COMPARATIVE ANALYSIS OF THE PROPERTIES OF TAMARACK (*Larix laricina* (Du Roi) K. Koch) PARTICLEBOARD AND THERMALLY TREATED ORIENTED STRAND BOARD (OSB)

By

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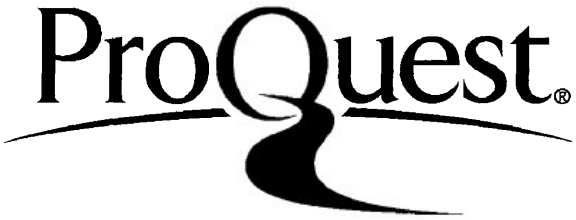

ABSTRACT

Engineered wood products (EWPs), for example, particleboard and oriented strand board (OSB), are normally made from wood residuals or small particles of under-utilized wood species for replacing solid sawn products as its cost effective, more uniform, and a more efficient method of using available timber resources. Although, denser and more uniform than conventional wood, particleboard is a cheaper and low strength composite material. In addition, lower stability of OSB is the main obstacle in the expansion into a larger segment of the market; even though other properties are comparable to plywood. Thermal modification is a relatively new technology attracting the attention of many industries for improving stability in an environmentally friendly way, and the use of thermally modified composite panels for structural purposes is of increasing interest. Therefore, this research was carried out focusing on the manufacturing of particleboard and thermally modified OSB. The purpose of the first aspect of the research was to investigate if the physical and mechanical properties of particleboard can be improved by using different types of raw material (juvenile wood, mature wood whole tree, mature wood heartwood from tamarack (*Larix laricina* (Du Roi) K. Koch)). For the second aspect of this research, the effect of heat-treatment temperatures (160^0C and 175^0C) on selected physical and mechanical properties of thermally modified OSB was determined.

The properties evaluated for both parts were bending (MOR and MOE) and bonding strength (IB), thickness swelling (TS), water absorption (WA), linear expansion (LE),

surface hardness (H), and face screw withdrawal strength (FS).

Results conducted from the first study showed that the mature whole tree board outperformed the minimum standard values on most selected properties. Comparing the effects of raw material, it is found that the heartwood board produced better physical properties and bonding strength compared to others, which is probably due to the high content of extractives present in the heartwood.

Results gathered from the second study indicate that wood variation not only exists in solid wood products, but also in the composite products. Low temperature treatment (160^{0}C) displayed a better dimensional stability than the control group without largely affecting mechanical properties in a negative way, such as FS and hardness. However, high temperature samples (175^{0}C) negatively affected mechanical properties, however, display better water resistance than the control group. For structural end use purposes, parallel to the long direction of OSB should be confirmed as it is the strength direction.

The results of this study suggest utilization of under-utilized species for particleboard manufacturing in the panel industry is possible, and the increased life span of exterior applications by using a low temperature ThermoWood treatment on OSB is a feasible process to allow new applications for OSB, including areas of higher moisture content where OSB currently cannot be utilized in these conditions.

Keywords: engineered wood products, raw material effects, physical and mechanical properties, tamarack, thermal modification.

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LIST OF ABBREVIATIONS

Anti-swelling Efficiency (ASE)

Analysis of Varaiance (ANOVA)

Diameter at Breast Height (DBH)

Diphenyl-methane-diisocyanate (MDI)

Equilibrium Moisture Content (EMC)

Engineered Wood Products (EWPs)

European Standards (EN)

Face Screw Withdrawal (FS)

Fiber Saturation Point (FSP)

Glued Laminated Timber (Glulam)

Hydroxyl Groups (-OH)

Internal Bonding (IB)

Irreversible Thickness Swelling (ITS)

Juvenile Wood (JW)

Low Density (LD)

Lightness Difference (ΔL^*)

Linear Expansion (LE)

Lakehead University Wood Science and Testing Facility (LUWSTF)

Laminated Veneer Lumber (LVL)

Moisture Content (MC)

Modulus of Elasticity (MOE)

Mature Heartwood (MH)

Modulus of Rupture (MOR)

Mature Whole Tree (MW)

Oil Heat Treatment (OHT)

Oriented Strand Board (OSB)

Phenol-formaldehyde (PF)

Potential of Hydrogen (pH)

Polymeric Isocyanate Binder (pMDI)

