas only Grade 1 MOR of yellow poplar was different. Sweetgum formed three sets, with the MOR of Grade 1 different from Grade 2 and the MOR of Grades 3 and 4 forming the third set; these differences are represented by the letters in Figure 4.

According to Senalik and Farber (2021), MOE and MOR for the three seasoned hardwood species examined in this study are as follows: red oak, MOE of 11,300 MPa and MOR 96 MPa (96,000 KPa); sweetgum, MOE of 11,300 MPa and MOR 86 MPa (86,000 KPa); and yellow poplar, MOE of 10,900 MPa and MOR 70 MPa (70,000 KPa). Differences in these results compared with the results from the present study can be the result of several different factors, including dimensional size, MC, and sample size.

The high COV values obtained for all species tested suggest a substantial level of variability, particularly in relation to average MOR. Other studies have shown similar levels of variability with a generally higher COV associated with MOR compared with MOE (Uzcategui et al. 2020a, 2020b; Khademibami et al. 2021).

Khademibami et al. (2021) determined the MOE and MOR for green red oak to be 9,610 MPa and 43.36 MPa, respectively. The higher values for MOE and MOR obtained in this study for red oak (i.e., 11,509 MPa and 50.85 MPa, respectively) can be easily attributed to the difference in the MC of the samples. Uzcategui (2021a) also obtained different results while testing the mechanical properties of red oak using small clear samples, reporting average MOE and MOR values of 12,000 MPa and 120 MPa, respectively. Testing for the mechanical properties of yellow poplar using small clear samples, Uzcategui (2020b) noted that the mean MOE and MOR recorded were 9,611 MPa and 83.4 MPa, respectively. The dimensional size of the samples tested was provided as a main reason for differences in the results, especially for MOR.

Using a nondestructive testing method, Franca et al. (2018a) estimated the stiffness and strength of small-sized samples of southern yellow pine, which is the conventional species used in the fabrication of CLT industrial mats. Their results showed that the COV for density had a low dispersion from the mean, but the COV associated with MOR suggested relatively moderate to high variability across all the sizes tested. These results are similar to what was recorded for Grade 2 southern yellow pine of different sizes, which showed the MOE to be moderately dispersed from the mean (ranging between 20% to 23%), but with a higher COV associated with MOR (ranging between 33% and 33.7%; Franca at al., 2018b).

Statistical relationship between the properties tested across species

The graphical representation of the relationship between MOE and MOR for each species tested across the different grades is shown in Figures 5 through 7. The level of significance (P-value) as well as the variations based on the coefficient of determination (R^2) of the parameters tested for all species across grades are provided in Table 3. Results show an overall significant relationship between density and MOE and the coefficient of determination shows that 13, 3, and 21 percent of the variation in MOE can be explained by density for red oak, sweetgum, and yellow poplar, respectively. Additionally, the variability in MOR that can be explained by density is 4, 7, and 9 percent in red oak, sweetgum, and yellow poplar, respectively.

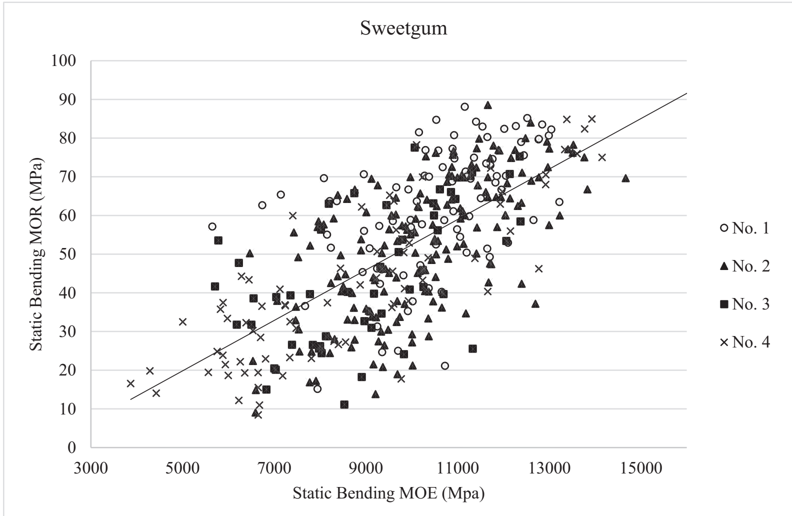

Figure 5.—Relationship between modulus of rupture (MOR) and modulus of elasticity (MOE) for sweetgum lumber. Regression line shows the relationship for all observations and is not based on grades.

