# MECHANICAL PROPERTIES OF UNDERUTILIZED SPECIES IN NORTHWESTERN ONTARIO

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# ABSTRACT

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Keywords: Bioeconomy, *Betula papyrifera,* forest industry, *Larix laricina,* mechanical properties, Ontario, *Picea glauca, Populus tremuloides,* property testing, wood products.

Increasing the utilization of available wood supply is becoming more important in sustaining market demand and developing future opportunities for Ontario's wood products in the growing bioeconomy. The objective of this paper is to determine the mechanical properties of commonly underutilized species in Ontario to identify possible commodity and value-added uses. In this study, four boreal species were measured to determine the basic mechanical properties. Each species was tested for modulus of elasticity (MOE), modulus of rupture (MOR), density and compression characteristics. The results concluded in statistically accurate MOR, MOE, density and compression values for each of the four species. Possible market opportunities and value-added uses for the species are viable.

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## ACKNOWLEDGMENTS

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# 1.0 INTRODUCTION

The global market demand for traditional forest products has continued to decline since the financial crisis of 2008 (Majumdar et al. 2017). This has had a long and significant impact on Ontario's forestry sector and Canadian economy at large (Majumdar et al. 2017). Globalization has further pressured these issues by increasing demand for natural resources, escalating environmental degradation, and increasing competition in natural resources industries (NRCAN 2020). Ontario's forest industry needs to generate new innovations and new markets to reinvigorate its position. The emerging bioeconomy provides an opportunity for the forest industry to take advantage of a multitude of economic benefits while simultaneously supporting sustainable development objectives (Maloney 2018; Dietz et al. 2018; EESC 2018).

The forest bioeconomy can provide uses for more than just the bole of the tree, for example the slash, bark, spent pulping liquor, wood shavings, and sawdust (Puddister et al. 2011). Bioenergy, biochemicals, and biomaterials are created from parts of trees that are left as harvesting residues, burned in slash piles, or become landfill (Majumdar et al. 2017). Many are aligned with a sector of the industry, for example bioenergy exists in many pulp mills and lumber mills using waste stream by-products to produce electricity and heat (Balat and Ayar 2003). Many pulp mills are aligned with chemical biorefinery opportunities recovering valuable chemicals from their spent liquors (Van Heiningen 2006). Biomaterials cover a wide range of products that are manufactured from trees processed in different ways. Engineered wood products such as glue-laminated timber, cross-laminated timber, oriented strand lumber, and oriented strand board are one avenue of biomaterials that is growing in demand within Canada and internationally (UNECE 2017). Improving utilization of species through engineered wood products provides an opportunity to add value beyond the traditional lumber and pulp industries (Majumdar et al. 2017).

The utilization of white birch (*Betula papyrifera* Marsh.), eastern larch (*Larix laricina* (Du Roi) K. Koch.), trembling aspen (*Populus tremuloides* Michx.), and white spruce (*Picea glauca* (Moench) Voss.) in Ontario's forest sector is mainly in construction lumber, structural engineered products, panel board products, and pulp and paper. There is a significant change in the wood market away from traditional structural products towards engineered wood and value-added products (WAI 2003). These markets can provide better utilization of commercial and under-utilized tree species increasing the overall value of the harvest. Understanding the wood properties of Ontario's tree species contributes to finding alternative end-products and markets that increase their utilization and value (Pers. Comm. M. Leitch).

The physical, chemical, and mechanical properties of a species largely impact their suitability for end-uses and potential value-added. The common mechanical properties tested for the purpose of engineering wood products are modulus of elasticity (MOE), modulus of rupture (MOR), and compression parallel to the grain (Record 1914). Mechanical and physical properties are closely correlated to the density of the wood thus density is a useful measurement to understanding the strength of the wood (Shmulsky and Jones 2019).

The literature review will focus on; species distribution, habitat conditions, limitations to harvesting, physical and mechanical properties, current utilizations, as well as the value-added potential.

Research was guided by the following questions: What is the current extent of harvesting for each species? What are the current utilizations of each species? How can the mechanical properties determined in this study increase their market value?

## 1.1 OBJECTIVE

The objective of this study is to determine the mechanical properties of white birch, Eastern larch, poplar, and white spruce from the Thunder Bay Ecoregion (3W) in order to increase their utilization and market value potential.

# 2.0 LITERATURE REVIEW

## 2.1 SPECIES

### 2.1.1 White Birch

White birch grows on a wide variety of sites in mixed-forests or in pure stands (Farrar 2016). It is shade-intolerant and typically an early colonizer following disturbance (Farrar 2016). Its leaves, buds, and seeds are an important source of food for many birds and animals (MNRF 2016). Mature trees are 21-24 m tall and commonly 25-30 cm in diameter in good natural form (Uchytil 1991). They are a short-lived species with most trees living less than 120 years (Uchytil 1991). White birch comprises 8% of Ontario's growing stock (MNRF 2016). Clearcutting with scarification is the most common silvicultural system used for white birch, although many other systems are applicable (Uchytil 1991).

### 2.1.2 Eastern Larch

Eastern larch or tamarack is found on cold, wet, and poorly-drained sites (Farrar 2016). It is common in sphagnum bogs and muskegs, although it is found to grow better on moist, well-drained, light soils (Farrar 2016). Tamarack is a shade-intolerant species often first to colonize bogs and organic sites after fire in the boreal (Burns and Honkala 1990). It is often observed to self-prune, developing clear bole lengths in 25-30 year-old trees (Burns and Honkala 1990). Mature trees are 15-23 m in height and generally 46-51 cm in diameter (Uchytil 1991). They live up to 140 years (Uchytil 2991). Tamarack is found in low proportions comprising only 1.5% of Ontario's growing stock volume (MNRF 2016). Even-aged management is suggested with a clearcut adaptation or seed-tree cutting considered the best silvicultural system as it germinates better in open (Johnston 1990). However, reestablishment often requires site preparation such as slash disposal and herbicide (Burns and Honkala 1990).

### 2.1.3 Poplar

Poplar, or trembling aspen, occurs on a variety of sites often in pure stands (Farrar 2016). It is an aggressive pioneer species and major cover type due to its root suckering capabilities (Howard 1996). Often poplar only lives up to 70 years old (Howard 1996). Poplar provides important breeding, foraging, and resting habitat for many birds and mammals (Howard 1996). It commonly grows to 15 m in height and 40 cm in diameter, however good form deteriorates with age. Poplar represents 22% of Ontario's growing stock volume (MNRF 2016). Prescribed burning and clearcutting will promote the growing conditions for poplar (Howard 1996). Over time, pure poplar stands tend to deteriorate as other conifers succeed to replace the forest (Farrar 2016; Howard 199).

### 2.1.4 White Spruce

White spruce occurs in a variety of sites and climate conditions (Farrar 2016). Favorable seedbeds for white spruce are mineral soils, thin organic soils, and rotten downed woody debris (Abrahamson 2015). Establishment occurs throughout stand development, including early and late-succession following fire disturbance (Abrahamson 2015). Many wildlife species use late-seral white spruce cover for important habitat (Abrahamson 2015). Mature trees are typically 25-28 m tall and 60-90 cm in diameter (Abrahamson 2015). They typically have a straight bole with vertically continuous branches (Abrahamson 2015). White spruce has a moderate lifespan living 100-250 years (Abrahamson 2015). White spruce represents 4% of Ontario's growing stock volume (MNRF 2016). Regeneration of white spruce following harvest usually requires scarification or planting (Abrahamson 2015).

## 2.2 WOOD PROPERTIES

### 2.2.1 Chemical and Physical Properties

The physical, chemical, and mechanical properties of each species largely impact their suitability for end-uses and potential value-added. Relevant characteristics for each species are broadly summarized in Table 1.0. Each of these characteristics, alone and in combination, determine the possible uses or have differentiating characteristics which may prove higher value in one market than another (Mullins and McKnight 1981).

Earlywood and latewood colour and function influences both value in appearance and value over time (Mullins and McKnight 1981). Their final form in the wood is dependent on the age, species, and rate of growth (Mullins and McKnight 1981). After a number of years, the tree ceases to produce sap and organic substances; the extractives fill the cells forming the heartwood (Mullins and McKnight 1981). These extractives can have various applications including oils, tannins, gums, dyes, and glues used in food preservation to medicine (De Jong and Gosselink 2014). Spruce has relatively low content of extractives leaving the colour pale, whereas eastern larch has a high content giving a prominent colour. The amount, of extractives in the heartwood is also related to durability, weight, resistance to decay and permeability (Mullins and McKnight 1981). Depending on the end-use, these features may be advantageous or limiting.

The presence of extractives can increase the decay resistance from fungi (Woodard and Milner 2016). Extractives can limit the permeability in the formation of tyloses (Woodard and Milner 2016). Low permeability is proved advantageous in the use of certain species for barrel staves where tight cooperage is desired (Woodard and Milner 2016). However, for other uses, low permeability can make preservative treating more difficult (Wheeler 2001). Extractives can cause greater density and weight which are important factors for use in construction (Woodard and Milner 2016). Extractives may cause slight increases in the compressive strength and hardness (Mullins and McKnight 1981).

Colour, grain texture, grain figure, and deviations of these characteristics formed by the earlywood, latewood, and heartwood can provide visual aesthetics to the end-user. Pattern making and colour in the carving and design of the product may be considered when differentiating between species (Mullins and McKnight 1981).

Shrinkage can affect visual and structural properties of the wood. Shrinking and swelling occur as the wood changes moisture content in response to relative humidity and temperature of the environment (Ecklemen n.d). It is influential in the loss of value during the drying process (Mullins and McKnight 1981). Shrinkage can also vary in earlywood and latewood and is affected by the density of the species (Mullins and McKnight 1981). End-uses must consider the ease and cost of drying.

Table 1.0. Summary of physical and mechanical wood properties per species.

| Characteristic | White spruce | Eastern larch | White birch | Poplar |
|---|---|---|---|---|
| Relative common size | Medium in height and diameter | Small to medium in height and diameter | Medium-tall in height and medium diameter | Medium-tall in height and medium diameter |
| Colour of the wood | Creamy white, hint of yellow | Heartwood is generally yellow-brown to brown, sapwood is whiteish | Creamy white, brownish core | Light in colour, white to greyish-white |
| Growth-ring figure | Distinct | Prominent | Faint | Faint |
| Transition from earlywood to latewood | Gradual | Abrupt | Conspicuous | Conspicuous |
| Texture and grain | Fine and even texture, consistently straight grain | Coarse texture, commonly spiral grain | Fine and even texture, uniform grain | Fine texture, uniform grain |
| Weight (air-dry) | Moderate | Moderate | Moderate | Light |
| Strength | Weak to moderate bending and compressive strength, moderate stiffness, low in impact resistance | High bending and compressive strength, low resistance to impact | Generally a strong and hard wood, lower resistance to sudden impact | Medium strength, resistance to wear is high considering its low-density |
| Shrinkage | Moderate shrinkage, seasons well | Moderate shrinkage, tendency to warp, requires above average care | High shrinkage, seasons satisfactorily but slow | Moderate shrinkage, seasons satisfactorily, slightly more care required |
| Other properties | Glues well, little tendency to split, low ability to hold nails | Difficult to penetrate with preservatives | Smooth finish, good machining capabilities, high nail and screw holding ability, can be readily treated with preservatives | Little danger of splitting, holds nails well, easy to glue |

(Source: Mullins and McKnight 1981)

2.2.1 Mechanical and Physical Properties

The cellular structure of wood explains many of the differences in properties found between species and provides the unique properties for its utilization (Shmulsky and Jones 2019). The physicomechanical properties are mainly determined by the porosity, thickness of the cell walls, variety and proportion of the cell types, and moisture content (Shmulsky and Jones 2019). Properties such as density, hardness, and bending strength are derived from the cell structures and arrangements (Wiedenhoeft 2010). The strength and resistance to deformation are referred to as its mechanical properties (Shmulsk and Jones 2019). Modulus of rupture (MOR), modulus of elasticity (MOE), and compression parallel to the grain, are three mechanical properties of interest to engineering uses of wood. Density, a physical property, is closely correlated to the structure and strength properties of the wood thus it is a useful measurement to understanding the mechanical properties (Shmulsky and Jones 2019).

Modulus of rupture (MOR) is the maximum load-carrying capacity of a bending specimen (Kretschmann 2010). Modulus of elasticity (MOE) is the measure for the stress that can be applied to a bending specimen prior to the point where deformation or failure prevents the recovery of the specimen after the load is removed (Kretschmann 2010). Maximum stress is the measure of the force that can be sustained by compression of a specimen parallel to the grain (Kretschmann 2010). Table 2.1 summarizes the mechanical properties of the four species that are reported in other studies.

Variations in density within a species are influenced by the local site conditions where it is grown, climate, growth stresses, and genetic source (Mullins and McKnight 1981; Shmulsky and Jones 2019). Fiber and tracheid length, cell wall thickness, proportions of cell type, uniformity, extractive contents, and form development are heritable traits that affect the wood quality and strength properties of wood (Schmulsky and Jones 2019). Thus, it is imperative to determine the strength of the wood in relation to its locale for the application to be effective. Table 2.2 summarizes the densities of the four species that are reported in other studies.

Table 2.1. Comparison of MOR, MOE, and maximum stress properties from the present study with those reported by Jessome (2000) and Kennedy (1965) (in MPa).

| Species | Property | Jessome[a] | Kennedy[b] |
|---|---|---|---|
| White birch | MOR | 94.8 | 94.8 |
| | MOE | 12,900.0 | 12,846.0 |
| | Max. Stress | 44.7 | 44.7 |
| Eastern larch | MOR | 76.0 | 75.9 |
| | MOE | 9,380.0 | 9,414.4 |
| | Max. Stress | 44.8 | 44.8 |
| Poplar | MOR | 67.6 | 67.6 |
| | MOE | 11,200.0 | 11,277.6 |
| | Max. Stress | 36.3 | 36.3 |
| White spruce | MOR | 62.7 | 62.7 |
| | MOE | 9,930.0 | 10,002.8 |
| | Max. Stress | 36.9 | 36.9 |

Note: [a] eastern Canadian provinces, [b] various Canadian provinces

Table 2.2. Densities reported by Jessome (1977), Singh (1984), and Kennedy (1965) (in $g/cm^3$).

| | Moisture Content | Jessome[a] | Singh[b] | Kennedy[c] |
|---|---|---|---|---|
| White birch | 12% | 0.571 | 0.481 | - |
| | Dry | 0.588 | 0.556 | 0.59 |
| Eastern larch | 12% | 0.506 | 0.458 | - |
| | Dry | 0.544 | 0.530 | 0.54 |
| Poplar | 12% | 0.408 | 0.401 | - |
| | Dry | 0.424 | 0.458 | 0.42 |
| White spruce | 12% | 0.372 | 0.386 | - |
| | Dry | 0.393 | 0.432 | 0.39 |

Note: [a] eastern Canadian provinces,[b] Canadian prairie provinces,[c] various Canadian provinces

## 2.3 UTILIZATION

### 2.3.1 White Birch

White birch represents 3% of Ontario's annual harvest (MNRF 2016). It is used commercially for veneer, plywood, and pulpwood (Uchytil 1991). Birch is also used in furniture and cabinet making, flooring, other specialty items, and is commonly used as fuelwood (Uchytil 1991). Low quality birch is used for boxes, pallets, and crates. The white colour wood and odourless-tasteless properties allow the best quality wood to be used as popsicle sticks, toothpicks, disposable utensils and medical tongue depressors (Walker 1989).