Parallel Strand Lumber (PSL)

Relative Humidity (RH)

The American National Standard for Particleboard (ANSI)

The American Society for Testing and Materials (ASTM)

Total Color Difference (ΔE^*)

The Canadian Standards Association (CSA)

The Natural Resources Research Institute's (NRRI) Center

Thickness Swelling (TS)

Urea-formaldehyde (UF)

Ultraviolet Light (UV)

Volatile organic chemicals (VOCs)

Water Absorption (WA)

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CHAPTER 1

INTRODUCTION

1.1 Background

Wood resources have significantly changed as a result of human use and management resulting in lower quality of available timber. This has led to a change in some of the products produced in order to utilize this lower quality fibre supply. One area that has expanded is the engineered wood products (EWPs) sector where lower quality fibre is used in a variety of products that do not require large pieces of solid lumber, rather flakes, strands or wafer are utilized combined with resins and presses. This process allows the production of large panels without the need for veneer-sized logs. In addition to creating a valuable product from a fibre source that was traditionally not used, consumers will pay more for many of these wood products that have been environmentally certified by a third party (Grönroos and Bowyer, 1999).

In 2011, the wood-based panel market in North America was essentially flat with an increase in the export markets (Eastin, 2012). For example, exports of North American structural panels increased by 14%, with oriented strand board (OSB) recording the largest increase at +16.5%, followed by plywood at +8.1% (Eastin, 2012). In 2012, the North American particleboard industry produced more than 3.2 billion ft^2 (0.3 billion m^3) of this type of building material (Deoman, 2014).

In order to maintain the balance between supply and demand in the panel industry, as well as protecting the wood resource, it is important to explore more usable wood species currently under-utilized and employ new technology during the production process (Eastin, 2012).

Fortunately, some under-utilized species like tamarack *(Larix laricina* (Du Roi) K. Koch*)* are available and can be used in the panel industries (Leitch et al., 2011), particularly with new innovative technologies to add valuable properties such as thermal treatments to increase dimensional stability and fungal and moisture resistance without jeopardizing the environment (Finnish ThermoWood Association, 2003).

Numerous studies have focused on the properties of particleboard produced using different adhesives and non-wood materials like sunflower stalk and needle litter (Alma et al., 2005; Bektas et al., 2005; Nemli et al., 2008), fewer studies have investigated the use of under-utilized species as the raw material and the raw material effect on the properties of particleboard in North America. Additionally, thermally modified OSB has been attracting attention recently, however, most are interested in the high temperature treatment and pre-treated OSB strands instead of post-treated OSB panels in the low temperature treatment (Del Menezzi, 2004; Goroyias and Hale, 2002; Kotilainen, 2000; Paul et al., 2006; Paul et al., 2007). Therefore, it is important to understand the concept of sustainable development by fully utilizing the forest resources in the panel industries and utilizing new

technologies such as thermal modification to not only extend the life cycle of the panel products but also find utilization in new applications.

1.2 Objectives

This research is attempting to use under-utilized species like tamarack to expand the wood fibre resources available to the panel industry and applying ordinary products like OSB to a thermal modification process in order to extend the life cycle of OSB and create new applications for a modified product.

In order to achieve the long-term goals, this research can be divided into two parts:

1) Production and property testing of tamarack particleboard and

2) Property testing of thermally modified OSB.

The testable objectives for part 1 were to manufacture particleboard from different tamarack raw materials, and:

i) test the raw material effects on the properties of particleboard by comparing juvenile, mature heartwood, and mature whole tamarack.

For part 2 of this research, specific objectives were to treat OSB panels at two temperature levels in a thermal modification kiln, and:

i) test the variance of the control panels,

ii) test the effects of temperatures by comparing a low temperature cook (160° C wood temperature) and a high temperature cook (175° C wood temperature) with corresponding controls for dimensional stability and mechanical property measurements, and

iii) test the difference between parallel and perpendicular MOE and MOR to the long axis of the OSB control panels.

1.3 Organization of the Thesis

The general introduction is presented in Chapter 1 including the objectives of this research. Chapter 2 provides a comprehensive literature review of previous studies on tamarack, engineered wood products, including OSB, particleboard, and their processes and properties, thermal modification and its changes to the wood structure and properties, and the combination of thermal technology and wood products. Chapter 3 presents the materials and methods used in this study. Chapter 4 discusses the performance of particleboard made from different raw materials. The differences between two thermal modification temperature cook levels and their corresponding controls are discussed in this chapter as well. The general conclusions from this study and recommendations for future research are summarized in Chapter 5. The literature reference list follows Chapter 5 along with appendices.