Figures 5 through 7 provide support for a strong positive linear relationship between MOE and MOR across all three species. These data also indicate an influence of grade on the MOR and MOE, where visualizing the charts in the two-dimensional space shows that the distribution of Grade 1 for all tested species was clustered at the top bound of the charts and Grade 4 clustered at the lowest bound of the charts. Table 3 shows that the percentage of the variability in MOR that can be explained by MOE is 38 percent for red oak, 47 percent for sweetgum, and 48 percent for yellow poplar.

MOE and MOR are the predominant mechanical properties used to ascertain the end use of wood materials. MOE provides information on the stiffness of the wood and is a good comprehensive measure of wood strength, whereas MOR gives information about the maximum stress or weight a wood material can sustain before failure or rupture (Uzcategui et al. 2019). Therefore, these parameters were used to ascertain the possibility of using these species in the manufacture of CLT industrial mats. Variations in wood structural characteristics such as density, latewood proportion, ring width, microfibril angle, and fiber length are largely responsible for variations in the mechanical properties of sawn timber, mainly the MOE and MOR (Bendtsen and Senft 1986, Cave and Walker 1994, Downes et al. 2002, Alteyrac et al. 2006), which can have a significant impact on potential end use (Kretschmann 2010). Hence, before selection of various low-valued hardwood species for potential use in fabrication of industrial mats, it is imperative to evaluate certain mechanical properties, particularly those related to load bearing (Baillères et al. 2012).

A similar investigation conducted by Green and McDonald (1993) focused on examining the mechanical properties of red oak using nondestructive testing methodology and revealed that although the coefficient of determination may not have been particularly high for the relationship between MOE and MOR, there was a statistically significant connection between these two crucial mechanical properties. This

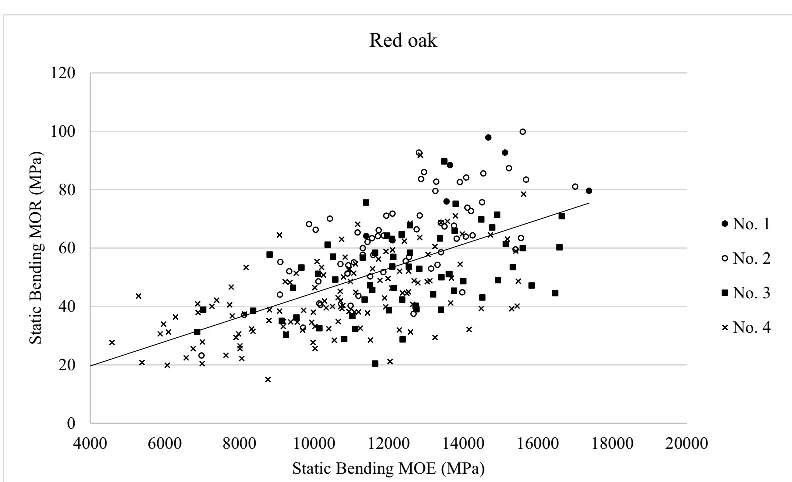

Figure 6.—Relationship between modulus of rupture (MOR) and modulus of elasticity (MOE) of red oak lumber. Regression line shows the relationship for all observations and is not based on grades.

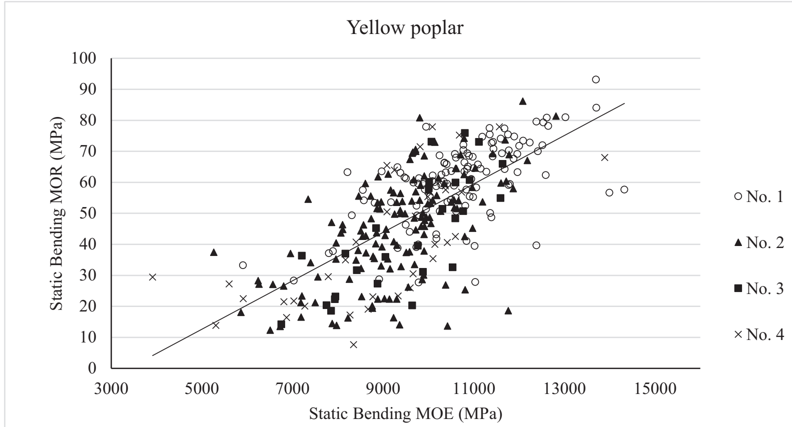

Figure 7.—Relationship between modulus of elasticity (MOE) and modulus of rupture (MOR) for yellow poplar lumber. Regression line shows the relationship for all observations and is not based on grades.

observation was further substantiated in a subsequent study by Kretschmann and Green (1999), which was centered on the mechanical grading of oak timber. Their study concluded that there is a noteworthy relationship between MOE and MOR in oak timbers.