### 2.3.2 Eastern Larch

Larch represents less than 2.0% of Ontario's annual harvest (MNRF 2016). It is primarily used for making pulp products (Burns and Honkala 1990). However, it is also used for construction lumber, fuelwood, boxes, crates, boat ribs, and fish traps (Burns and Honkala 1990).

### 2.3.3 Poplar

Poplar is 18% of Ontario's annual harvest (MNRF 2016). It is used mainly for particleboard, pulpwood, and fuelwood (Howard 1996; Burns and Honkala 1990). Some lumber is made for boxes, crates, pallets, furniture and specialty products such as matchsticks and tongue depressors (Howard 1996; Mullins and McKnight 1981).

### 2.3.4 White Spruce

Spruces in general currently account for over 40% of Ontario's annual harvest in the past decade (MNRF 2016). White spruce is an important commercial species for production of dimensional lumber and pulpwood (Farrar 2016). Additional uses for instruments, transmission poles, matchsticks, and paneling are also common (Burns and Honkala 1990).

# 4.0 POTENTIAL FOR VALUE-ADDED

Canada's forest sector is facing financial and market challenges due to shifts in market demand, increasing trade barriers, and higher competitive pressures (Maloney 2018). It is suggested that there is an urgent need for the sector to transform or repurpose to ensure it remains an economic engine (Maloney 2018).

Value-added manufacturing in the forest industry contributes to both economic and employment growth in Canada (Maloney 2018). Value-added market opportunities derived from trees include bioenergy, advanced wood building construction, and biorefining to produce material alternatives in all industries (Maloney 2018). Growing market opportunities surround wood-pellet fuel manufacturing; structural engineered wood such as mass timber; unused residue applications such as bark-based adhesives; biomaterials made from lignin or cellulose filaments; as well as development of cellulose nanocrystals (Maloney 2018).

The government of British Columbia identifies key drivers to the success of generating more economic value per hectare. Notable drivers include:

- Promoting structural use of wood in commercial, institutional, and mid-rise buildings.
- Encouraging higher value product developments from mill waste.
- Identifying effective fibre merchandising so manufacturers access the correct fibres they can utilize.
- Increasing public and consumer awareness of climate-positive wood products.

(BC MFR 2009)

The faculty of forestry at the University of British Columbia identified the ability of several countries to create more economic value from wood (Figure 1.0).

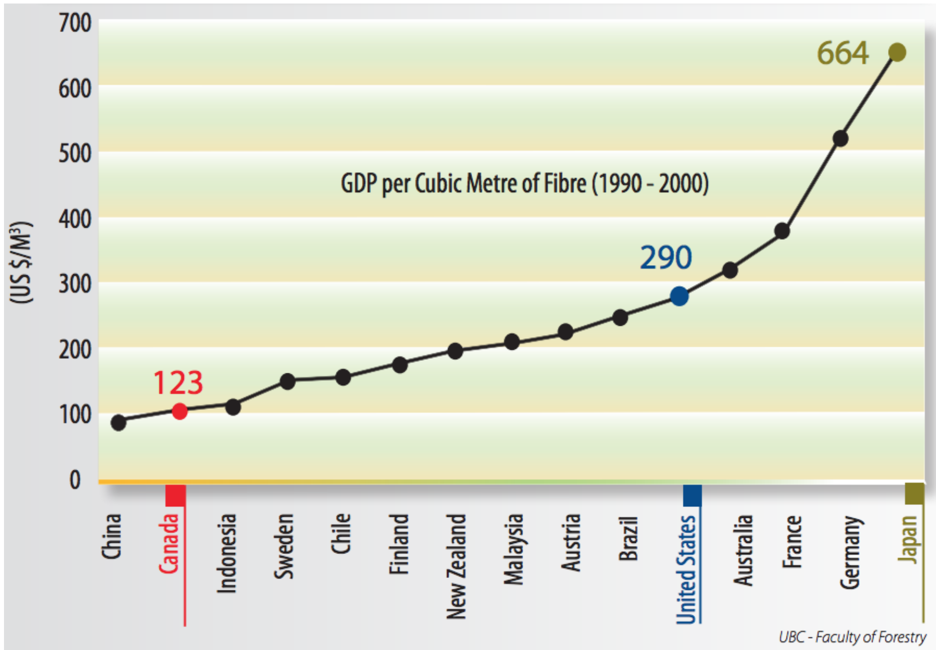


Figure 1.0. Canada's GDP per cubic meter of fibre in comparison to other countries.

Most value-added producers are constrained by lack of capacities to expand and secure a stable fiber supply (BC MFR 2009). They often depend on primary manufacturers for the species, dimensions, and grades of fiber required while primary manufacturers have difficulty redirecting the specific low-volume product lines (BC MFR 2009). Underutilized species, small diameter stems, and by-product residues can be a source to feed the value-added market as they do not directly compete with traditional sawlogs (BC MFR 2009).

In Ontario, the $2.2 billion value-added sector is primarily supplied from Quebec and the United States (Manson and Rose 2005). Ontario supplies only 38.1 % of its own value-added wood products sector demand (Manson and Rose 2005). Thus, market opportunities to diversify the uses of these species exist both within the province and internationally (Manson and Rose 2005).

The mechanical properties found in this study could help to identify value-added opportunities for white birch, eastern larch, poplar, and white spruce from northwestern Ontario.

# 3.0 METHODS AND MATERIALS

For this study, MOE, MOR, and compression parallel to the grain were the mechanical properties of interest. The physical property density was also measured in this study. Boles of white spruce, eastern larch, trembling aspen, and white birch were collected in the Thunder Bay area by the Lakehead University Wood Science and Testing Facility. A Wood Mizer LT 40 Hydraulic portable bandsaw mill was used to break the logs down into 2.5 cm thick boards, which were then stacked and stickered to air dry prior to further processing. Once the boards were dried to approximately 15% moisture content the boards were re-sawn into sample sticks. A table saw was used to cut the wood into 2 cm-height by 2 cm-width by 30cm-length test samples in accordance with the International Organization of Standardization parameters (ISO 1975) and American Society for Testing and Materials International (ASTM 2010) standards. Cull wood and pith samples were removed, and the clear samples were dried in a conditioning chamber set at 65% RH and 20° C for 14 days. Clear samples of each species were tested at 12% moisture content using a Tinius Olsen H10KT universal testing machine to determine MOE and MOR. It involves a three-point flexure tool which applies a constant load at a load rate of 8mm/minute until failure and generates MOE and MOR values in Megapascal pressure units (MPa). Results were generated through the Tinius Olsen Test Navigator software of the machine. Following MOE/MOR testing the samples were then further cut using a table saw into 2 cm-height by 2 cm-width by 6 cm-length samples for measuring compression parallel to the grain using the Tinius Olsen H50KT universal testing machine with a compression parallel to the grain testing tool. Further, 2 cm-height by 2 cm-width by 2cm-length samples were cut from the MOE/MOR samples and were used for density measurements. The samples were measured by weight and volume at 12% moisture content and then again when dry (samples were dried in a large oven set at 100° C for two days). Analysis of the data was completed using SPSS statistical software. Outliers in the data were identified using boxplots and whiskers and removed if outside the interquartile range using a multiplier of 3. Four white birch samples were removed from the MOE and MOR analysis due to a calculation discrepancy during data collection. The number of samples used per species and property test are summarized in Table 3.0. A univariate general linear model was used to determine the descriptive statistics and run the analysis of variance (ANOVA). Means were derived from the sample sizes of 27 to 35 samples for each of the four species tested (see Table 3). The means were determined for six measurements: modulus of rupture (MPa), modulus of elasticity (MPa), density at 12% moisture content ($g/cm^3$), density when dry ($g/cm^3$), maximum load (kPa), and maximum stress (MPa).

Table 3.0. Summary of species sample count per mechanical and physical property tested.

| Species | Compression parallel to the grain | MOE/MOR | Density |
|---|---|---|---|
| White birch | 28 | 27 | 30 |
| Eastern larch | 33 | 34 | 34 |
| Poplar | 35 | 35 | 35 |
| White spruce | 34 | 34 | 34 |

# 4.0 RESULTS

## 4.1 MODULUS OF RUPTURE AND MODULUS OF ELASTICITY

The mean MOR of white birch (BW) was 76.91 MPa (9.28 MPa Std) with a minimum of 58.2 MPa. Larch (LA) mean MOR was 68.28 MPa (10.16 MPa Std) with a minimum of 45.5 MPa. Poplar (PT) mean MOR was 67.03 MPa (6.56 MPa Std) with a minimum of 49.0 MPa. White spruce (SW) mean MOR was 52.32 MPa (7.09 MPa Std) with a minimum of 38.7 MPa. The distribution of the MOR data for each species is summarized in Figure 4.1.0 and the means and standard deviations are represented in Figure 4.1.1. The mean MOE of White birch was 7,772.22 MPa (1,231.204 MPa Std.) with a minimum of 5,540 MPa. Larch mean MOE was 6,948.82 MPa (1,230.025 MPa Std.) with a minimum of 4,850 MPa. Poplar was 7,704.00 MPa (956.440 MPa Std) with a minimum of 5,710 MPa. White spruce mean MOE was 6,106.76 MPa (1,247.76 MPa Std) with a minimum of 5,040 MPa. The distribution of the MOE data for each species is summarized in Figure 4.1.2 and the means and standard deviations are represented in Figure 4.1.3. A summary of the results are presented in Table 4.3.0.

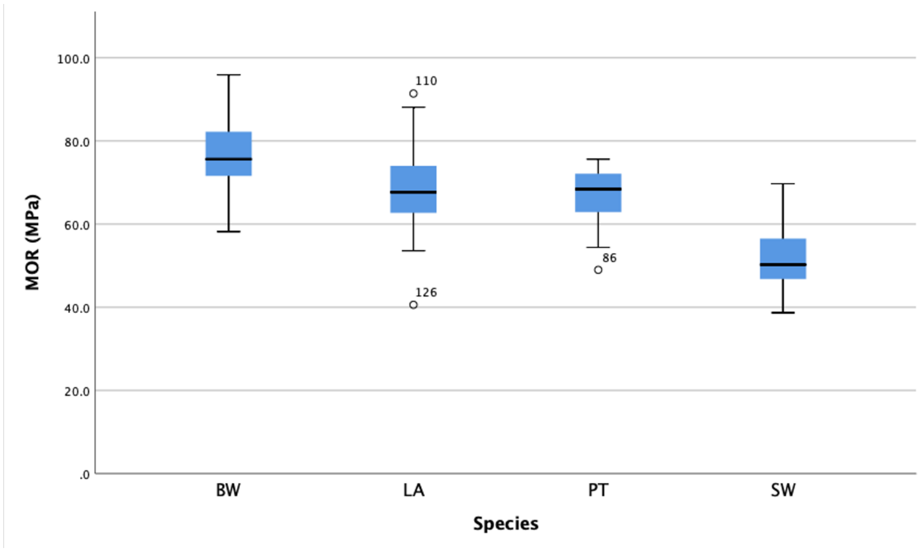


Figure 4.1.0. Boxplot and whisker distribution of the MOR results for each of the four study species. The whiskers are the minimum and maximum values, the box identifies the interquartile range and median line, and the circle points identify outliers using a multiplier of 1.5 from the interquartile range. Outliers were only removed if determined using a multiplier of 3 as suggested by Hoaglin and Iglewicz (1987).

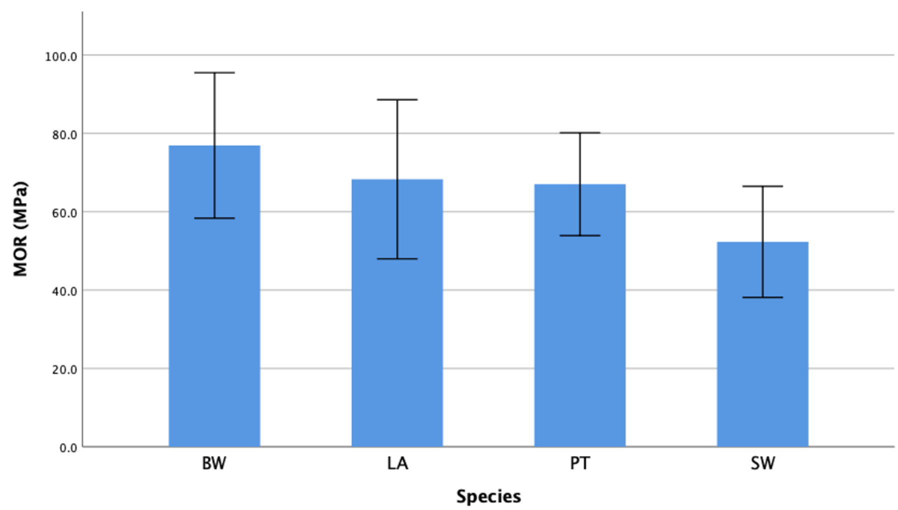


Figure 4.1.1. Mean MOR per study species. Error bars represent ±2 Standard Deviations.

