Variability in the Mechanical Properties of Commercially Available Thermally Modified Hardwood Lumber

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Research indicates that users of thermally modified wood lack information regarding the improved performance and any variations that may exist for the “same” product when manufactured by different companies. The goal of this study was to evaluate the variability in mechanical properties of three thermally modified hardwoods and determine the variability between three different manufacturers. To determine the hardness, bending (modulus of elasticity and module of rupture) and shrinkage values, testing was conducted following ASTM standard D143. The samples were conditioned at 20 °C and a relative humidity of 65% until they reached an equilibrium moisture content before testing. Analysis of variance was used to determine the variability within and between the different processes used by each company. Seven out of 18 (39%) tests indicated that there were statistical differences regarding the mechanical performances of the wood samples. Yellow poplar had the least variation between companies (only difference in equilibrium moisture content, EMC) and red maple had the most (hardness, tangential shrinkage, and EMC). While the means for these properties were statistically different, the differences in application for hardness and EMC are slight. For example, the largest difference between processes in hardness was 83.6 kg, for tangential shrinkage, 0.45% and 1.37% for EMC. These differences are suggested to be inconsequential when compared to the values that exist between different species of untreated wood.

Keywords: Thermally modified lumber; ANOVA; Yellow poplar; Red maple; White Ash; Mechanical properties; ASTM D143

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INTRODUCTION

One of the innovative products that has gained attention in the U.S. lumber market is thermally modified (TM) lumber, which has a large variety of exterior and interior uses including the following: musical instruments, guns stocks, decking applications, outdoor and indoor furniture, siding, roofing, door and window frames, and flooring. Thermally modified wood (TMW) has been available since the early 1990s in Europe, where it was developed as an alternative to tropical hardwoods and preservative treated wood for exterior applications. Tropical hardwoods are in high demand for furniture applications, with inelastic prices (Odoom 2001); they provide an alternative to chemically treated wood and are attractive due to regulations in place to reduce the use of toxic substances. Thermally modified wood products provide opportunities for the use of low-value timber, due to their increased performance against biological organisms and increased dimensional stability, potentially increasing the value of public and private lands with low-value wood, *i.e.*, lower value species, quality, and size (Baynes *et al.* 2014).

Thermally modified wood products have been available in the United States since 2004 when Westwood Corp started exhibiting thermally-treated wood products at fairs, and companies such as Jartek Inc. and Stellac Inc also started exhibiting TMW products (Sandberg and Kutnar 2016). By 2012, Canada and the United States had seven and ten manufacturers of TMW, respectively.

The adoption of TMW has had limited success according to Donahue and Winandy (2014), which is showcased by the low production levels reported by the United Nations Economic Commission for Europe (UNECE) and the Food and Agriculture Organization (FAO) (2013) in the Forest Products Annual Market review. These sources indicate that the volume production of TMW between 2012 and 2013 was around 315,000 m^3 in Europe and 100,000 m^3 in the United States. This was the last report from the Forest Products Annual Market review containing this information, since consumers and producers were hesitant to provide updated information.

Thermal modification is a great way to increase some of the physical performance characteristics of wood, *e.g.*, the durability against fungi, which is increased due to the degradation of hemicelluloses found in the wood, *e.g.*, sugars (Alen *et al.* 2012; Wardell 2015). Thermally modified wood products, such as decking, are competitively priced in comparison to traditional premium decking or tropical species such as Ipe wood. However, the current market for TMW in the U.S. is still hesitant to try this product (Gamache 2017), as more than three-fifths of the professional users of decking materials were not familiar with TMW products. Potential consumers still know little about the advantages and disadvantages of TMW, and there is an additional concern about the possible decrease in mechanical strength (Wang *et al.* 2012). Although there is some general knowledge that TMW could be more resistant to water absorption and have an increased resistance to decay, there is still no national or international consensus on TMW standards (Sandberg and Kutnar 2016; and Schnabel *et al.* 2007). Europe has technical specifications for spruce and pine, as shown in “DS/CEN/TS 15679 Thermally Modified Timber – Definitions and Characteristics”. Additionally, in Europe TMW has a certificate for “Quality Mark TMT”, certifying that the product conforms to the requirements of EN ISO/IEC 17067, which is specified by wood species, occasionally grading, manufacturers, and types of treatments. It is also certified with the “DIN 68800 Wood Preservation”. (CEN, 2007; EPH, 2015 and Willeitner 2012). The development of standards would provide safety and reliability and raise the confidence of users, which typically leads to market share expansion.

The mechanical properties (hardness, static bending, dimensional stability, and equilibrium moisture content, EMC) of TMW tend to vary based on the schedule used for modification. These schedules are the combination of treatment temperatures and treatment times, and atmosphere inside the kiln (air or nitrogen), which are different for each species (Esteves and Pereira 2008). Most of the samples had thickness of 1 inch. Thermally modified wood can be produced using a closed or open drying system. The way an open system works is that chamber decreases the moisture content in the chamber to 0% and then the system reinjects steam to condition the wood to a moisture content of 2%. A closed system maintains the steam in the chamber, creating additional pressure in the chamber (Ghiassi and Lourenço 2018). Figure 1 shows the differences in the process when working a closed system and an open system. During the thermal process, heat removes various organic compounds and changes the cellular structure, limiting the ability of the wood to absorb water (Sandberg and Kutnar 2016).