CHAPTER 2

LITERATURE REVIEW

2.1 Tamarack

2.1.1 The Tree and Its Silviculture

Tamarack is an under-utilized deciduous conifer species native to North America (Natural Resources Canada, 2011), which has the largest range from northwestern territories to Newfoundland and south to the northeastern United States (Figure 1). The low utilization of tamarack is due to its relatively high density, high content of spiral grain, high possibility of checking, twisting, warping, as well as a low resistance to impact (Yang and Hazenberg, 1987).

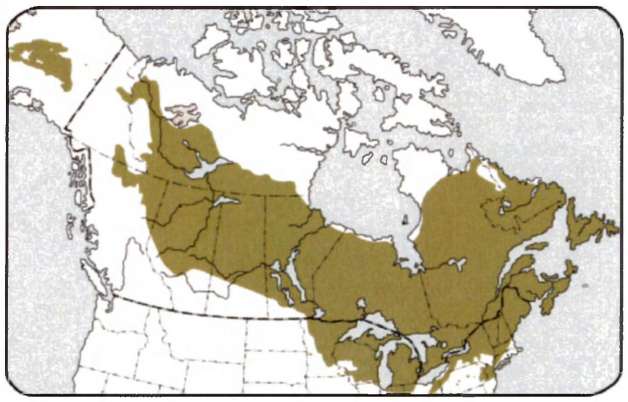

Figure 1. Distribution of Tamarack in North America (Source: Natural Resources Canada, 2011).

Tamarack can tolerate a variety of climatic and soil conditions, such as high soil moisture, high acidity and low soil temperatures resulting in its wide distribution (Burns, 1990). The most common habitat for tamarack is wet to moist organic soils, and the optimum environment for the growth of tamarack is on moist well-drained

and light soil, however, it cannot survive if it is exposed to flooding or drought for a long duration (White, 2006; Zhang and Koubaa, 2008). Mature tamarack trees can grow as high as 15- to 23-m in height and as thick as 36- to 51-cm in diameter at breast height (DBH). Tamarack forms both pure and mixed stands in the boreal forests of Canada. In mixed stands, it is usually associated with black spruce (*Picea mariana* (Mill.) B.S.P.), balsam fir (*Abies balsamea*), and white spruce (*Picea glauca* (Moench) Voss) (Burns, 1990; Zhang and Koubaa, 2008). Tamarack is also known to be a shade intolerant species, although juvenile trees can tolerate some shade during growth while mature trees need to be dominant in order to survive (Burns, 1990).

2.1.2 Variances of Tamarack

Wood variance occurs both within a tree and between individual trees (Yang and Hazenberg, 1987; Zobel and Buijtenen, 1989). Within tree variance usually refers to the difference between crown and butt in the longitudinal direction, sapwood and heartwood in the radial direction, as well as cellular differences between juvenile and mature wood (Bowyer et al., 2003). Generally, a maturing tree contains both juvenile wood in the crown and juvenile and mature wood in the butt with the mature wood encasing the juvenile core (Figure 2) (Jozsa and Middleton, 1994). With respect to sapwood and heartwood, the juvenile core of the stem makes up the inner portion of the heartwood with the mature wood making up the outer portion of the heartwood followed by the sapwood located between the heartwood and bark (Miller, 2011).

Specifically for tamarack, density, growth rate, latewood proportion, and tracheid

length are highly variable from pith to bark (Burns, 1990; Yang et al., 1986; Zhang and Koubaa, 2008). Wood density shows an initial decrease from the pith to a minimum and then follows a slight increasing trend toward the bark. The heartwood density of tamarack is, however, higher than that in the sapwood due to the high content of arabio-galactane which adds mass without changing volume (Srinivasan et al., 1999). Tracheid length increases from the pith outwards to bark (Balatinecz, 1982; Yang and Hazenberg, 1987). Chemically, hemicelluloses and lignin content are higher in the sapwood than in the heartwood (Balatinecz, 1982).