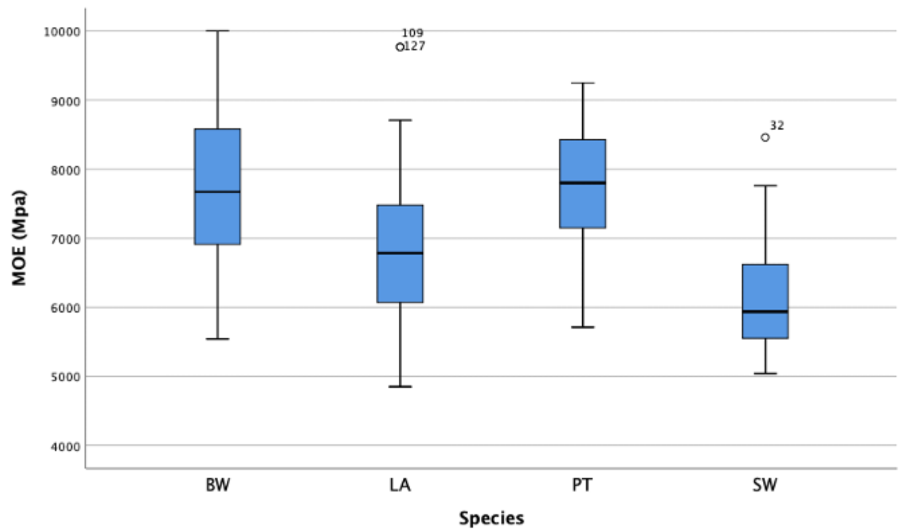


Figure 4.1.2. Boxplot and whisker distribution of the MOE results for the four study species (Chart elements described in Figure 4.1.0).

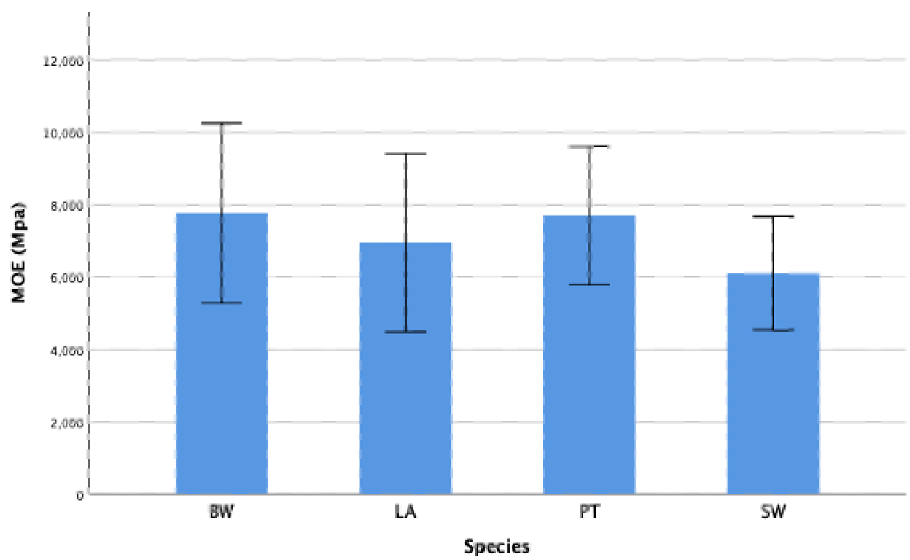


Figure 4.1.3. Mean MOE per study species. Error bars represent ±2 Standard Deviations.

The MOE test did not have equal variances across the species according to the Lavene's Test completed in SPSS. The results of the Lavene's Tests are summarized in Table 4.1.0. Equal variances is a required assumption to perform an ANOVA, however for the purposes of this study, an ANOVA and post-hoc were completed regardless. The ANOVA determined significant differences (p = <0.01, **α** = 0.05) in MOR and MOE means between species. The results of the ANOVA for the MOE and MOR tests are presented in Table 4.1.1. Tukey, LSD, and Duncan post-hoc results all determined the mean differences are statistically significant between each species relationship with two exceptions; larch and poplar for MOR and white birch and poplar for MOE, were not statistically significant at the **α** = 0.05 level. The multiple comparisons post hoc for the MOE and MOR results are detailed in Table 4.1.2 and 4.1.3 respectively. The post-hoc subsets for the MOE and MOR results are detailed in Table 4.1.4 and 4.1.5 respectively.

Table 4.1.0. Levene's Test of Equality of Error Variances for MOE and MOR tests.

| Levene's Test of Equality of Error Variances a,b | | Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|---|---|
| MOE (mPa) | Based on Mean | 2.799 | 3 | 126 | 0.043 |
| | Based on Median | 2.749 | 3 | 126 | 0.046 |
| | Based on Median and with adjusted df | 2.749 | 3 | 115.41 | 0.046 |
| | Based on trimmed mean | 2.84 | 3 | 126 | 0.041 |
| MOR (mPa) | Based on Mean | 3.686 | 3 | 126 | 0.014 |
| | Based on Median | 3.132 | 3 | 126 | 0.028 |
| | Based on Median and with adjusted df | 3.132 | 3 | 109.32 | 0.029 |
| | Based on trimmed mean | 3.657 | 3 | 126 | 0.014 |

a Dependent variable: MOE (Mpa) or MOR (mPa)

b Design: Intercept + species

Table 4.1.1. ANOVA results for MOE and MOR tests.

| Tests of Between-Subjects Effects | | | | | |
|---|---|---|---|---|---|
| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
| Dependent Variable: MOE (Mpa) | | | | | |
| Corrected Model | 59286885.505a | 3 | 19762295.17 | 17.6 | 0.0000 |
| Intercept | 6542241872 | 1 | 6542241872 | 5823 | 0.0000 |
| species | 59286885.51 | 3 | 19762295.17 | 17.6 | 0.0000 |
| Error | 141555003.7 | 126 | 1123452.411 | | |
| Total | 6759539000 | 130 | | | |
| Corrected Total | 200841889.2 | 129 | | | |
| Dependent Variable: MoR (Mpa) | | | | | |
| Corrected Model | 58251758.003a | 3 | 19417252.67 | 16 | 0.00000 |
| Intercept | 7190926657 | 1 | 7190926657 | 5914 | 0.00000 |
| species | 58251758 | 3 | 19417252.67 | 16 | 0.00000 |
| Error | 153216438.9 | 126 | 1216003.483 | | |
| Total | 7427091200 | 130 | | | |
| Corrected Total | 211468196.9 | 129 | | | |

a R Squared = .275 (Adjusted R Squared = .258)

b R Squared = .295 (Adjusted R Squared = .278)

Table 4.1.2. Multiple comparison post-hoc of MOE results.

| Dependent Variable: MOE (Mpa) | | Multiple Comparisons | | | | |
|---|---|---|---|---|---|---|
| (I) species | (J) species | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
| | | | | | Lower Bound | Upper Bound |
| Tukey HSD | | | | | | |
| BW | LA | 823.40* | 273.225 | 0.016 | 112.02 | 1534.78 |
| | PT | 68.22 | 271.492 | 0.994 | -638.65 | 775.09 |
| | SW | 1665.46* | 273.225 | 0 | 954.07 | 2376.84 |
| LA | BW | -823.40* | 273.225 | 0.016 | -1534.78 | -112.02 |
| | PT | -755.18* | 255.228 | 0.019 | -1419.7 | -90.65 |
| | SW | 842.06* | 257.071 | 0.007 | 172.74 | 1511.38 |
| PT | BW | -68.22 | 271.492 | 0.994 | -775.09 | 638.65 |
| | LA | 755.18* | 255.228 | 0.019 | 90.65 | 1419.7 |
| | SW | 1597.24* | 255.228 | 0 | 932.71 | 2261.76 |
| SW | BW | -1665.46* | 273.225 | 0 | -2376.84 | -954.07 |
| | LA | -842.06* | 257.071 | 0.007 | -1511.38 | -172.74 |
| | PT | -1597.24* | 255.228 | 0 | -2261.76 | -932.71 |
| Least Square Difference - LSD | | | | | | |
| BW | LA | 823.40* | 273.225 | 0.003 | 282.69 | 1364.1 |
| | PT | 68.22 | 271.492 | 0.802 | -469.05 | 605.5 |
| | SW | 1665.46* | 273.225 | 0 | 1124.75 | 2206.16 |
| LA | BW | -823.40* | 273.225 | 0.003 | -1364.1 | -282.69 |
| | PT | -755.18* | 255.228 | 0.004 | -1260.27 | -250.09 |
| | SW | 842.06* | 257.071 | 0.001 | 333.32 | 1350.79 |
| PT | BW | -68.22 | 271.492 | 0.802 | -605.5 | 469.05 |
| | LA | 755.18* | 255.228 | 0.004 | 250.09 | 1260.27 |
| | SW | 1597.24* | 255.228 | 0 | 1092.15 | 2102.32 |
| SW | BW | -1665.46* | 273.225 | 0 | -2206.16 | -1124.75 |
| | LA | -842.06* | 257.071 | 0.001 | -1350.79 | -333.32 |
| | PT | -1597.24* | 255.228 | 0 | -2102.32 | -1092.15 |

* The mean difference is significant at the .05 level.

Table 4.1.3. Multiple comparison post-hoc of MOR results.

| Dependent Variable: MOR (Mpa) | | Multiple Comparisons | | | | |
|---|---|---|---|---|---|---|
| (I) species | (J) species | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
| | | | | | Lower Bound | Upper Bound |
| Tukey HSD | | | | | | |
| BW | LA | 696.97 | 284.257 | 0.073 | -43.13 | 1437.08 |
| | PT | 49.58 | 282.454 | 0.998 | -685.83 | 784.99 |
| | SW | 1653.15* | 284.257 | 0 | 913.04 | 2393.25 |
| LA | BW | -696.97 | 284.257 | 0.073 | -1437.08 | 43.13 |
| | PT | -647.39 | 265.533 | 0.075 | -1338.75 | 43.96 |
| | SW | 956.18* | 267.45 | 0.003 | 259.83 | 1652.52 |
| PT | BW | -49.58 | 282.454 | 0.998 | -784.99 | 685.83 |
| | LA | 647.39 | 265.533 | 0.075 | -43.96 | 1338.75 |
| | SW | 1603.57* | 265.533 | 0 | 912.22 | 2294.93 |
| SW | BW | -1653.15* | 284.257 | 0 | -2393.25 | -913.04 |
| | LA | -956.18* | 267.45 | 0.003 | -1652.52 | -259.83 |
| | PT | -1603.57* | 265.533 | 0 | -2294.93 | -912.22 |
| Least Square Difference - LSD | | | | | | |
| BW | LA | 696.97* | 284.257 | 0.016 | 134.44 | 1259.51 |
| | PT | 49.58 | 282.454 | 0.861 | -509.39 | 608.54 |
| | SW | 1653.15* | 284.257 | 0 | 1090.61 | 2215.68 |
| LA | BW | -696.97* | 284.257 | 0.016 | -1259.51 | -134.44 |
| | PT | -647.39* | 265.533 | 0.016 | -1172.88 | -121.91 |
| | SW | 956.18* | 267.45 | 0 | 426.9 | 1485.45 |
| PT | BW | -49.58 | 282.454 | 0.861 | -608.54 | 509.39 |
| | LA | 647.39* | 265.533 | 0.016 | 121.91 | 1172.88 |
| | SW | 1603.57* | 265.533 | 0 | 1078.09 | 2129.05 |
| SW | BW | -1653.15* | 284.257 | 0 | -2215.68 | -1090.61 |
| | LA | -956.18* | 267.45 | 0 | -1485.45 | -426.9 |
| | PT | -1603.57* | 265.533 | 0 | -2129.05 | -1078.09 |

Based on observed means.

The error term is Mean Square(Error) = 1123452.411.

* The mean difference is significant at the .05 level.

Table 4.1.4. Duncan and Turkey post-hoc subsets of the MOE results.

| MOE (Mpa) | | | Subset | | |
|---|---|---|---|---|---|
| | Species | N | 1 | 2 | 3 |
| Tukey HSD | SW | 34 | 6106.76 | | |
| | LA | 34 | | 6948.82 | |
| | PT | 35 | | | 7704 |
| | BW | 27 | | | 7772.22 |
| | Sig. | | 1 | 1 | 0.994 |
| Duncan | SW | 34 | 6106.76 | | |
| | LA | 34 | | 6948.82 | |
| | PT | 35 | | | 7704 |
| | BW | 27 | | | 7772.22 |
| | Sig. | | 1 | 1 | 0.797 |

Means for groups in homogeneous subsets are displayed.
The error term is Mean Square(Error) = 1123452.411.
Uses Harmonic Mean Sample Size = 32.146. Alpha = .05.

Table 4.1.5. Duncan and Turkey post-hoc subsets of the MOR results.

| MOR (Mpa) | | | Subset | | |
|---|---|---|---|---|---|
| | Species | N | 1 | 2 | 3 |
| Tukey HSD | SW | 34 | 6425 | | |
| | LA | 34 | | 7381.18 | |
| | PT | 35 | | 8028.57 | |
| | BW | 27 | | 8078.15 | |
| | Sig. | | 1 | 0.06 | |
| Duncan | SW | 34 | 6425 | | |
| | LA | 34 | | 7381.18 | |
| | PT | 35 | | | 8028.57 |
| | BW | 27 | | | 8078.15 |
| | Sig. | | 1 | 1 | 0.857 |

Means for groups in homogeneous subsets are displayed.
The error term is Mean Square(Error) = 1216003.483.
Uses Harmonic Mean Sample Size = 32.146. Alpha = .05.

4.2 COMPRESSION PARALLEL TO THE GRAIN

The mean maximum load of White birch (BW) was 15,332.41 kPa (1,452.605 kPa Std) with the lowest value of 11,930 kPa. Larch (LA) mean maximum load was 17,066.97 kPa (1,795.278 kPa Std) with the lowest value of 12,620 kPa. Poplar (PT) mean maximum load was 13,986.29 kPa (1,172.602 kPa Std) with the lowest value of 10,500 kPa. White spruce (SW) mean maximum load was 13,318.24 kPa (1,590.250 kPa Std). The distribution of the max load for each species is summarized in Figure 4.3.0 and the means and standard deviations are represented in Figure 4.3.1. The mean maximum stress of White birch was 38.957 MPa (3.246 MPa Std.), Larch was 44.307 MPa (4.665 MPa Std.), Poplar was 37.089 MPa (3.124 MPa Std), and White spruce was 33.179 MPa (3.487 MPa Std). The distribution of the max stress for each species is summarized in Figure 4.3.2 and the means and standard deviations are represented in Figure 4.3.3. A summary of the results are presented in Table 4.3.0.