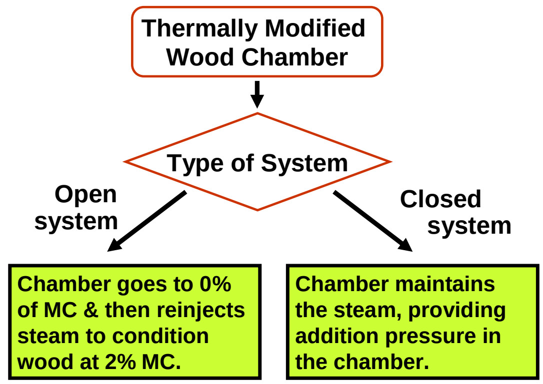

Fig. 1. Difference between open system and closed system (Ghiassi and Lourençọ 2018)

Performance metrics, *e.g.*, splitting, EMC, shrinkage and swelling, and water absorption show decreasing trends depending on the level of treatment (temperature levels and exposure times). Other properties, *e.g.*, durability, surface hardness, bending, and modulus of elasticity, increased under certain treatment conditions but decreased under others (Esteves and Pereira 2008).

The goal of this work was to evaluate the variability in mechanical properties of TMW made from yellow poplar (*Liriodendron tulipifera*), red maple (*Acer rubrum*), and white ash (*Fraxinus americana*), and determine the variability in certain mechanical properties between three commercial producers of these species.

EXPERIMENTAL

Methodology

The purpose of this evaluation was to determine variability in mechanical performance for TMW produced by the three companies. Three different TMW species were provided from three companies (sources) to measure their mechanical performance. ASTM procedures (ASTM D143 2014; ASTM D4442 2016; ASTM D49336 2016) were followed to conduct each mechanical test (hardness, static bending, EMC, and dimensional stability).

Each source used a different commercial system to thermally modify their wood. Company 1 used an open system, while company 2 used a closed system during their modification process. Company 3 was the only manufacturer that used both closed and open systems and, according to the experts in the company, obtained better results from a closed system. The samples provided by company 3 were modified with a closed system. The schedules used for these samples were not provided by the company for proprietary reasons.

The sample size was limited to 14 treated samples per species from each company, since the materials for each species were donated. The samples provided by each company were 1 inch thick. Each company donated a total of 42 samples for a total of 126 samples tested. Specimens for each specific test were prepared from different individual boards to increase reliability. The companies provided random samples selected from a single production batch, but were not able provide untreated samples, so there were no control values to compare the performance of the TMW. However, for the species tested, the average mechanical properties are well known (Hill 2007).

Once the specimens were cut to the dimensions required by each standard, the samples were stored in a temperature and humidity-controlled room with the conditions set to a temperature of 23 °C ± 2 °C and a relative humidity (RH) of 67% ± 1%. Each specimen was weighed each week. Once the weight of each specimen became constant over time, the sample was determined to have reached the equilibrium of moisture content and was ready to be tested. All samples’ weight was consistent over the weeks or the weight was increasing no more than 0.01 pounds.

Hardness Testing Using ASTM Standard D143 (Modified)

Hardness is defined as the resistance of wood to indentation using a 25.4 mm ball, also known as the Janka hardness test, and it was measured using the ASTM standard D143 (2014). All specimens were weighed before and after testing. To determine how the thermal modification effected the performance of the surface hardness by using ASTM standard D143 (2014) testing methods, the specimens were cut to dimensions of 1 in by 2 in by 6 in (50.8 mm by 50.8 mm by 152.4 mm). The test used a ball of 0.444 inches in diameter, with a projected area of the ball on the test specimen of 1 cm^2, with two penetrations on the tangential surface.

Static Bending (MOE, MOR) Testing Using ASTM Standard ASTM D143

ASTM standard D143 (2014) was used to measure the performance of the TMW in terms of static bending, with a specimen size of 1 in by 1 in by 16 in (25 mm by 25 mm by 410 mm). The load-deflection curves were recorded, and the testing was finished after the maximum load was reached for all static bending tests.

Radial and Tangential Shrinkage Testing Using ASTM Standard D143 (Modified)

ASTM standard D143 (2014) was used to determine the dimensional stability performance by estimating the radial and tangential shrinkage. The specimen size was modified to dimensions of 0.75 in by 0.75 in by 1 in (19 mm by 19 mm by 25 mm), due to dimensional limitations by the lumber provided.

The specimens were weighed, and their length was measured before undergoing oven drying. The oven was set to a temperature of 103 °C ± 2 °C until a constant mass was reached. Once the specimens reached a constant mass, their weight and length were measured again.