These previous research endeavors align with the outcomes of this study, which similarly underscores the presence of a significant relationship between MOR and MOE and the importance of visual grading. Notably, all species examined during this study, across the various grades, met the minimum MOE requirements stipulated for the fabrication of CLT panels as specified in the ANSI/APA-PRG320 standard. Moreover, our regression analysis in this study provides robust evidence of a significant association between MOE and MOR across all species and grades. Considering these findings, it is rational to assert that MOE serves as a reliable indicator that the MOR values of all species tested across different grades would be sufficient to meet the demands of producing CLT panels intended for use in the timber industrial mats sector.

Conclusions

This study examined the physical and mechanical properties of three underutilized hardwood species of different grades using samples that represent the size and quality varieties of materials available in the US market. The goal of this work was to ascertain the potential use of these materials in the manufacture of CLT industrial mats. A comparison of the mean density of the different hardwood species associated with grade showed that all grades of red oak had a higher density than southern yellow pine and that the average density of sweetgum is similar to that of southern yellow pine, which is the traditional wood used in manufacturing CLT industrial mats.

An important finding of this research was that all species tested, regardless of grade, had a mean MOE that exceeded the required mean for lumber used in CLT manufacturing. This suggests that these hardwood species possess promising strength characteristics for meeting those required for production of CLT. Also, this study suggests that in some instances, higher grades of sweetgum and yellow poplar may be used in place of lower-grade red oak lumber, thereby

Table 3.—Coefficient of determination (R^2) and P-value for the relationship between density, modulus of elasticity (MOE), and modulus of rupture (MOR) for all species across grades.

		R^2 (coefficient of determination between variables)		
Species	Grade	Density and MOE	Density and MOR	MOE and MOR
Red oak	1	0.20 (0.3720ns)[a]	0.01 (0.8397ns)	0.24 (0.3283)
	2	0.12 (0.0052*)	0.03 (0.1862ns)	0.45 (<0.0001*)
	3	0.14 (0.0024*)	0.14 (0.0012*)	0.18 (0.0006)
	4	0.11 (0.0002*)	0.05 (0.0081*)	0.34 (<0.0001*)
	Overall	0.13 (<0.0001*)	0.04 (0.0007*)	0.38 (<0.0001*)
Sweetgum	1	0.06 (0.0249*)	0.34 (<0.0001*)	0.23 (<0.0001*)
	2	0.19 (<0.0001*)	0.21 (<0.0001*)	0.41 (<0.0001*)
	3	0.07 (0.0567ns)	0.04 (0.1563ns)	0.29 (<0.0001*)
	4	0.04 (0.0942ns)	0.06 (0.033*)	0.67 (<0.0001*)
	Overall	0.03 (0.0006*)	0.07 (<0.0001*)	0.47 (<0.0001*)
Yellow poplar	1	0.49 (<0.0001*)	0.34 (<0.0001*)	0.35 (<0.0001*)
	2	0.28 (<0.0001*)	0.07 (0.0011*)	0.34 (<0.0001*)
	3	0.07 (0.180ns)	0.07 (0.1755ns)	0.60 (<0.0001*)
	4	0.03 (0.2762ns)	0.08 (0.1038ns)	0.46 (<0.0001*)
	Overall	0.21 (<0.0001*)	0.09 (<0.0001*)	0.48 (<0.0001*)

* Significant at $P \leq 0.05$.
[a] P-value; ns = not significant.

encouraging the use of available species and grades. Furthermore, these results revealed a linear relationship between the MOE and MOR as well as evidence of normality and homoscedasticity for all species tested. This suggests that the MOE can serve as an indicator to determine if the MOR meets the required strength standard for CLT manufacturing. The importance of visual grading in determining lumber strength was also evident from these results. Specifically, as lumber grade decreased, there was also a noticeable decrease in both MOE and MOR. This highlights the importance of proper grading for ensuring the quality and performance of materials used in fabrication of CLT products.

Future studies are needed to further define the underlying viability of these underutilized hardwoods (red oak, yellow poplar, and sweetgum) and how these materials change over time. For example, evaluations of the natural biological durability against biodeterioration agents like basidiomycete decay fungi and termites and how they influence the physical and mechanical properties of this material are important for predicting service life. Field testing of fabricated hardwood CLT industrial mats exposed to environmental physical stressors is also important as well as evaluations related to adhesive failure, as these data will help to support the use of certain hardwood species in the manufacturing of CLT industrial mats and help create standards specifically intended for CLT mats. It is also important to consider the fabrication of CLT industrial mats by mixing the species, for instance mixing higher-density red oak with lower-density yellow poplar and exposing the fabricated CLT to mechanical and biological evaluation.

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