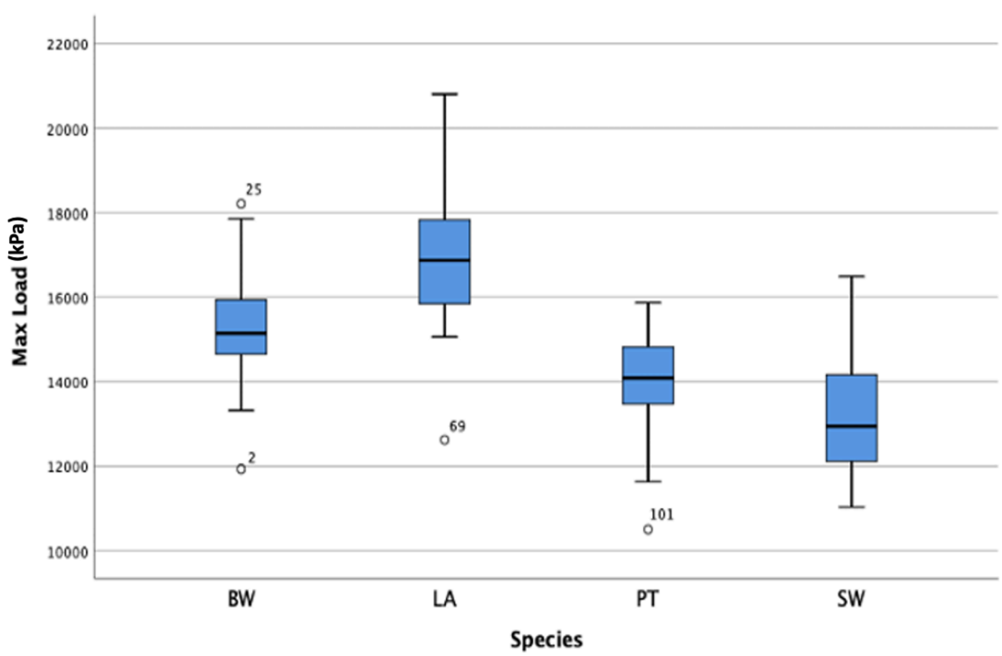


Figure 4.2.0. Boxplot and whisker distribution of the Max Load (kPa) for each of the four study species (Chart elements described in Figure 4.1.0).

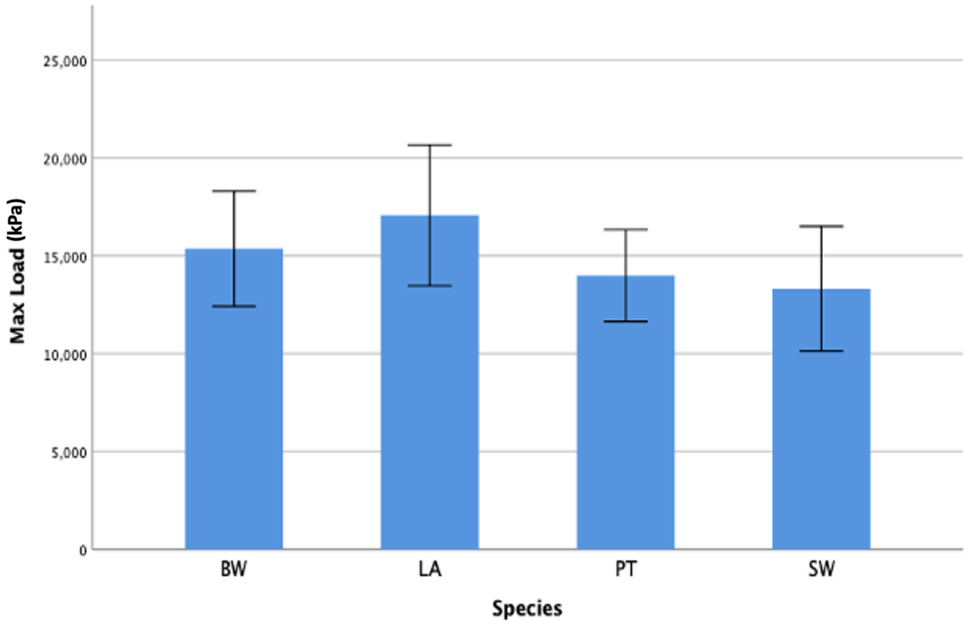


Figure 4.2.1 Mean Max Load per study species. Error bars represent ±2 Standard Deviations.

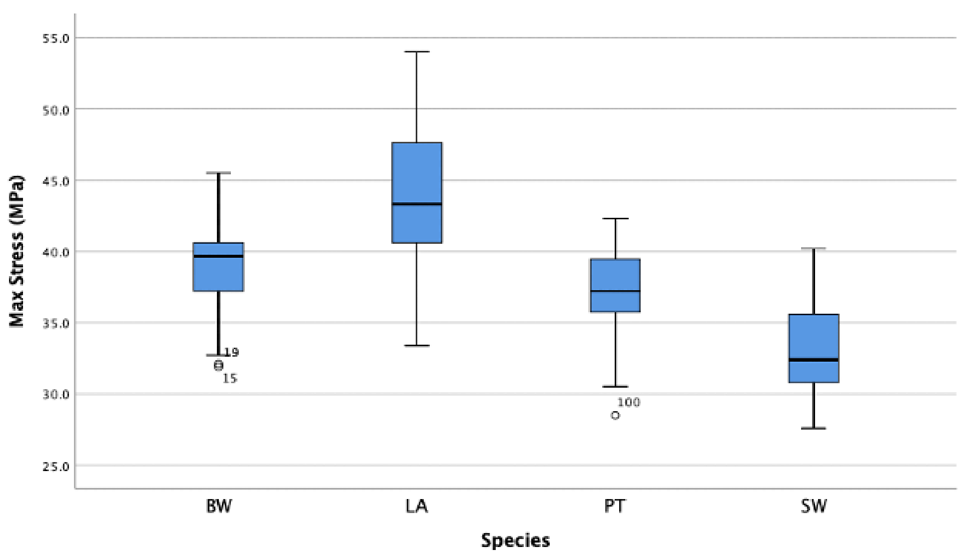


Figure 4.2.2. Boxplot and whisker distribution of the Max Stress (MPa) for the four study species (Chart elements described in Figure 4.1.0).

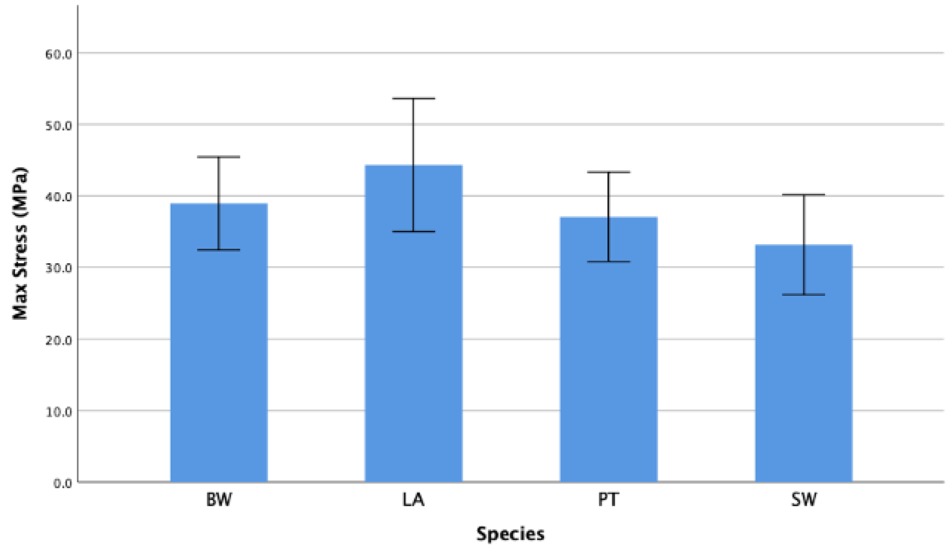


Figure 4.2.3. Mean Max Stress per study species. Error bars represent ±2 Standard Deviations.

The data for maximum load had equal variances across the species according to the results of the Lavene's Test. The data for maximum stress, however, did not show equal variances across the species; an ANOVA was completed despite this assumption being violated. The results of the Levene's Test are summarized Table 4.2.0. The ANOVA determined significant (p = <0.01, **α** = 0.05) differences in the means between species for both tests. The results of the ANOVA for the maximum load and maximum stress test are presented in Table 4.2.1. Turkey, LSD, and Duncan post-hoc results for the maximum load test all determined the mean differences are statistically significant in each specie relationship except between White spruce and Poplar which were not statistically significant at the **α** = 0.05. The Turkey and Duncan post-hoc results for the maximum stress test determined the mean differences are statistically significant in each specie relationship except between Poplar and White birch at the **α** = 0.05, whereas the LSD post-hoc determined the mean differences were statistically significant between all specie relationships. The multiple comparison post-hoc for the maximum load and maximum stress results are detailed in Table 4.2.2 and 4.2.3 respectively. The post-hoc subsets for the maximum load and maximum stress results are detailed in Table 4.2.4 and 4.2.5 respectively.

Table 4.2.0. Levene's Test of Equality of Error Variances for maximum load and maximum stress.

| Levene's Test of Equality of Error Variances a,b | | Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|---|---|
| Max_load | Based on Mean | 1.94 | 3 | 127 | 0.126 |
| | Based on Median | 1.611 | 3 | 127 | 0.19 |
| | Based on Median and with adjusted df | 1.611 | 3 | 118.318 | 0.19 |
| | Based on trimmed mean | 1.924 | 3 | 127 | 0.129 |
| Max_stress | Based on Mean | 2.819 | 3 | 126 | 0.042 |
| | Based on Median | 2.111 | 3 | 126 | 0.102 |
| | Based on Median and with adjusted df | 2.111 | 3 | 114.144 | 0.103 |
| | Based on trimmed mean | 2.782 | 3 | 126 | 0.044 |

a Dependent variable: Max_load(kPa)or Max_stress (mPa)
b Design: Intercept + species

Table 4.2.1. ANOVA results for maximum load and maximum load and maximum stress.

| Tests of Between-Subjects Effects | | | | | |
|---|---|---|---|---|---|
| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
| Dependent Variable: Max_load | | | | | |
| Corrected Model | 274648039.361a | 3 | 91549346.5 | 39.76 | 0 |
| Intercept | 29034664526 | 1 | 2.9035E+10 | 12609.878 | 0 |
| Sample | 274648039.4 | 3 | 91549346.5 | 39.76 | 0 |
| Error | 292421739.3 | 127 | 2302533.38 | | |
| Total | 29599444100 | 131 | | | |
| Corrected Total | 567069778.6 | 130 | | | |
| Dependent Variable: Max_stress | | | | | |
| Corrected Model | 2150.159a | 3 | 716.72 | 52.686 | 0 |
| Intercept | 190124.601 | 1 | 190124.601 | 13976.091 | 0 |
| Sample | 2150.159 | 3 | 716.72 | 52.686 | 0 |
| Error | 1714.049 | 126 | 13.604 | | |
| Total | 194598.21 | 130 | | | |
| Corrected Total | 3864.208 | 129 | | | |

a R Squared = .484 (Adjusted R Squared = .472)
b R Squared = .556 (Adjusted R Squared = .546)

Table 4.2.2. Multiple comparison post-hoc of maximum load results.

| Dependent Variable: Max_load (kPa) | | Multiple Comparisons | | | | |
|---|---|---|---|---|---|---|
| (I) species | (J) species | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
| | | | | | Lower Bound | Upper Bound |
| Tukey HSD | | | | | | |
| BW | LA | -1734.56* | 386.227 | 0 | -2740.05 | -729.06 |
| | PT | 1346.13* | 381.031 | 0.003 | 354.16 | 2338.09 |
| | SW | 2014.18* | 383.561 | 0 | 1015.63 | 3012.73 |
| LA | BW | 1734.56* | 386.227 | 0 | 729.06 | 2740.05 |
| | PT | 3080.68* | 368.185 | 0 | 2122.16 | 4039.21 |
| | SW | 3748.73* | 370.804 | 0 | 2783.39 | 4714.07 |
| PT | BW | -1346.13* | 381.031 | 0.003 | -2338.09 | -354.16 |
| | LA | -3080.68* | 368.185 | 0 | -4039.21 | -2122.16 |
| | SW | 668.05 | 365.388 | 0.265 | -283.19 | 1619.29 |
| SW | BW | -2014.18* | 383.561 | 0 | -3012.73 | -1015.63 |
| | LA | -3748.73* | 370.804 | 0 | -4714.07 | -2783.39 |
| | PT | -668.05 | 365.388 | 0.265 | -1619.29 | 283.19 |
| Least Square Difference - LSD | | | | | | |
| BW | LA | -1734.56* | 386.227 | 0 | -2498.83 | -970.28 |
| | PT | 1346.13* | 381.031 | 0.001 | 592.14 | 2100.12 |
| | SW | 2014.18* | 383.561 | 0 | 1255.18 | 2773.18 |
| LA | BW | 1734.56* | 386.227 | 0 | 970.28 | 2498.83 |
| | PT | 3080.68* | 368.185 | 0 | 2352.11 | 3809.26 |
| | SW | 3748.73* | 370.804 | 0 | 3014.98 | 4482.49 |
| PT | BW | -1346.13* | 381.031 | 0.001 | -2100.12 | -592.14 |
| | LA | -3080.68* | 368.185 | 0 | -3809.26 | -2352.11 |
| | SW | 668.05 | 365.388 | 0.07 | -54.99 | 1391.09 |
| SW | BW | -2014.18* | 383.561 | 0 | -2773.18 | -1255.18 |
| | LA | -3748.73* | 370.804 | 0 | -4482.49 | -3014.98 |
| | PT | -668.05 | 365.388 | 0.07 | -1391.09 | 54.99 |

Based on observed means.

The error term is Mean Square(Error) = 2302533.380.

* The mean difference is significant at the .05 level.

Table 4.2.3. Multiple comparison post-hoc maximum stress results.

| Dependent Variable: Max_stress (Mpa) | | Multiple Comparisons | | | | |
|---|---|---|---|---|---|---|
| (I) species | (J) species | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval Lower Bound | Upper Bound |
| Tukey HSD | | | | | | |
| BW | LA | -5.361* | 0.9477 | 0 | -7.828 | -2.894 |
| | PT | 1.869 | 0.9352 | 0.194 | -0.566 | 4.303 |
| | SW | 5.778* | 0.9412 | 0 | 3.327 | 8.228 |
| LA | BW | 5.361* | 0.9477 | 0 | 2.894 | 7.828 |
| | PT | 7.230* | 0.8949 | 0 | 4.9 | 9.56 |
| | SW | 11.139* | 0.9013 | 0 | 8.792 | 13.485 |
| PT | BW | -1.869 | 0.9352 | 0.194 | -4.303 | 0.566 |
| | LA | -7.230* | 0.8949 | 0 | -9.56 | -4.9 |
| | SW | 3.909* | 0.8881 | 0 | 1.597 | 6.222 |
| SW | BW | -5.778* | 0.9412 | 0 | -8.228 | -3.327 |
| | LA | -11.139* | 0.9013 | 0 | -13.485 | -8.792 |
| | PT | -3.909* | 0.8881 | 0 | -6.222 | -1.597 |
| Least Square Difference - LSD | | | | | | |
| BW | LA | -5.361* | 0.9477 | 0 | -7.236 | -3.486 |
| | PT | 1.869* | 0.9352 | 0.048 | 0.018 | 3.719 |
| | SW | 5.778* | 0.9412 | 0 | 3.915 | 7.64 |
| LA | BW | 5.361* | 0.9477 | 0 | 3.486 | 7.236 |
| | PT | 7.230* | 0.8949 | 0 | 5.459 | 9.001 |
| | SW | 11.139* | 0.9013 | 0 | 9.355 | 12.922 |
| PT | BW | -1.869* | 0.9352 | 0.048 | -3.719 | -0.018 |
| | LA | -7.230* | 0.8949 | 0 | -9.001 | -5.459 |
| | SW | 3.909* | 0.8881 | 0 | 2.152 | 5.667 |
| SW | BW | -5.778* | 0.9412 | 0 | -7.64 | -3.915 |
| | LA | -11.139* | 0.9013 | 0 | -12.922 | -9.355 |
| | PT | -3.909* | 0.8881 | 0 | -5.667 | -2.152 |

Based on observed means.