Equilibrium of Moisture Content (EMC) Testing Using ASTM Standard D4933

ASTM standard D4933 (2016) was used to precisely estimate the equilibrium of moisture content (EMC) of each treatment, company, and species. The size of each specimen was 19 mm by 25 mm by 19 mm. The first step was to condition the samples until they reached a constant mass under the following conditions: a temperature of 21 °C and a RH of 65%. Periodic weighing was performed to record the mass changes and make sure the mass was constant over time. Then the samples were oven-dried at a temperature of 103 °C for at least 2 d, until a constant mass was reached, and the mass was recorded to estimate the EMC percentage of each sample.

RESULTS AND DISCUSSION

A normality test was conducted before an analysis comparing the statistical differences between companies was conducted. For the data that did not fit the normal distribution, instead of an ANOVA, a non-parametric test, *i.e.*, a Kruskal-Wallis test, was conducted. The results of the normality test compared to an alpha of 0.05 are shown in Table 1.

Table 1. Normality Test for Each Species

Species	Test	*p*-value	Normal Distribution
Yellow poplar	Modulus of elasticity	0.862	Yes
Yellow poplar	Modulus of rupture	0.315	Yes
Yellow poplar	Hardness	0.374	Yes
Yellow poplar	Radial shrinkage	0.893	Yes
Yellow poplar	Tangential shrinkage	0.234	Yes
Yellow poplar	Equilibrium of moisture content	0.893	Yes
Red maple	Modulus of elasticity	0.292	Yes
Red maple	Modulus of rupture	0.007	No
Red maple	Hardness	0.356	Yes
Red maple	Radial Shrinkage	0.006	No
Red maple	Tangential Shrinkage	0.005	No
Red maple	Equilibrium of moisture content	0.080	Yes
Ash	Modulus of elasticity	0.649	Yes
Ash	Modulus of rupture	0.231	Yes
Ash	Hardness	0.799	Yes
Ash	Radial Shrinkage	0.000	No
Ash	Tangential Shrinkage	0.280	Yes
Ash	Equilibrium of moisture content	0.085	Yes

While the focus of this work was to evaluate the differences in the properties between the commercial systems, a comparison of the author's results to the untreated values from literature also added insight into the potential improvements that these processes provide.

Modulus of Elasticity (MOE)

There were significant differences in the MOEs between the three commercial processes for white ash, as shown in Table 2.

Table 2. Modulus of Elasticity Results

Test	Species	*p*-value
MOE	Yellow poplar	0.762
MOE	Red maple	0.140
MOE	Ash	0.002

A graphical representation of the means and standard deviation for the ash samples is shown in Fig. 2, where the bar plot shows that the mean value from company 1 was higher than the other two companies, and that the mean values between company 1 and company 3 were the same. An explanation for this behavior could be related to company 1 using a different system, *i.e.*, an open system, to thermally treat the wood, whereas company 2 and company 3 both used a closed system. However, it should be noted that all companies used different schedules for their thermal modification process. For MOE, an open system showed better performance in comparison to a closed system.

Boonstra *et al.* (2007) suggest that the increases in MOE due to thermal modification is related to the "degradation of the hemicelluloses, disrupting the load-sharing capacity of the lignin-hemicelluloses matrix, and increase of the relative amount of crystalline cellulose." They also suggest that increased cross linking of the lignin network increased the rigid structure around the cellulose microfibrils/fibrils and improves the strength of the middle lamella.

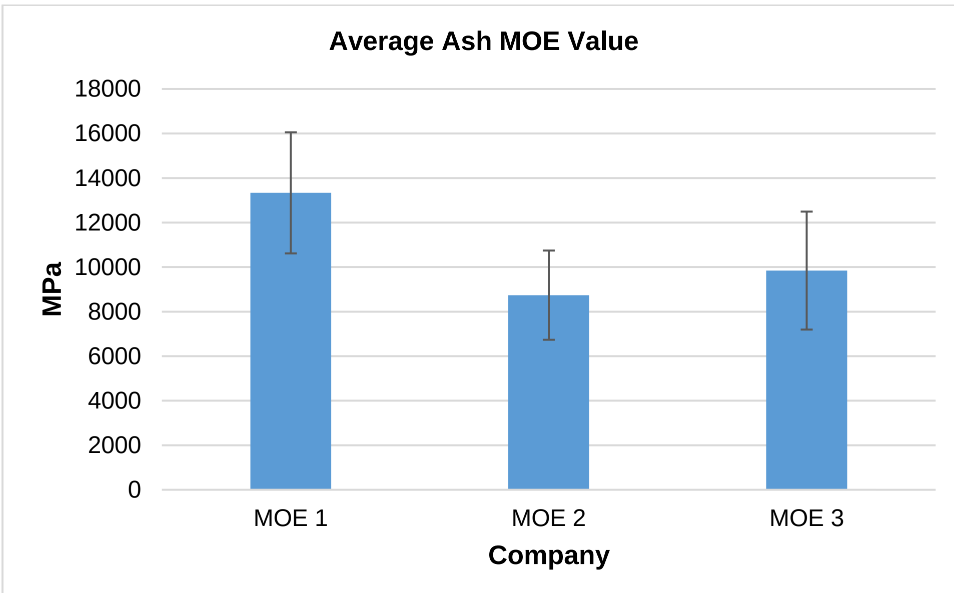

Fig. 2. Average and Standard Deviation for Ash MOE Values for the product of each company.