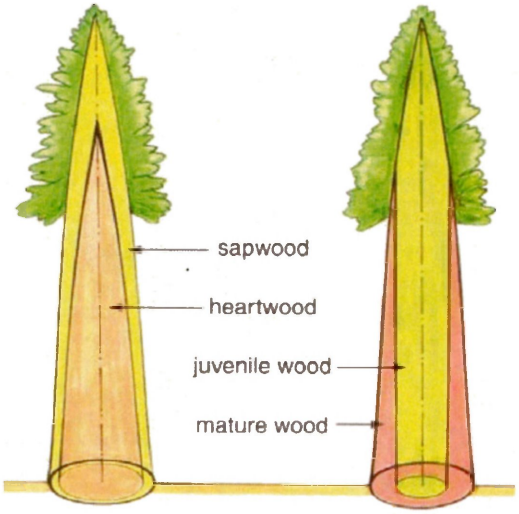

Figure 2. Juvenile and Mature Wood Distributions within a Tree (Source: Jozsa and Middleton, 1994).

Juvenile wood possesses some undesirable features for specific wood utilization purposes, namely, the higher longitudinal and volumetric shrinkage, higher content of reaction wood and spiral grain and higher degree of knottiness (Yang et al., 1986; Zobel and Buijtenen, 1989). However, juvenile wood does display good flexure properties like elasticity due to the larger microfibril angles of the S1, S2 and S3 secondary wall layers, while the microfibril angles in mature wood produces stiffer

properties due to the lower microfibril angle of the S2 layer in comparison to the larger microfibril angles of the S1 and S3 layers (Figure 3) (Bowyer et al., 2003; Zhang and Koubaa, 2008).

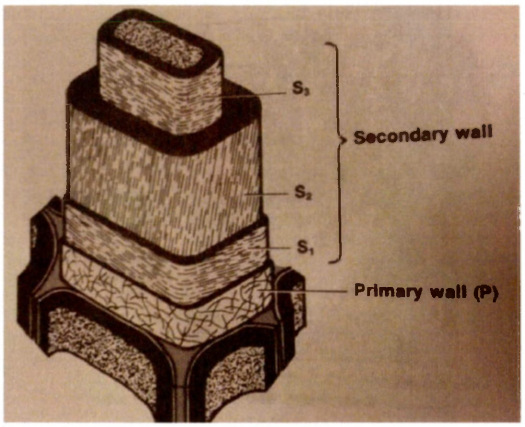

Figure 3. Diagram of a mature cell wall layering (Source: Bowyer et al., 2003).

The different types and quantities of extractives, many water soluble extractives, provide the heartwood of tamarack unique properties compared to sapwood such as darker color, harder to impregnate, and higher durability (Srinivasan et al., 1999; Wang and DeGroot, 1996). Additionally, a unique oily and greasy feel in the heartwood of tamarack is likely due to the presence of the flavanonols and ferulic acid esters (Nair and Rudloff, 1959).

2.1.3 Properties of Tamarack

Density is the most useful physical property since it determines wood stability, strength, and firmness. Generally, the denser the wood, the higher the strength and firmness the wood will be (Bowyer et al., 2003). For instance, variation in the density of naturally grown tamarack positively affected wood hardness (Bustos et al., 2009). It has been reported that tamarack wood is moderately heavy, especially

compared to eastern spruce species (white spruce, black spruce, and red spruce (*Picea rubens* (Sarg.)), pine species (white pine (*Pinus strobus*), red pine (*Pinus reisnosa*), and jack pine (*Pinus banksianna*)) and balsam fir (Balatinecz, 1982; Zhang and Koubaa, 2008).

Moisture content (MC) determines wood shrinkage and will affect the dimensional stability of wood products (Zhang and Koubaa, 2008). Tamarack has a much higher shrinkage value in sapwood than that in heartwood, just like other softwoods (Balatinecz, 1982). Compared to other softwood, tamarack displays a relatively lower shrinkage value in all radial, tangential and volumetric aspects, especially true when compared with western larch (*Larix occidentalis*) (Table 1).

Table 1. Shrinkage Values of Selected Softwoods Native to Canada (Source: Bowyer et al., 2003).