The error term is Mean Square(Error) = 13.604.

* The mean difference is significant at the .05 level.

Table 4.2.4. Duncan and Turkey post-hoc subsets of the maximum load results.

| Max_load | | | Subset | | |
|---|---|---|---|---|---|
| | Species | N | 1 | 2 | 3 |
| Tukey HSDa,l | SW | 34 | 13318.24 | | |
| | PT | 35 | 13986.29 | | |
| | BW | 29 | | 15332.41 | |
| | LA | 33 | | | 17066.97 |
| | Sig. | | 0.289 | 1 | 1 |
| Duncana,b,c | SW | 34 | 13318.24 | | |
| | PT | 35 | 13986.29 | | |
| | BW | 29 | | 15332.41 | |
| | LA | 33 | | | 17066.97 |
| | Sig. | | 0.078 | 1 | 1 |

Means for groups in homogeneous subsets are displayed.
The error term is Mean Square(Error) = 2302533.380.
Uses Harmonic Mean Sample Size = 32. Alpha = .05.

Table 4.2.5. Duncan and Turkey post-hoc subsets of the maximum stress results.

| Max_stress | | | Subset | | | |
|---|---|---|---|---|---|---|
| | Species | N | 1 | 2 | 3 | 4 |
| Tukey HSDa,l | SW | 34 | 33.179 | | | |
| | PT | 35 | | 37.089 | | |
| | BW | 28 | | 38.957 | | |
| | LA | 33 | | | 44.318 | |
| | Sig. | | 1 | 0.181 | 1 | |
| Duncana,b,c | SW | 34 | 33.179 | | | |
| | PT | 35 | | 37.089 | | |
| | BW | 28 | | | 38.957 | |
| | LA | 33 | | | | 44.318 |
| | Sig. | | 1 | 1 | 1 | 1 |

Means for groups in homogeneous subsets are displayed.
The error term is Mean Square(Error) = 13.604.
Uses Harmonic Mean Sample Size = 3: Alpha = .05.

4.3 DENSITY

The mean density at 12% moisture content (MC) of White birch (BW) was 0.603 g/cm$^3$ (0.032 g/cm$^3$ Std), Larch (LA) was 0.579 g/cm$^3$ (0.041 g/cm$^3$ Std), Poplar (PT) was 0.459 g/cm$^3$ (0.030 g/cm$^3$ Std), and White spruce (SW) was 0.391 g/cm$^3$ (0.026 g/cm$^3$ Std). The distribution of the density data at 12% MC for each species is summarized in Figure 4.2.0 and the means and standard deviations are represented in Figure 4.2.1. The mean dry density of White birch was 0.565 g/cm$^3$ (0.032 g/cm$^3$ Std.), Larch was 0.542 g/cm$^3$ (0.039 g/cm$^3$ Std.), Poplar was 0.431 g/cm$^3$ (0.028 g/cm$^3$ Std), and White spruce was 0.369 g/cm$^3$ (0.027 g/cm$^3$ Std). The distribution of the dry density data for each species is summarized in Figure 4.2.2 and the means and standard deviations are represented in Figure 4.2.3. The results are summarized in Table 4.3.0

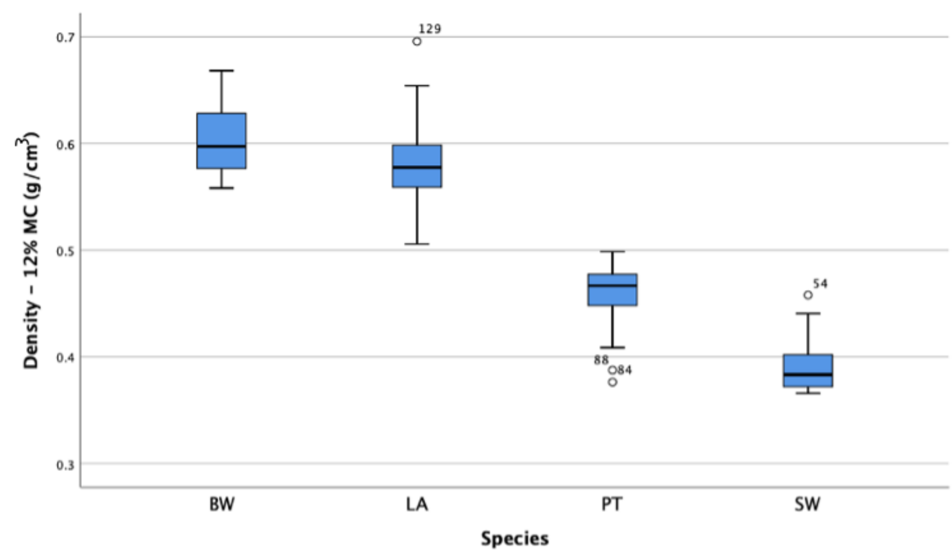


Figure 4.3.0. Boxplot and whisker distribution of the densities of each study species at 12% moisture content (Chart elements described in Figure 4.1.0).

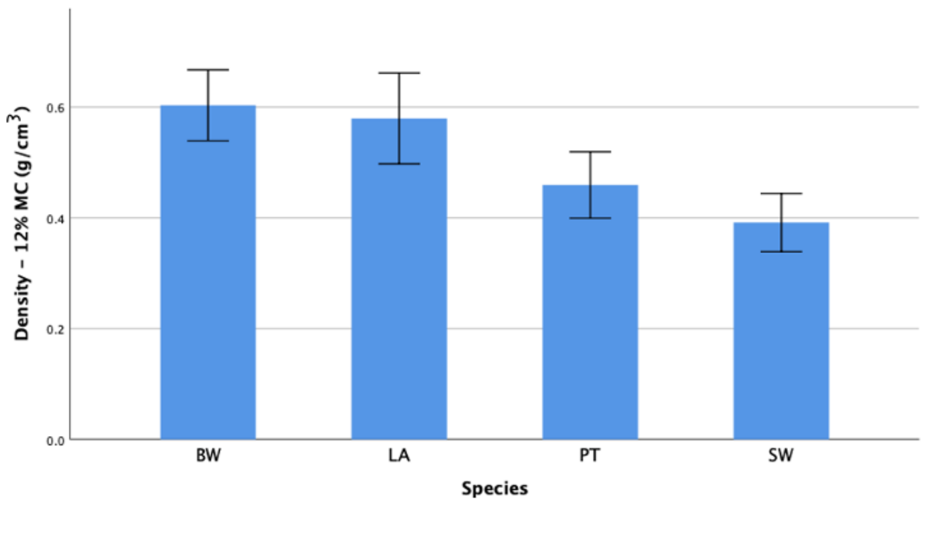


Figure 4.3.1. Mean densities per study species at 12% moisture content. Error bars represent ±2 Standard Deviations.

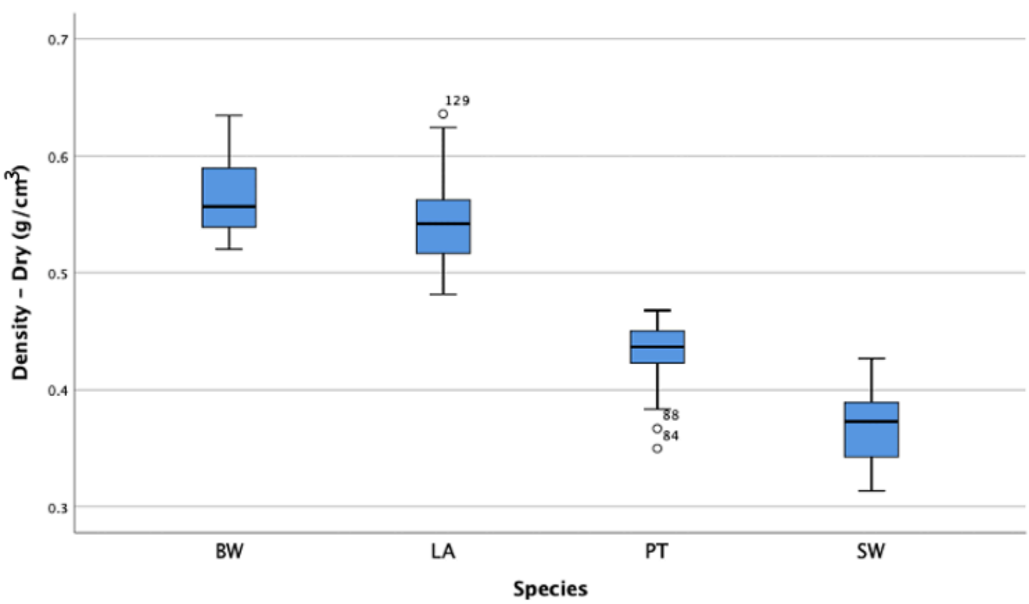


Figure 4.3.2. Boxplot and whisker distribution of the density results when dry for the four study species (Chart elements described in Figure 4.1.0).

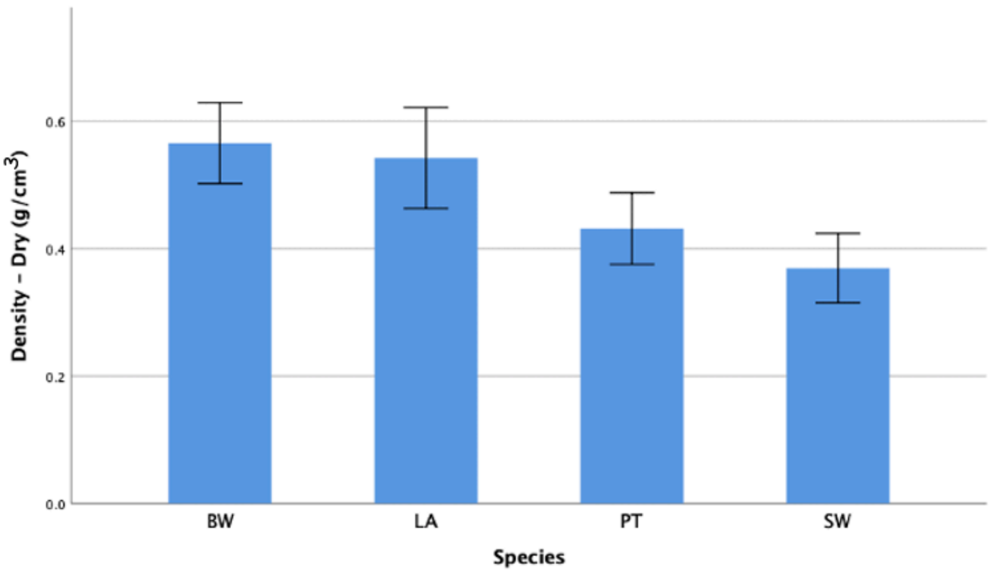

Figure 4.3.3. Mean densities per study species when dry. Error bars represent ±2 Standard Deviations.

Both the data for density when at 12% MC and when dry had equal variances according to the results of the Lavene's Test. The results of the Lavene's Test are summarized in Table 4.3.0. The ANOVA determined significant ($p = <0.01$, $\alpha = 0.05$) differences in the means between species for both tests. The ANOVA results are summarized in Table 4.3.1. Turkey, LSD, and Duncan post-hoc results all determined the mean differences are statistically significant in each specie relationship at the $\alpha$ = 0.05. The multiple comparison post-hoc for the maximum load and maximum stress results are detailed in Table 4.3.2 and 4.3.3 respectively. The post-hoc subsets for the maximum load and maximum stress results are detailed in Table 4.3.4 and 4.3.5 respectively.

Table 4.3.0. Levene's Test of Equality of Error Variances for density at 12% MC and when Dry.

| Levene's Test of Equality of Error Variances a,b | | Levene Statistic | df1 | df2 | Sig. |
|---|---|---|---|---|---|
| Density, 12% | Based on Mean | 1.462 | 3 | 129 | 0.228 |
| | Based on Median | 1.541 | 3 | 129 | 0.207 |
| | Based on Median and with adjusted df | 1.541 | 3 | 115.26 | 0.208 |
| | Based on trimmed mean | 1.534 | 3 | 129 | 0.209 |
| Density, Dry | Based on Mean | 1.775 | 3 | 129 | 0.155 |
| | Based on Median | 1.743 | 3 | 129 | 0.162 |
| | Based on Median and with adjusted df | 1.743 | 3 | 118.26 | 0.162 |
| | Based on trimmed mean | 1.842 | 3 | 129 | 0.143 |

a Dependent variable: Density, 12% MC (g/cm^3) or Density Dry (g/cm^3)

b Design: Intercept + species

Table 4.3.1. ANOVA results for density at 12% MC and when Dry.

| Tests of Between-Subjects Effects | | | | | |
|---|---|---|---|---|---|
| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
| Dependent Variable: | Density, 12% MC | | | | |
| Corrected Model | .989a | 3 | 0.33 | 307.359 | 0.000 |
| Intercept | 34.245 | 1 | 34.245 | 31939.668 | 0.000 |
| V1 | 0.989 | 3 | 0.33 | 307.359 | 0.000 |
| Error | 0.138 | 129 | 0.001 | | |
| Total | 35.06 | 133 | | | |
| Corrected Total | 1.127 | 132 | | | |
| | | | | | |
| Dependent Variable: | Density, Dry | | | | |
| Corrected Model | .845b | 3 | 0.282 | 274.766 | 0.000 |
| Intercept | 30.155 | 1 | 30.155 | 29426.8 | 0.000 |
| V1 | 0.845 | 3 | 0.282 | 274.766 | 0.000 |
| Error | 0.132 | 129 | 0.001 | | |
| Total | 30.859 | 133 | | | |
| Corrected Total | 0.977 | 132 | | | |

a R Squared = .877 (Adjusted R Squared = .874)

b R Squared = .865 (Adjusted R Squared = .862)