Table 3. Descriptive Statistics for the MOE Test Results

Company	Species	Test	Mean (MPa)	Std. Dev.	Coef. Var.	Median (MPa)
1	Yellow poplar	MOE	12502	2287	18.30	12710
2	Yellow poplar	MOE	12868	2260	17.56	12885
3	Yellow poplar	MOE	12229	2323	19.00	12025
1	Red maple	MOE	13260	874	6.59	13271
2	Red maple	MOE	13058	1366	10.46	13376
3	Red maple	MOE	14646	1022	6.98	14727
1	Ash	MOE	13336 (A)	2719	20.39	13971
2	Ash	MOE	8740 (B)	2004	22.93	9336
3	Ash	MOE	9844 (B)	2649	26.91	10118

The average MOE values for the TM yellow poplar samples from the three companies were higher than the value reported for untreated materials (10900 MPa) (Hill 2007). The TMW samples showed a performance increase of 14%, 17%, and 12% for company 1, company 2, and company 3, respectively. A similar trend occurred with red maple, where the MOE value for the untreated red maple lumber was 11300 MPa (Hill 2007). The ash values from company 1, company 2, and company 3 showed an incremental performance increase of 16%, 19%, and 26%, respectively. Ash was the only species to show a different trend, where the samples from company 2 and company 3 had a 31% and 20% lower MOE than untreated ash (12000 MPa) (Hill 2007). However, Company 1 had an 11% increase in MOE compared to the untreated MOE value. The difference in MOE performance for ash could be related to species and schedule differences, as suggested by Esteves and Pereira (2008). However, this seems unlikely, given the same behavior was not noticed for yellow poplar or red maple. Another factor to consider is that company 1 used an open system to treat their lumber, while company 2 used a closed system, and company 3 used both systems. The expected outcome for all three species was an increase in MOE as suggested by Donahue *et al.* (2011), who reported a slight increase in MOE (from 11100 MPa to 12258 MPa) for yellow poplar that was thermally modified using the ThermoWood ® treatment. The coefficient of variation shown was highest for ash, indicating that there was a greater level of dispersion around the mean. This was likely due to the small sample size and/or high variability within the process.

Modulus of Rupture (MOR)

No significant differences in the MOR values were found between the three companies, indicating that the different systems and schedules used in thermal modification did not affect the MOR performance. Table 4 shows the results obtained from the MOR testing for the three species studied.

Table 4. Modulus of Rupture Results

Test	Species	*p*-value
MOR	Yellow poplar	0.164
MOR	Red maple	0.258*
MOR	Ash	0.124
Note: an asterisk (*) means that the data was not normally distributed, and a Kruskal-Wallis test was conducted instead.		

The standard deviation, the mean, and median values for each company are displayed in Table 5. The mean values obtained from the tests conducted showed that for yellow poplar the values were between 64.3 and 81.2 MPa, for red maple the values were between 75.7 and 88.87 MPa and for ash the values were between 49.5 and 68.2 MPa. Results from Adewopo and Patterson (2011) gave mean values between 107.6 and 140.5 MPa for red oak, and between 81.5 and 110.7 MPa for sweetgum, showcasing a higher performance for these species compared to the three species treated in this study. The species treated by Adewopo and Patterson (2011) used the following conditions: a treatment temperature between 93 °C and 204 °C and a treatment duration between 2 h to 8 h. These conditions could have contributed to the better performance obtained by Adewopo and Patterson (2011), when compared to the species in this study.

Table 5. Descriptive Statistics for the MOR Test Results

Company	Species	Test	Mean (MPa)	Std. Dev.	Coef. Var.	Median (MPa)
1	Yellow poplar	MOR	77.09	26.13	33.89	80.34
2	Yellow poplar	MOR	81.2	18.63	22.94	83.68
3	Yellow poplar	MOR	64.27	26.49	41.22	65.78
1	Red maple	MOR	75.71	25.82	34.11	81.79
2	Red maple	MOR	88.87	21.64	24.35	93.03
3	Red maple	MOR	79.54	22.58	28.39	87.43
1	Ash	MOR	49.53	18.33	37.02	54.35
2	Ash	MOR	68.17	18.04	26.47	67.10
3	Ash	MOR	56.97	19.83	34.80	55.33

The MOR values for the TM yellow poplar from company 1 and company 2 were higher (10% and 15%, respectively) than the MOR values for unmodified wood reported by Hill (2007) (69.7 MPa). However, the MOR value for company 3 was 8% lower than the value reported by Hill (2007). The TM red maple samples from all three companies had lower values than that the values reported for unmodified wood (92.0 MPa) (Hall, 2007). The average MOR value for company 1, company 2, and company 3 showed a decrease in performance of 19%, 4%, and 15%, respectively. A similar trend occurred with ash, where the obtained MOR value for untreated ash (Hill 2007) was 103.0 MPa, and the values from company 1, company 2, and company 3, were 70%, 41% and 58% less, respectively. The coefficient of variance showed higher values for every test that was perform, which is expected since the samples showed different levels of resistance to fail, this resulted on having values that are not similar and high dispersion.