Species Common Names	Shrinkage (Green to Oven Dry) %		
	Radial	Tangential	Volumetric
Tamarack	**3.7**	**7.4**	**13.6**
Larch, western	4.5	9.1	14.0
Black spruce	4.1	6.8	11.3
Balsam fir	2.9	6.9	11.2
Douglas-fir (Interior North)	3.8	6.9	10.7

Note: The values for Douglas-fir (*Pseudotsuga menziesii*) depends on the locations, the interior north includes Washington and the states of Idaho, Montana, and Wyoming, showing the lowest values of shrinkage when compared to other locations.

Nature durability is described as the ability of wood to defend against decay. Generally, heartwood of species that display natural durability commonly display

darker colors compared to sapwood (Srinivasan et al., 1999). For example, eastern white cedar (*Thuja occidentalis*) displays a high decay resistance of the heartwood and as expected, its heartwood displays a light brown color compared to its white sapwood (Mullins and McKnight, 1981); however, for western hemlock (*Tsuga heterophylla* (Raf.) Sarg), which is a slightly resistant to decay species, displays a light color with little difference between heartwood and sapwood (Mullins and McKnight, 1981). Specifically, tamarack shows a russet to reddish-brown heartwood color and is rated as slight to moderately durable (Table 2) (Balatinecz, 1982; Bowyer et al., 2003). The degree of durability depends on the larch species, age of trees, and decay fungus (Morris et al., 2011; Srinivasan et al., 1999).

Table 2. Comparative Resistance of Heartwood Decay (Source: Bowyer et al., 2003).

Resistant or very resistant	Moderately resistant	Slightly or nonresistant
Cedars	Douglas-fir	True firs (western and eastern)
Bald cypress	Pine, eastern white	Spruces
Catalpa	Larch, western	Poplars
Junipers	**Tamarack**	Hemlocks
Yew, pacific		

Mechanical properties essentially are the strength properties of a species wood and should be taken into consideration primarily when wood products are used in structural situations. Tamarack displays a relatively high modulus of elasticity (MOE) (9400MPa), a moderate modulus of rupture (MOR) (79MPa) and relatively, low resistance to impact (side hardness: 3.3kN) when compared to other softwoods (Table 3) (Bowyer et al., 2003). Thus, tamarack has the potential to be used as a

structural material as well as an alternative tree species for wood products since the strength properties, especially the bending and compressive strength, are stronger than other conifers found in the boreal forest (Balatinecz, 1982; White, 2006). In addition, the good moulding and planning properties of tamarack provides the possibility that tamarack is an excellent wood for high-quality products such as flooring (Bustos et al., 2009), however, during machining it requires more attention since tamarack has a tendency to warp due to the presence of spiral grain (Bustos et al., 2009; Mullins and McKnight, 1981).

Table 3. Mechanical Properties of Some Softwood Native to Canada (Source: Balatinecz, 1982; Bowyer et al., 2003).

Species Common Names	Moisture Content (%)	Specific Gravity (g/cm^3)	Modulus of Rupture (*kPa*)	Modulus of Elasticity (*MPa*)	Hardness (side) *kN*
Tamarack	**Green**	**0.48**	**47000**	**8600**	**3.3**
	12		**79000**	**9400**	
Western Larch	Green	0.55	60000	11400	4.3
	12		10700	14300	
Jack pine	Green	0.42	43000	8100	—
	12		78000	10200	
Black spruce	Green	0.41	41000	9100	
	12		79000	10500	
Douglas-fir	Green	0.45	52000	11100	3.0
	12		88000	13600	
Balsam fir	Green	0.34	36000	7800	—
	12		59000	9600	

2.1.4 Utilization of Tamarack

Pulp products are where tamarack is most commonly consumed in the United States. Other than for pulp, the moderate durability and rot resistance give tamarack the

opportunity to be used as posts, poles, railroad ties (treated) and other wood products in Northwest Ontario. Additionally, locally companies used tamarack as mine timbers in Thunder Bay; dogsled runners, boat ribs and fish traps are made from young tamarack stems in interior Alaska, and wooden ship construction used knees from larger trees historically (Burns, 1990; Mullins and McKnight, 1981; Zhang and Koubaa, 2008). As a result of its natural variability in properties, using all parts of trees in the most efficient manner in the most appropriate industry can improve the competitiveness of the forestry sector, suggesting that tamarack can be used for many end use products, such as bio-products, veneer, and fencing, due to the axial and radial variability, as well as the different properties of heartwood and sapwood (Leitch et al., 2011).