Table 4.2.2. Multiple comparison post-hoc of the Density at 12% MC results.

| Dependent Variable: Density, 12% MC (g/cm^3) | | Multiple Comparisons | | | | |
|---|---|---|---|---|---|---|
| (I) species | (J) species | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
| | | | | | Lower Bound | Upper Bound |
| Tukey HSD | | | | | | |
| BW | LA | .023* | 0.008 | 0.024 | 0.002 | 0.045 |
| | PT | .143* | 0.008 | 0 | 0.123 | 0.165 |
| | SW | .211* | 0.008 | 0 | 0.190 | 0.233 |
| LA | BW | -.023* | 0.008 | 0.024 | -0.045 | -0.002 |
| | PT | .120* | 0.008 | 0 | 0.100 | 0.141 |
| | SW | .188* | 0.008 | 0 | 0.167 | 0.209 |
| PT | BW | -.143* | 0.008 | 0 | -0.165 | -0.123 |
| | LA | -.120* | 0.008 | 0 | -0.141 | -0.100 |
| | SW | .067* | 0.008 | 0 | 0.047 | 0.088 |
| SW | BW | -.211* | 0.008 | 0 | -0.233 | -0.190 |
| | LA | -.188* | 0.008 | 0 | -0.209 | -0.167 |
| | PT | -.067* | 0.008 | 0 | -0.088 | -0.047 |
| Least Square Difference - LSD | | | | | | |
| BW | LA | .023* | 0.008 | 0.005 | 0.007 | 0.040 |
| | PT | .143* | 0.008 | 0 | 0.128 | 0.160 |
| | SW | .211* | 0.008 | 0 | 0.195 | 0.228 |
| LA | BW | -.023* | 0.008 | 0.005 | -0.040 | -0.007 |
| | PT | .120* | 0.008 | 0 | 0.105 | 0.136 |
| | SW | .188* | 0.008 | 0 | 0.172 | 0.204 |
| PT | BW | -.143* | 0.008 | 0 | -0.160 | -0.128 |
| | LA | -.120* | 0.008 | 0 | -0.136 | -0.105 |
| | SW | .067* | 0.008 | 0 | 0.052 | 0.083 |
| SW | BW | -.211* | 0.008 | 0 | -0.228 | -0.195 |
| | LA | -.188* | 0.008 | 0 | -0.204 | -0.172 |
| | PT | -.067* | 0.008 | 0 | -0.083 | -0.052 |

Based on observed means.

The error term is Mean Square(Error) = .001.

* The mean difference is significant at the .05 level.

Table 4.2.3. Multiple comparison post-hoc of the Density when Dry results.

| Dependent Variable: Density, Dry (g/cm^3) | | | Multiple Comparisons | | | |
|---|---|---|---|---|---|---|
| (I) species | (J) species | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
| | | | | | Lower Bound | Upper Bound |
| Tukey HSD | | | | | | |
| BW | LA | .023* | 0.008 | 0.022 | 0.002 | 0.044 |
| | PT | .134* | 0.008 | 0 | 0.113 | 0.155 |
| | SW | .196* | 0.008 | 0 | 0.175 | 0.217 |
| LA | BW | -.0234* | 0.008 | 0.022 | -0.044 | -0.002 |
| | PT | .110* | 0.008 | 0 | 0.091 | 0.131 |
| | SW | .172* | 0.008 | 0 | 0.153 | 0.193 |
| PT | BW | -.134* | 0.008 | 0 | -0.155 | -0.113 |
| | LA | -.110* | 0.008 | 0 | -0.131 | -0.091 |
| | SW | .062* | 0.008 | 0 | 0.042 | 0.082 |
| SW | BW | -.196* | 0.008 | 0 | -0.217 | -0.175 |
| | LA | -.172* | 0.008 | 0 | -0.193 | -0.153 |
| | PT | -.062* | 0.008 | 0 | -0.082 | -0.042 |
| Least Square Difference - LSD | | | | | | |
| BW | LA | .023* | 0.008 | 0.004 | 0.007 | 0.039 |
| | PT | .134* | 0.008 | 0 | 0.118 | 0.150 |
| | SW | .196* | 0.008 | 0 | 0.180 | 0.212 |
| LA | BW | -.023* | 0.008 | 0.004 | -0.039 | -0.007 |
| | PT | .110* | 0.008 | 0 | 0.096 | 0.126 |
| | SW | .172* | 0.008 | 0 | 0.157 | 0.188 |
| PT | BW | -.134* | 0.008 | 0 | -0.150 | -0.118 |
| | LA | -.110* | 0.008 | 0 | -0.126 | -0.096 |
| | SW | .062* | 0.008 | 0 | 0.047 | 0.077 |
| SW | BW | -.196* | 0.008 | 0 | -0.212 | -0.180 |
| | LA | -.172* | 0.008 | 0 | -0.188 | -0.157 |
| | PT | -.062* | 0.008 | 0 | -0.077 | -0.047 |

Based on observed means.

The error term is Mean Square(Error) = .001.

* The mean difference is significant at the .05 level.

Table 4.2.4. Duncan and Turkey post-hoc subsets of the Density at 12% MC results.

| Density, 12% MC (g/cm^3) | | | Subset | | | |
|---|---|---|---|---|---|---|
| | Species | N | 1 | 2 | 3 | 4 |
| Tukey HSDa,b,c | SW | 34 | 0.391 | | | |
| | PT | 35 | | 0.459 | | |
| | LA | 34 | | | 0.579 | |
| | BW | 30 | | | | 0.603 |
| | Sig. | | 1 | 1 | 1 | 1 |
| Duncan a,b,c | SW | 34 | 0.391 | | | |
| | PT | 35 | | 0.459 | | |
| | LA | 34 | | | 0.579 | |
| | BW | 30 | | | | 0.603 |
| | Sig. | | 1 | 1 | 1 | 1 |

Means for groups in homogeneous subsets are displayed.
The error term is Mean Square(Error) = .001.
Uses Harmonic Mean Sample Size = 33.152. Alpha = .05.

Table 4.2.5. Duncan and Turkey post-hoc subsets of the Density when Dry results.

| Density, Dry (g/cm^3) | | | Subset | | | |
|---|---|---|---|---|---|---|
| | Species | N | 1 | 2 | 3 | 4 |
| Tukey HSDa,b,c | SW | 34 | 0.369 | | | |
| | PT | 35 | | 0.431 | | |
| | LA | 34 | | | 0.542 | |
| | BW | 30 | | | | 0.565 |
| | Sig. | | 1 | 1 | 1 | 1 |
| Duncan a,b,c | SW | 34 | 0.369 | | | |
| | PT | 35 | | 0.431 | | |
| | LA | 34 | | | 0.542 | |
| | BW | 30 | | | | 0.565 |
| | Sig. | | 1 | 1 | 1 | 1 |

Means for groups in homogeneous subsets are displayed.
The error term is Mean Square(Error) = .001.
Uses Harmonic Mean Sample Size = 33.152. Alpha = .05.

Table 4.3.0 Mechanical and physical properties of four underutilized species in northwestern Ontario.

| Property | White birch | Eastern larch | Poplar | White spruce |
|---|---|---|---|---|
| MOE (MPa) | 7,772.22 (±1,231.204) | 6,948.82 (±1,230.025) | 7,704.00 (±956.440) | 6,106.76 (±1,247.76) |
| MOR (MPa) | 76.92 (±9.27) | 68.28 (±10.15) | 67.03 (±6.56) | 52.32 (±7.09) |
| Maximum Stress (MPa) | 38.957 (±3.246) | 44.307 (±4.665) | 37.089 (±3.124) | 33.179 (±3.487) |
| Maximum Load (kPa) | 15,332.41 (±1,452.605) | 17,066.97 (±1,795.278) | 13,986.29 (±1,172.602) | 13,318.24 (±1,590.250) |
| Density at 12% MC (g/cm$^3$) | 0.603 (±0.032) | 0.579 (±0.041) | 0.459 (±0.030) | 0.391 (±0.026) |
| Density dry (g/cm$^3$) | 0.565 (±0.032) | 0.542 (±0.039) | 0.431 (±0.028) | 0.369 (±0.027) |

Note: Mean results are listed with the standard deviations of ±2Std in the brackets.

# 5.0 DISCUSSION

Comparisons of MOR, MOE, and compression parallel to the grain results of this study to those of Jessome (2000) and Kennedy (1965) are summarized in Table 5.1. Comparisons of the density results of this study to those of Jessome (1977), Singh (1984), and Kennedy (1965) are summarized in Table 5.2. Additional reported densities can be found in Gonzalez' (1990) summary of studies for comparison of measures from various regions within Canada, the United States, and intercontinentally.

White birch MOR and MOE results are lower than the averages reported by Jessome (1977) and Kennedy (1965) (Table 5.1). The maximum stress measure for compression parallel to the grain is more similar to the other two studies (Table 5.1). The density at 12% MC is slightly higher than Jessome (1977) and Kennedy (1965), and much higher than Singh (1984) (Table 5.2). The density at oven-dry is very similar to the other three studies (Table 5.2).

Eastern larch result for MOR is slightly lower than the averages reported by Jessome (1977) and Kennedy (1965) (Table 5.1). The result for MOE is much lower than the averages reported in the other two studies (Table 5.1). The maximum stress measure for compression parallel to the grain is quite similar to other two studies (Table 5.1). The density at 12% MC is slightly higher than Jessome (1977) and Kennedy (1965), and much higher than Singh (1984) (Table 5.2). The density at oven-dry is very similar to the other three studies (Table 5.2).

Table 5.1. Comparison of MOR, MOE, and maximum stress properties from the present study with those reported by Jessome (2000) and Kennedy (1965) (in MPa).

| | Property | Present Study | Jessome[a] | Kennedy[b] |
|---|---|---|---|---|
| White birch | MOR | 76.9 | 94.8 | 94.8 |
| | MOE | 7,772.2 | 12,900.0 | 12,846.0 |
| | Max. Stress | 38.9 | 44.7 | 44.7 |
| Eastern larch | MOR | 68.3 | 76.0 | 75.9 |
| | MOE | 6,948.8 | 9,380.0 | 9,414.4 |
| | Max. Stress | 44.3 | 44.8 | 44.8 |
| Poplar | MOR | 67.0 | 67.6 | 67.6 |
| | MOE | 7,704.0 | 11,200.0 | 11,277.6 |
| | Max. Stress | 37.1 | 36.3 | 36.3 |
| White spruce | MOR | 52.3 | 62.7 | 62.7 |
| | MOE | 6,106.8 | 9,930.0 | 10,002.8 |
| | Max. Stress | 33.18 | 36.9 | 36.9 |

Note: [a] eastern Canadian provinces,[b] various Canadian provinces

Table 5.2. Comparison of densities from the present study with those reported by Jessome (1977), Singh (1984), and Kennedy (1965) (in g/cm$^3$).

| | Moisture Content | Present study | Jessome[a] | Singh[b] | Kennedy[c] |
|---|---|---|---|---|---|
| White birch | 12% | 0.603 | 0.571 | 0.481 | - |
| | Dry | 0.565 | 0.588 | 0.556 | 0.59 |
| Eastern larch | 12% | 0.579 | 0.506 | 0.458 | - |
| | Dry | 0.542 | 0.544 | 0.530 | 0.54 |
| Poplar | 12% | 0.459 | 0.408 | 0.401 | - |
| | Dry | 0.431 | 0.424 | 0.458 | 0.42 |
| White spruce | 12% | 0.391 | 0.372 | 0.386 | - |
| | Dry | 0.369 | 0.393 | 0.432 | 0.39 |

Note: [a] eastern Canadian provinces,[b] Canadian prairie provinces,[c] various Canadian provinces

Poplar MOR result is very similar to the averages reported by Jessome (1977) and Kennedy (1965) (Table 5.1). The result for MOE is much lower than the averages reported in the other two studies (Table 5.1). The maximum stress measure for compression parallel to the grain is quite similar (Table 5.1). The density at 12% MC is slightly higher than those reported by Jessome (1977), Kennedy (1965), and Singh (1984) (Table 5.2). The density when oven-dry is very similar to the other three studies (Table 5.2).

White spruce MOR result is lower than the averages reported by Jessome (1977) and Kennedy (1965) (Table 5.1). The result for MOE is much lower than the averages reported in the other two studies (Table 5.1). The maximum stress measure for compression parallel to the grain is similar to the other two studies (Table 5.1). The density at 12% MC and when oven-dry are quite similar to those reported by Jessome (1977), Kennedy (1965), and Singh (1984) (Table 5.2).

Some differences in the results of this study to the other studies may be due to slightly different processing and calculation methods; the specific instruments and standards for testing are assumed but were not stated (Alemdag 1984; Singh 1986). The other studies included in the comparison here sampled data from outside northwestern Ontario. Regional variation of vegetation, climatic zones, as well as natural genetic variation are likely reasons for the differences reported here (Alemdag 1984; Singh 1986).

Wood is described as an orthotropic material; it has unique and independent mechanical properties on the longitudinal, radial, and tangential axes (Kretschmann 2010). Inherent variability in mechanical properties occurs along the stem of an individual tree and within individuals of the same species depending on localized growing conditions (i.e. soil and site conditions, or growing space) (Kretschmann 2010; Cown 2001). These sources of variability were not accounted for in the scope of this study.

# 6.0 CONCLUSION

Ontario's forest industry needs to generate new innovations and new markets to reinvigorate its position. Engineered wood products are growing in demand within Canada and internationally. This provides an opportunity to add value beyond the traditional lumber and pulp industries. White birch, eastern larch, poplar, and white spruce are four species in northwestern Ontario where alternative end-products and markets could increase their utilization and value.

The common mechanical properties tested for the purpose of engineering wood products are modulus of elasticity (MOE), modulus of rupture (MOR), and compression parallel to the grain. The properties vary within a species depending on the climate and genetic variation in the region. Therefor it is necessary to determine the properties of the species grown in northwestern Ontario.

In this study, modulus of elasticity (MOE), modulus of rupture (MOR), compression parallel to the grain, as well as density was determined of four underutilized species in northwestern Ontario using ASTM standards to derive statistically sound results. Future research can use the results to evaluate potential value-added uses of these species for engineered wood products.