The author's results were similar to those obtained by Donahue *et al.* (2011) for yellow poplar, who reported a slight decrease in performance for MOR, from 103 MPa to 97 MPa. The average values reported by Donahue *et al.* (2011) were also higher than the values obtained by the authors. Literature suggests that thermal modification can result either an increase (Donahue *et al.* 2011; Esteves and Pereira 2009) or a decrease (Stamm *et al.* 1946; Bengtsson *et al.* 2002; Esteves and Pereira 2009) in MOR and given the mixed results between species for this work, the authors hypothesize that the differences noted were due to the different schedules used by each company for each species.

Hardness

There was no significant difference in the hardness values for the different companies for both the yellow poplar and ash samples (as shown in Table 6).

Table 6. The *p*-values for Yellow Poplar, Red Maple, and Ash Samples

Test	Species	*p*-value
Hardness	Yellow Poplar	0.324
Hardness	Red Maple	0.007
Hardness	Ash	0.565

The red maple samples showed a statistical difference between the average hardness values for the three companies, which indicated that the system used, or the schedule, influenced the hardness. The results of the Tukey test are presented in Fig. 3, where the plot shows that company 2 had higher hardness values in comparison to company 1 (18%) and company 3 (12%) and the mean values were similar between company 1 and company 3.

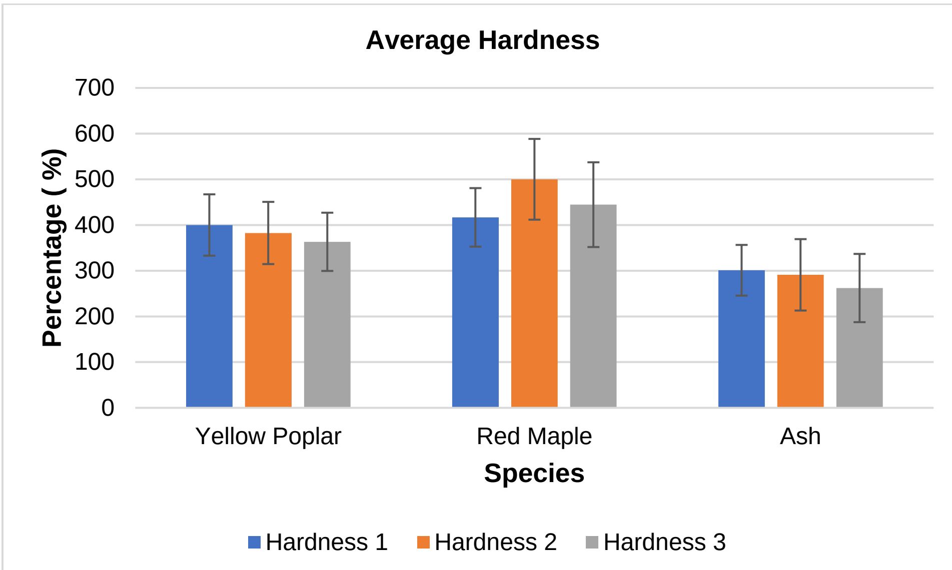

Fig. 3. Average and standard deviation for the hardness values

The descriptive statistics from the hardness tests (Table 7), indicated that the red maple hardness values for the company 1 and company 2 were lower than the mean hardness values for company 3 samples, and even with high standard deviation values.

Table 7. Descriptive Statistics for the Hardness Test Results

Company	Species	Test	Mean (kg)	Std. Dev.	Coef. Var.	Median (kg)
1	Yellow poplar	Hardness	291.02	78.11	26.85	266.94
2	Yellow poplar	Hardness	301.00	55.43	18.42	295.15
3	Yellow poplar	Hardness	262.13	74.66	28.48	248.93
1	Red maple	Hardness	416.76 (A)	67.09	16.10	425.02
2	Red maple	Hardness	500.04 (B)	68.08	13.61	486.25
3	Red maple	Hardness	444.52 (B)	63.73	14.34	430.82
1	Ash	Hardness	382.56	88.36	23.09	400.07
2	Ash	Hardness	400.02	64.05	16.01	386.82
3	Ash	Hardness	363.24	92.71	25.53	376.48