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# APPENDIX

Table A. Raw data of MOR and MOE test.

| sample | MOE (Mpa) | MoR (Mpa) | sample | MOE (Mpa) | MoR (Mpa) | sample | MOE (Mpa) | MoR (Mpa) | sample | MOE (Mpa) | MoR (Mpa) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| BW14 | 7970 | 75.6 | Sw14 | 6810 | 60.4 | Pt24 | 8240 | 73.7 | La32 | 7620 | 80.2 |
| BW19 | 6880 | 71.3 | Sw12 | 5780 | 46.4 | Pt6 | 7580 | 58 | La13 | 5620 | 59.9 |
| BW10 | 7230 | 72.5 | Sw23 | 7760 | 65.6 | Pt12 | 8940 | 74.2 | La27 | 5620 | 65.9 |
| BW25 | 8410 | 79.8 | Sw31 | 6750 | 53.9 | Pt28 | 6640 | 61.8 | La6 | 6480 | 68.4 |
| BW5 | 5870 | 66.4 | Sw34 | 8460 | 69.7 | Pt32 | 6100 | 57.4 | La28 | 6700 | 74.2 |
| BW16 | 5540 | 58.2 | Sw20 | 6320 | 56.5 | Pt11 | 8100 | 68.4 | La31 | 6160 | 64.8 |
| BW9 | 8260 | 81.9 | Sw25 | 5770 | 44.8 | Pt22 | 7960 | 70.3 | La10 | 8540 | 88.1 |
| BW4 | 6380 | 75 | Sw21 | 5640 | 48.8 | Pt29 | 8400 | 69.6 | La33 | 6400 | 56.6 |
| BW22 | 9800 | 92.5 | Sw27 | 5700 | 54.8 | Pt14 | 7930 | 70.6 | La18 | 7460 | 69.5 |
| BW21 | 9100 | 87.8 | Sw30 | 5800 | 56.4 | Pt25 | 8890 | 75.3 | La17 | 7480 | 72 |
| BW15 | 7670 | 73 | Sw33 | 6650 | 62.2 | Pt17 | 8440 | 72.9 | La5 | 6800 | 71.3 |
| BW1 | 6920 | 63.9 | Sw18 | 6620 | 52.8 | Pt16 | 7230 | 72.2 | La12 | 6050 | 73.7 |
| BW18 | 8160 | 72 | Sw2 | 5870 | 49.5 | Pt33 | 7640 | 66.3 | La26 | 9770 | 74.6 |
| BW7 | 9140 | 87.9 | Sw13 | 5930 | 50 | Pt21 | 7620 | 69.3 | La9 | 8710 | 91.4 |
| Bw30 | 8930 | 68.8 | Sw1 | 5200 | 48.3 | Pt2 | 7440 | 65 | La29 | 6650 | 71.5 |
| Bw32 | 7940 | 75.7 | Sw7 | 5550 | 49.6 | Pt19 | 8360 | 66.5 | La15 | 5480 | 62.8 |
| Bw26 | 7510 | 78.2 | Sw19 | 5350 | 48.9 | Pt30 | 7360 | 64 | La30 | 6340 | 65.7 |
| Bw31 | 8370 | 78.9 | Sw24 | 5240 | 43.7 | Pt7 | 8610 | 72.1 | La2 | 5340 | 64.1 |
| Bw28 | 9870 | 95.9 | Sw29 | 6000 | 51.4 | Pt4 | 6230 | 54.4 | La24 | 7470 | 73 |
| Bw20 | 7620 | 84 | Sw6 | 5060 | 38.7 | Pt9 | 7070 | 60.9 | La23 | 8180 | 59.4 |
| Bw11 | 10000 | 93.2 | Sw8 | 5550 | 46.7 | Pt18 | 8870 | 75.6 | La4 | 6770 | 63.7 |
| Bw8 | 7140 | 73.5 | Sw10 | 6410 | 50.5 | Pt15 | 9250 | 72.7 | La21 | 6070 | 60 |
| Bw27 | 6910 | 71.9 | Sw28 | 5940 | 51.5 | Pt26 | 5870 | 49 | La14 | 7310 | 62.7 |
| Bw3 | 6860 | 80.4 | Sw4 | 7370 | 67.2 | Pt3 | 7970 | 68.2 | La1 | 6210 | 60.4 |
| Bw2 | 8750 | 82.5 | Sw5 | 6620 | 56.7 | Pt8 | 8430 | 72.1 | La7 | 7020 | 78.4 |
| Bw6 | 6910 | 70.3 | Sw26 | 5980 | 45.5 | Pt34 | 6810 | 56.4 | La20 | 8500 | 77.7 |
| Bw29 | 5710 | 65.7 | Sw9 | 5290 | 46.2 | Pt31 | 8420 | 74.5 | La19 | 6930 | 64.8 |
| | | | Sw32 | 7080 | 59.2 | Pt35 | 7040 | 65.2 | La22 | 7310 | 74 |
| | | | Sw22 | 5840 | 47.5 | Pt13 | 5710 | 60 | La34 | 7050 | 66.9 |
| | | | Sw3 | 5130 | 46.8 | Pt1 | 5980 | 61.8 | La8 | 4850 | 40.6 |
| | | | Sw17 | 5040 | 49.3 | Pt23 | 8750 | 71.6 | La25 | 9770 | 69.7 |
| | | | Sw15 | 6510 | 59.5 | Pt10 | 7660 | 65.7 | La16 | 5730 | 53.6 |
| | | | Sw16 | 6390 | 46.3 | Pt36 | 8740 | 71.5 | La11 | 5370 | 56.9 |
| | | | Sw11 | 6220 | 53.6 | Pt20 | 7560 | 68 | La3 | 8500 | 85.1 |
| | | | | | | Pt5 | 7800 | 70.7 | | | |

Table B. Raw data for compression parallel to the grain test.

| Sample | Max Load kPa | Max Stress MPa | Sample | Max Load kPa | Max Stress MPa | Sample | Max Load kPa | Max Stress MPa | Sample | Max Load kPa | Max Stress MPa |
|---|---|---|---|---|---|---|---|---|---|---|---|
| BW 15 | 14650 | 56 | SW 15 | 16100 | 39.4 | LA 5 | 16870 | 40.5 | PT 18 | 15020 | 39.8 |
| BW 16 | 11930 | 32.7 | SW 14 | 16140 | 38.4 | LA 9 | 20500 | 53.1 | PT 28 | 13470 | 35.9 |
| BW 2 | 15700 | 36.6 | SW 27 | 13280 | 33.2 | LA 11 | 16250 | 40.6 | PT 29 | 14640 | 39.3 |
| BW 1 | 15830 | 36.4 | SW 7 | 14160 | 35.8 | LA 14 | 18240 | 47.7 | PT 31 | 14360 | 37.8 |
| BW 19 | 15340 | 39.8 | SW 9 | 11790 | 29.5 | LA 25 | 19410 | 47.9 | PT 26 | 10500 | 28.5 |
| BW 22 | 14890 | 40.2 | SW 16 | 11320 | 28.2 | LA 8 | 12620 | 33.4 | PT 8 | 14780 | 39 |
| BW 17 | 15800 | 40.8 | SW 1 | 12490 | 31.3 | LA 10 | 19790 | 52.8 | PT 21 | 13920 | 36.8 |
| BW 13 | 15430 | 39.6 | SW 31 | 13940 | 34.1 | LA 19 | 17470 | 45.9 | PT 32 | 11780 | 31.1 |
| BW 6 | 17390 | 39.3 | SW 4 | 16420 | 39.8 | LA 24 | 17710 | 47.6 | PT 6 | 12720 | 33.7 |
| BW 7 | 15940 | 43.2 | SW 8 | 12620 | 32 | LA 17 | 16500 | 40.8 | PT 2 | 13590 | 36.1 |
| BW 26 | 13320 | 36.1 | SW 5 | 15260 | 37 | LA 26 | 20800 | 54 | PT 12 | 14000 | 37 |
| BW 14 | 14430 | 39.2 | SW 17 | 12700 | 32.3 | LA 23 | 17300 | 43.3 | PT 17 | 15270 | 40.1 |
| BW 11 | 17400 | 38.9 | SW 23 | 15100 | 37.1 | LA 28 | 16470 | 43.3 | PT 27 | 14770 | 35.6 |
| BW 18 | 16000 | 40.8 | SW 12 | 11740 | 29.5 | LA 2 | 16580 | 40 | PT 22 | 14580 | 39.1 |
| BW 32 | 14760 | 38.1 | SW 32 | 13050 | 31.7 | LA 20 | 18390 | 49 | PT 7 | 13400 | 35.6 |
| BW 8 | 13600 | 31.9 | SW 19 | 12960 | 32.4 | LA 12 | 17300 | 45.3 | PT 10 | 13810 | 37 |
| BW 23 | 16580 | 43.4 | SW 2 | 12000 | 30.3 | LA 30 | 15450 | 42.4 | PT 3 | 14080 | 37.3 |
| BW 9 | 15780 | 41.3 | SW 34 | 15800 | 38 | LA 32 | 20100 | 52.7 | PT 25 | 15490 | 41.5 |
| BW 3 | 17860 | 40.1 | SW 30 | 14190 | 35.6 | LA 31 | 16640 | 43.9 | PT 33 | 13320 | 35.6 |
| BW 29 | 13520 | 32.1 | SW 10 | 12780 | 32 | LA 18 | 17510 | 46.1 | PT 20 | 14210 | 37.6 |
| BW 25 | 15010 | 40.4 | SW 24 | 11090 | 27.9 | LA 4 | 15200 | 40.6 | PT 1 | 13720 | 36.4 |
| BW 31 | 15100 | 40 | SW 33 | 16490 | 40.2 | LA 7 | 17830 | 43.2 | PT 34 | 12620 | 33.4 |
| BW 27 | 13580 | 36 | SW 18 | 13830 | 34 | LA 34 | 15060 | 40.1 | PT 35 | 15870 | 42.3 |
| BW 5 | 14660 | 38.2 | SW 20 | 13590 | 34.3 | LA 27 | 15840 | 42.1 | PT 13 | 12940 | 34.2 |
| BW 20 | 18210 | 42.9 | SW 28 | 13890 | 34.4 | LA 3 | 18940 | 48.6 | PT 4 | 11630 | 30.5 |
| BW 4 | 15140 | 39.8 | SW 13 | 13010 | 32.4 | LA 22 | 17600 | 46.6 | PT 16 | 14860 | 39.6 |
| BW 21 | 14960 | 39.7 | SW 29 | 12490 | 31.4 | LA 21 | 15910 | 41.3 | PT 15 | 14120 | 37.3 |
| BW 10 | 14420 | 37.8 | SW 3 | 12920 | 34 | LA 13 | 15060 | 39.9 | PT 24 | 15010 | 39.9 |
| BW 24 | 17410 | 45.5 | SW 11 | 12840 | 31.9 | LA 33 | 17060 | 45 | PT 19 | 14120 | 37.2 |
| | | | SW 6 | 12110 | 30.8 | LA 6 | 15570 | 40.7 | PT 30 | 14050 | 37.6 |
| | | | SW 22 | 11570 | 29.6 | LA 16 | 16500 | 43.3 | PT 23 | 13480 | 36.6 |
| | | | SW 26 | 11030 | 27.6 | LA 29 | 15250 | 40.3 | PT 5 | 15100 | 40.1 |
| | | | SW 21 | 12690 | 33.1 | LA 1 | 15490 | 40.5 | PT 9 | 13540 | 36.3 |
| | | | SW 25 | 11430 | 28.9 | | | | PT 14 | 15110 | 40.2 |
| | | | | | | | | | PT 36 | 15640 | 42.1 |

Table C. Raw data for density measurements.

| sample | Density 12% | Density Dry | sample | Density 12% | Density Dry | sampl | Density 12% | Density Dry | sample | Density 12% | Density Dry |
|---|---|---|---|---|---|---|---|---|---|---|---|
| BW14 | 0.5787059 | 0.5428133 | Sw14 | 0.4369368 | 0.4020541 | Pt20 | 0.4607391 | 0.430314 | La32 | 0.65412946 | 0.624299 |
| BW19 | 0.5669248 | 0.533831 | Sw12 | 0.3720971 | 0.3742009 | Pt5 | 0.4530355 | 0.4271798 | La13 | 0.53890774 | 0.499306 |
| BW10 | 0.5742093 | 0.5392457 | Sw23 | 0.3890969 | 0.3891354 | Pt6 | 0.4206223 | 0.3988688 | La27 | 0.58897629 | 0.551527 |
| BW25 | 0.5834262 | 0.5495254 | Sw31 | 0.3905738 | 0.3575648 | Pt24 | 0.4714189 | 0.4458431 | La6 | 0.59937647 | 0.556936 |
| BW5 | 0.5763337 | 0.537962 | Sw34 | 0.4392941 | 0.4066768 | Pt12 | 0.473548 | 0.4407018 | La28 | 0.59349525 | 0.559709 |
| BW16 | 0.6041589 | 0.5660366 | Sw20 | 0.3909717 | 0.3853333 | Pt28 | 0.4707242 | 0.4440909 | La31 | 0.57570022 | 0.532027 |
| BW9 | 0.5955249 | 0.5543124 | Sw25 | 0.3854555 | 0.3811451 | Pt32 | 0.4086177 | 0.383352 | La10 | 0.61708901 | 0.582422 |
| BW4 | 0.5989342 | 0.5593014 | Sw21 | 0.3828079 | 0.3403568 | Pt11 | 0.4579956 | 0.4300342 | La33 | 0.52148026 | 0.491065 |
| BW22 | 0.6682164 | 0.6307895 | Sw27 | 0.3658687 | 0.3372784 | Pt22 | 0.4776663 | 0.4524704 | La18 | 0.58880289 | 0.55699 |
| BW21 | 0.6380675 | 0.6085414 | Sw30 | 0.3940954 | 0.3731328 | Pt29 | 0.4663113 | 0.4366593 | La17 | 0.58995296 | 0.568954 |
| BW15 | 0.5778305 | 0.5521437 | Sw33 | 0.4405682 | 0.4037631 | Pt25 | 0.4845182 | 0.4527393 | La5 | 0.56610476 | 0.516585 |
| BW1 | 0.5581526 | 0.5202107 | Sw18 | 0.3764995 | 0.3397975 | Pt17 | 0.4759385 | 0.4481478 | La12 | 0.59772727 | 0.558786 |
| BW18 | 0.5664077 | 0.5309038 | Sw2 | 0.3660258 | 0.3695272 | Pt16 | 0.484187 | 0.4526604 | La26 | 0.65219756 | 0.609395 |
| BW7 | 0.6170671 | 0.5808864 | Sw13 | 0.3836888 | 0.3725783 | Pt33 | 0.4621976 | 0.4367053 | La9 | 0.62507463 | 0.593671 |
| Bw17 | 0.6015466 | 0.5686323 | Sw1 | 0.3661035 | 0.338668 | Pt21 | 0.4577131 | 0.4285221 | La29 | 0.57877249 | 0.534409 |
| Bw24 | 0.631393 | 0.5316121 | Sw7 | 0.4020412 | 0.3963927 | Pt2 | 0.4408042 | 0.4161056 | La15 | 0.53835417 | 0.489526 |
| Bw13 | 0.5875655 | 0.5537529 | Sw19 | 0.3686226 | 0.3381503 | Pt19 | 0.4859256 | 0.4572013 | La30 | 0.51466009 | 0.482801 |
| Bw23 | 0.665 | 0.63456 | Sw24 | 0.3731498 | 0.3545542 | Pt30 | 0.4753656 | 0.444635 | La2 | 0.59846316 | 0.555456 |
| Bw32 | 0.5604636 | 0.5256221 | Sw29 | 0.378279 | 0.358473 | Pt7 | 0.4986325 | 0.4671271 | La24 | 0.57830923 | 0.54203 |
| Bw26 | 0.626169 | 0.5896083 | Sw6 | 0.3657982 | 0.3135675 | Pt4 | 0.376318 | 0.3497964 | La23 | 0.57471163 | 0.543306 |
| Bw31 | 0.5787066 | 0.5414567 | Sw8 | 0.3658805 | 0.3366667 | Pt9 | 0.4290206 | 0.3996375 | La4 | 0.53141649 | 0.487486 |
| Bw28 | 0.6543938 | 0.6128945 | Sw10 | 0.379902 | 0.3818402 | Pt18 | 0.4770701 | 0.4464901 | La21 | 0.55904915 | 0.516737 |
| Bw20 | 0.6356065 | 0.5936291 | Sw28 | 0.4111155 | 0.3952476 | Pt15 | 0.4667108 | 0.4408997 | La14 | 0.53862788 | 0.500856 |
| Bw11 | 0.60318 | 0.5667489 | Sw4 | 0.4578431 | 0.4266868 | Pt26 | 0.3874897 | 0.3668364 | La1 | 0.56290391 | 0.52227 |
| Bw8 | 0.6473228 | 0.6127339 | Sw5 | 0.43093 | 0.3885208 | Pt3 | 0.4684411 | 0.4366887 | La7 | 0.57671906 | 0.539711 |
| Bw27 | 0.624232 | 0.5848094 | Sw26 | 0.3754031 | 0.375178 | Pt8 | 0.4957173 | 0.4613751 | La20 | 0.60142553 | 0.569966 |
| Bw3 | 0.6283032 | 0.5903175 | Sw9 | 0.3760101 | 0.3626559 | Pt34 | 0.4131447 | 0.3884432 | La19 | 0.57106 | 0.532468 |
| Bw2 | 0.5933458 | 0.5491908 | Sw32 | 0.3691379 | 0.3424414 | Pt31 | 0.4924111 | 0.4678862 | La22 | 0.59569474 | 0.562336 |
| Bw6 | 0.5765616 | 0.5391144 | Sw22 | 0.3721016 | 0.3509762 | Pt35 | 0.4922732 | 0.4638803 | La34 | 0.52249495 | 0.48175 |
| Bw29 | 0.5750399 | 0.5600481 | Sw3 | 0.3892999 | 0.3621875 | Pt13 | 0.4396938 | 0.4089309 | La8 | 0.69570953 | 0.635837 |
| | | | Sw17 | 0.4075 | 0.3765879 | Pt1 | 0.4534724 | 0.4268143 | La25 | 0.57057778 | 0.541915 |
| | | | Sw15 | 0.4383463 | 0.4081764 | Pt23 | 0.4432424 | 0.4184379 | La16 | 0.57324295 | 0.52757 |
| | | | Sw16 | 0.3701889 | 0.3233333 | Pt10 | 0.4678542 | 0.4367243 | La11 | 0.50580247 | 0.494742 |
| | | | Sw11 | 0.3978487 | 0.3926474 | Pt36 | 0.4931848 | 0.4621808 | La3 | 0.60461384 | 0.567535 |
| | | | | | | pt27 | 0.4532977 | 0.427114 | | | |

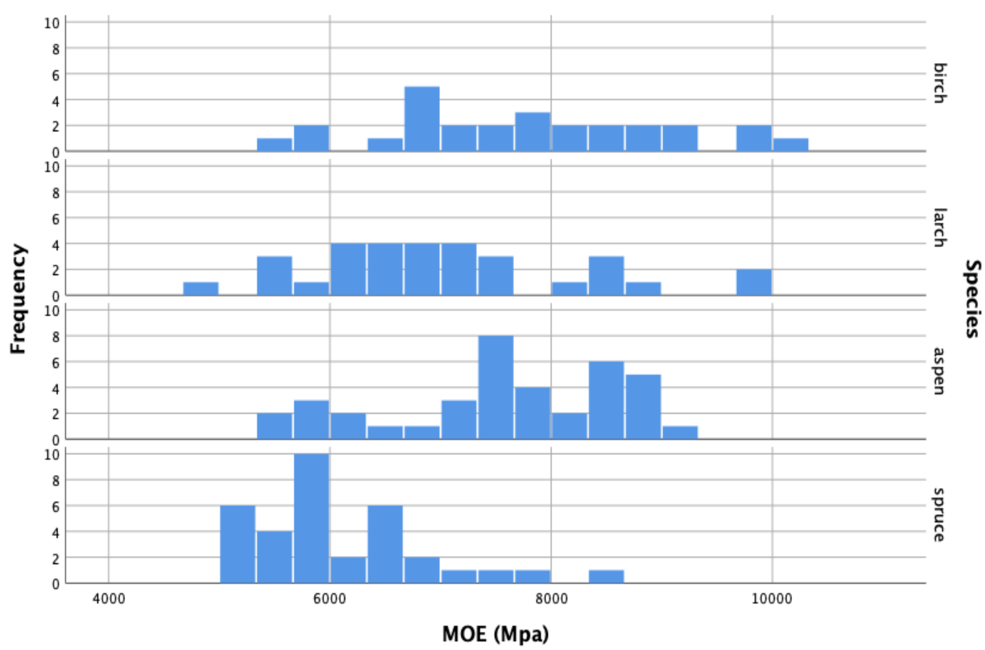


Figure A. Frequency distribution for MOE test.

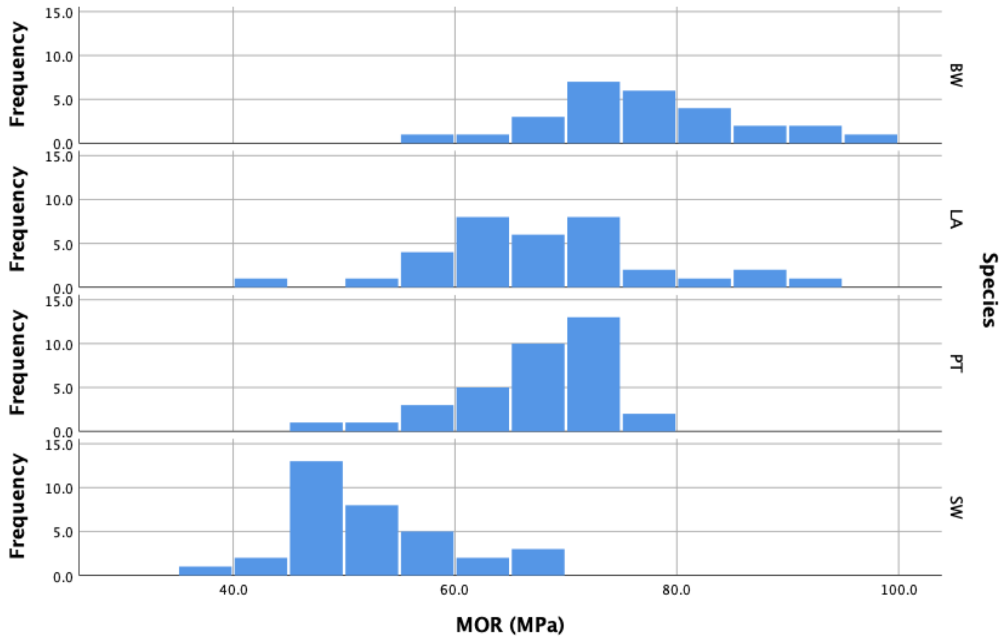


Figure B. Frequency distribution for MOR test.

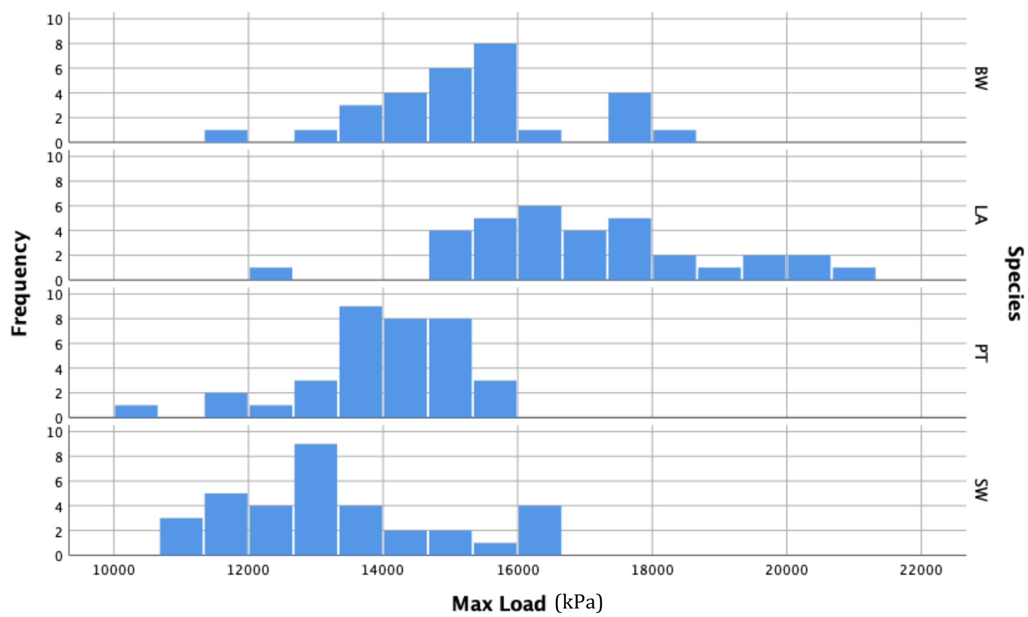


Figure C. Frequency distribution for max load test.

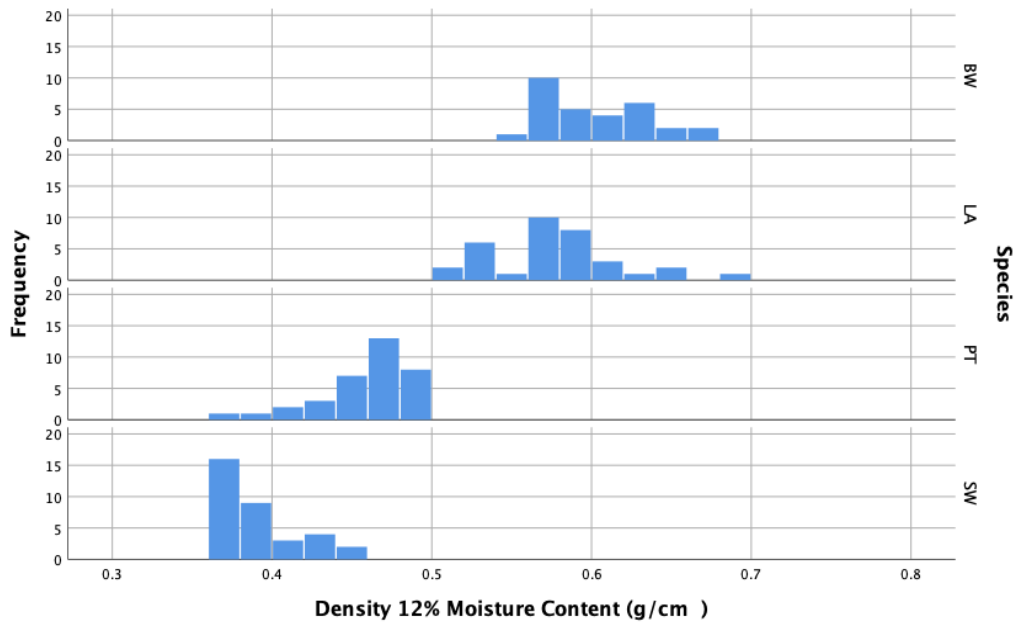


Figure D. Frequency distribution for density at 12% MC.

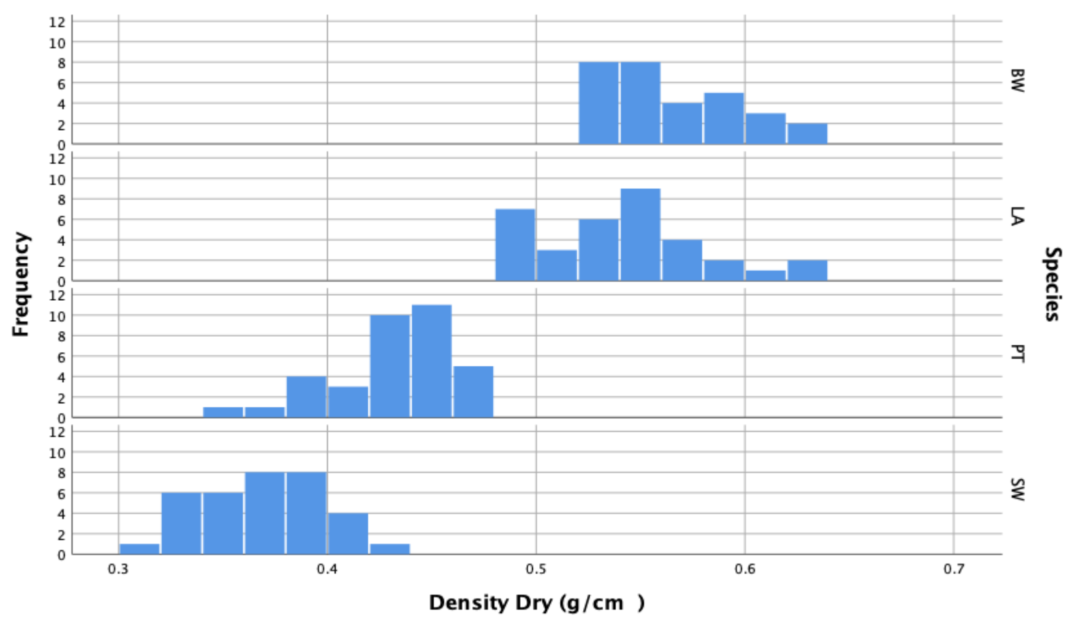


Figure E. Frequency distribution for density dry.