The hardness values obtained for all three TMW species were lower than to untreated wood (335 kg to 672 kg); values (Hill 2007). Specifically, thermally modified yellow poplar hardness was 3% to 15% lower than untreated hardness 430.9 kg, red maple (same words, different data as YP), and ash (same words, different values). The decrease in hardness between the manufacturers could have been due to the different schedules used and the use of different systems (closed *vs*. open) to treat the lumber. The hardness values reported for TMW are often contradictory, with some reporting higher values and others reporting lower values (Esteves and Pereira 2009). For North American hardwoods, lower hardness values are typically found (Donahue *et al*. 2011; Salca and Hiziroglu 2014; Sandberg and Kutnar 2016). While many have reported lower hardness values for TMW, none have clearly identified the chemical, macro, or micro-structural changes directly responsible; only broad suggestions have been indicated, such as hardness decreases with to deterioration of the cell wall structure after the heat treatment Salca and Hiziroglu (2014). The influence of thermal modification on cell wall structure has been reviewed (Esteves and Pereira 2009). The authors' hardness results are similar to those obtained by Donahue *et al*. (2011), where the hardness values yellow poplar and basswood at treatment temperatures of 200 °C and 210 °C, decreased from untreated values between 0% to 9% for basswood and between 38% to 54% for yellow poplar. The coefficient of variance showed higher values for company 1 and 3 for each specie studied. This could be addressed due to low amount of samples studied and high dispersion of the results obtained.

Equilibrium of Moisture Content (EMC)

There was a significant difference in the EMC values between the companies for the three species studied under the following conditions: a temperature of 21 °C and a relative humidity (RH) of 65%. The results are summarized in Table 8.

Table 8. EMC Test Results

Test	Species	*p*-value
EMC	Yellow poplar	0.000
EMC	Red maple	0.000
EMC	Ash	0.000

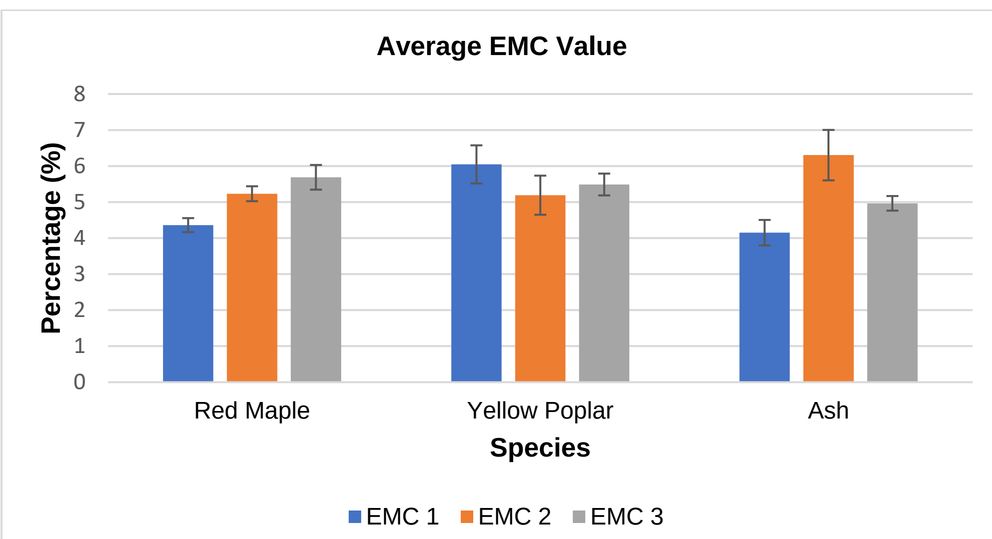

Fig. 4. Average and standard deviation for the EMC values from three companies

Figure 4 show the interval plot and the confidence intervals for each mean. These confidence intervals showed that none of the EMC values obtained had the same mean values between companies for any of the species studied. The difference in EMC values between the companies was significant for each species, and all mean values fell withing the range of 4% to 6% (Table 9), which indicated a large reduction in EMC from unmodified wood (12% EMC).

Table 9. Descriptive Statistics for the EMC Test Results

Company	Species	Test	Mean (%)	Std. Dev.	Median (%)
1	Yellow poplar	EMC	6.046 (A)	0.529	6.159
2	Yellow poplar	EMC	5.191 (B)	0.543	5.234
3	Yellow poplar	EMC	5.488 (B)	0.302	5.496
1	Red maple	EMC	4.360 (A)	0.194	4.317
2	Red maple	EMC	5.232 (B)	0.207	5.185
3	Red maple	EMC	5.688 (C)	0.343	5.630
1	Ash	EMC	6.303 (A)	0.700	6.200
2	Ash	EMC	4.151 (B)	0.350	4.001
3	Ash	EMC	4.934 (C)	0.228	4.930

The EMC values from the three companies for each wood species studied showed statistically significant differences. For yellow poplar, the EMC of wood from company 1 was 15% higher than that from company 2 and 10% higher than wood from company 3. For red maple, the EMC for wood from company 2 was 18% higher than that from company 1 and the 26% larger than that from by company 3. For ash, the EMC of wood from company 1 was 41% higher than that from company 2 and 17% higher than wood from company 3. The results obtained showed that company 2 and company 3 tended to have similar values again, while company 1 had different values. This could be due to company 1 using an open system. In a closed system, the steam stays in the chamber, which creates pressure. An open system reduces the moisture content to 0% and eliminates steam from the chamber and then reinjects the steam to condition the wood.

While the difference in EMC values between the companies was significant for each species, all mean values fell within the range of 4% to 6% (Table 9), which indicated a large reduction in EMC from unmodified wood at 12% EMC, as estimated by the Hailwood-Horribin model (Simpson 1998). Simpson also stated that while the Hailwood-Horribin model estimates can be influenced by hysteresis and extractive consent, they can be "considered reasonable estimates for practical applications." For example, Bond *et al.* (2018) found that for yellow- poplar conditioned at 20 °C and 70% relative humidity the average EMC was 10.8%, only 1.2% below the Hailwood-Horribin model.

These results showed small differences, due to the low variability between the samples and how similar the results were for each company, which were attributed to the different schedules used by the companies for each species. In treatments with a high exposure time and temperature, the EMC tended to decrease.

Dimensional Stability

The shrinkage for the tangential sections of yellow poplar had no statistical differences, but the red maple and ash samples had statistical differences between the three companies (Table 10). For the radial section, the three species had *p*-values greater than 0.05, meaning that there were no statistical differences between the companies.

Table 10. Dimensional Stability Test Results

Test	Species	*p*-value
Shrinkage-tangential	Yellow poplar	0.356
Shrinkage-tangential	Red maple	0.002*
Shrinkage-tangential	Ash	0.034
Shrinkage-radial	Yellow poplar	0.178
Shrinkage-radial	Red maple	0.299*
Shrinkage-radial	Ash	0.922*
Note: an asterisk (*) means that the data was not normally distributed, and a Kruskal-Wallis test was conducted instead		

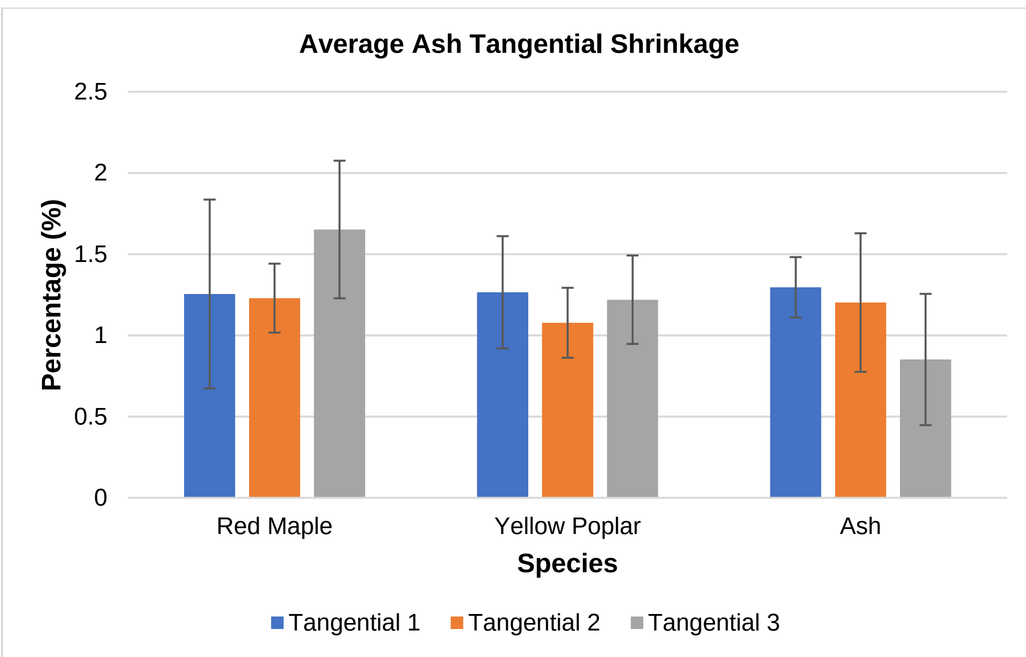

Fig. 5. Average and standard deviation for the three species´ tangential shrinkage results from three companies

Figure 5 displays the Tukey analysis for the tangential section of the species studied. The results showed that company 1 had higher shrinkage values in comparison to the other two companies, and means were shared between companies 1 and 2. Table 11 shows the descriptive statistics for the dimensional stability test, which showed low standard deviation values and similar values between the mean and the median.

Table 11. Descriptive Statistics for the Dimensional Stability Test Results

Company	Species	Test	Mean (%)	Std. Dev.	Median (%)
1	Yellow poplar	Radial shrinkage	1.21	0.33	1.24
2	Yellow poplar	Radial shrinkage	1.07	0.19	1.05
3	Yellow poplar	Radial shrinkage	1.01	0.33	1.05
1	Red maple	Radial shrinkage	1.02	0.28	1.05
2	Red maple	Radial shrinkage	0.93	0.33	0.96
3	Red maple	Radial shrinkage	1.17	0.33	1.02
1	Ash	Radial shrinkage	1.11	0.63	0.97
2	Ash	Radial shrinkage	0.87	0.30	0.78
3	Ash	Radial shrinkage	0.97	0.59	0.73
1	Yellow poplar	Tangential shrinkage	1.27	0.40	1.20
2	Yellow poplar	Tangential shrinkage	1.08	0.10	1.10
3	Yellow poplar	Tangential shrinkage	1.22	0.40	1.20
1	Red maple	Tangential shrinkage	1.26 (A)	0.30	1.10
2	Red maple	Tangential shrinkage	1.22 (A)	0.20	1.10
3	Red maple	Tangential shrinkage	1.65 (B)	0.30	1.70
1	Ash	Tangential shrinkage	1.30 (A)	0.58	1.32
2	Ash	Tangential shrinkage	1.20 (B)	0.21	1.19
3	Ash	Tangential shrinkage	0.85 (C)	0.42	0.86

Overall, two of the six tests conducted showed statistical differences, and the remainder showed no statistical differences, meaning the companies had similar results regarding dimensional stability performance. As mentioned in the literature review of ASTM standard D4933 (2016), dimensional stability is improved due by a decrease in equilibrium of moisture content, which primarily occurs due to a decrease of wood hygroscopicity affected by high temperatures (Dirol and Guyonnet 1993).

The dimensional stability for the tangential surface showed statistical differences for the red maple and ash samples. The difference of the tangential surface of red maple between company 1 and company 2 was 30%, and the difference between company 1 and company 3 was 27%. The difference for ash in the tangential surface between company 2 and company 3 was 34%, and the difference between company 2 and company 3 was 42%. For the ash values, the difference was more prominent, but when the values were compared to the untreated values, the performance was better. These improvements are discussed in the next section.

The results highlighted that the commercial processes had different schedules and technologies to thermally modify the wood. These schedules might vary between species and dimensions from each company. Sixty-one percent of the tests conducted showed that the performance of the wood samples was similar between companies.

There was a high likelihood of getting a different product from different companies, since these companies used different schedules and had different production systems, but the performance of the product between companies were practically similar. From an application perspective, the statistical differences, schedules, and systems used were not important since there was an incremental increase in dimensional stability and EMC performance. The yellow poplar samples showed little difference between the companies; the only difference was in the EMC values, which only varied 5% to 6%. This was evidence that consumers (architects) could obtain yellow poplar from any producer and expect similar performance; any difference would be so small in actuality that the consumer would not notice. The red maple samples showed statistical differences. Company 2 had a better hardness performance value, meaning that their product was better for flooring applications, and company 3 showed better performance for dimensional stability, which was better for siding applications. Regarding durability and static bending performance, red maple was not different from company to company. The ash samples showed that the MOE values for company 1 were higher, which was better for decking applications. The dimensional stability was the same for company 1 and company 2, while the performance was lower for the tangential section of wood produced by company 3. The performance of ash from the three companies was similar from a practical perspective. The EMC values improved from a MC of 12% to a MC of 5% for the three species, the radial shrinkage improved from a value of approximately 5% to a value of 1%, while the tangential shrinkage, with values ranging from 7% to 8%, improved to 1%.

As demonstrated by the performance obtained from each species and company, and the commercial processes obtained from the companies studied, TMW is starting to settle into a performance baseline within the industry. Producers continue to work on optimal schedules and practices for TMW.

Future work should include looking in the performance variability within each company's processes for each species, which would allow for developing increased quality control measures. Willems *et al.* (2015) suggests that to obtain a reliable product, it is necessary to have quality controls. Having uniform quality control methods may increase the opportunity to achieve similar performances for the three companies and species studied.

CONCLUSIONS

1. Seven out of 18 (39%) tests conducted indicated that there were statistical differences regarding the mechanical performances of the wood samples. However, from an application point of view, these differences are likely not noticeable in service, as all are a significant improvement over the properties of un-modified wood.
2. There was no difference between the hardness, MOE, and dimensional stability for yellow poplar between the three companies, indicating that the different schedules and processes resulted in in the same performance for these properties. However, the EMC for yellow poplar were significantly different between the three companies. None of the companies shared any of the mean values but, compared to the theoretical values of untreated wood, determined by the Hailwood-Horrobin equation (Simpson 1998), the values obtained for the samples provided by the three companies showed an improved performance for the EMC values. The improved performance shows that consumers can purchase TMW products from any of the producers and expect to get a product with a significant reduction in EMC.
3. The MOR, MOE, and radial shrinkage values for red maple showed no significant difference between the companies studied, indicating that the different schedules and processes resulted in in the same performance for these properties. However, there were

differences in hardness and tangential shrinkage values between the three companies. Company 2 had a 13 to 14% greater hardness value than company 1. Company 1 had 27% and 30% higher tangential shrinkage values than companies 2 and 3, respectively.

4. For white ash, there were no significant difference in values of MOR, hardness, and tangential shrinkage values. There were differences between MOE, EMC, and radial shrinkage values between the three companies, indicating that the schedule and process used influences these properties in white ash.
5. Statistical differences between the mean values for EMC and dimensional stability were found between the companies for yellow poplar, red maple, and ash. However, for all three companies, each species showed a significant reduction in both EMC and dimensional stability when compared to untreated wood values reported in the Wood Handbook (USDA, 2010).

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