2.2 Engineered Wood Products

Innovation in the forest products sector is essential to meet the challenges and demands of an ever increasing population (Hammett and Youngs, 2002). One group of wood composites is engineered wood products (EWPs) that occupy a large portion of the wood composite market (Maloney, 1996). Many EWPs are manufactured by binding strands, particles, fibers, and veneers of wood together with adhesives (Bowyer et al., 2003). These types of products using mixtures of species, smaller diameter stems, or even under-utilized species as the raw material increase the resource base available to the industry and allow increased utilization of each tree (Hammett and Youngs, 2002; McKeever, 1997).

The list of EWPs includes a range of derivative wood products such as plywood, oriented strand board (OSB), particleboard, glued laminated timber (glulam), laminated veneer lumber (LVL), parallel strand lumber (PSL) and so on, depending on the specific sizes of wood particles and the manufacturing processes used (Bowyer et al., 2003; Mullins and McKnight, 1981).

Specifically, plywood is using veneer from large-diameter trees and old-growth timber and gluing with adhesives under heat and intense pressure, with the orientation that the grain of every other layer is parallel to the first and the adjacent veneers lies at right angles (Bowyer et al., 2003). OSB is manufactured from thin wood strands that are created from small irregular logs bonded together with adhesives under heat and pressure (Maloney, 1996). Particleboard is a product made by compressing small particles of low valued wood and bonding with an adhesive (Bowyer et al., 2003). Glulam is produced by gluing together two or more thinner layers of lumber with the grain of all layers parallel to the length (Cai and Ross, 2010). Laminated veneer lumber requires veneer instead of lumber from logs of moderate to large size and bonded with adhesives with the orientation of all veneer layers' grain parallel to the long axis of the piece (Bowyer et al., 2003). Parallel strand lumber consists of relatively longer wood strands than those used for OSB from waste softwood veneer in the lengthwise direction combined with adhesives under heat and pressure (Maloney, 1996). Table 4 presents the bending properties of some selected wood products, and the properties result from the manufacturing

process that determines the end use of each product. For example, OSB has fairly consistent sized particles and they are oriented specifically in the panel while particleboard has variable sized particles that are also layered in a specific order. Some EWPs utilize layered veneers, so the panel construction is specific to end use potential (Bowyer et al., 2003).

Table 4. Static Bending Properties of Different Wood Products (Source: Cai and Ross, 2010).

Material	Specific Gravity (g/cm^3)	Modulus of Elasticity (GPa)	Modulus of Rupture (MPa)
Plywood	0.4-0.8	6.96-8.55	33.72-42.61
Oriented Strand board	**0.5-0.8**	**4.41-6.28**	**21.80-34.70**
Particleboard	**0.6-0.8**	**2.74-4.14**	**15.17-24.13**
Glued-laminated timber	0.4-0.6	9.00-14.50	28.61-62.62
Laminated veneer lumber	0.4-0.7	8.96-19.24	33.78-86.18

The EWPs market has grown very quickly in the last few decades from a limited list of products to a large list of full building-material commodity and specialized products. This recent explosion in EWPs is attributed to the need to use available wood more effectively and also the reduced size of many trees being harvested with decreased properties compared to old growth or more mature forests. Additionally, the ease of installation, excellent workability, good mechanical properties, beautiful appearance and longer design life than their organic natural counterparts following exposure to the same extent of rot or environmental conditions (Anderson, 2008; Bowyer et al., 2003; Wang and Xing, 2010).

However, the demand for structural panels such as the plywood industry in North America, and particleboard and OSB in Europe, actually decreased slightly during a considerable downward trend in EWPs markets during the past several years as a result of the global financial crisis around 2009 (Eastin, 2012). Fortunately, in the past two years, the structural panels (OSB and plywood) and particleboard industries are displaying strong signs of recovery in North America, especially in Canada where the economy remains strong (Eastin, 2012).

2.3 Particleboard

The classification of particleboard has been unclear for a long time. Even though some publications categorized particleboard as "non-structural panels" (Bowyer et al., 2003), others regarded it as structural panels and classified it as an EWPs because particleboard is being used in buildings, housing construction, furniture manufacturing, and interior decoration sectors worldwide, and is also approved by building codes and government agencies (Ashori and Nourbakhsh, 2008; Maloney, 1996). It is well know that the smaller the particles of the face layer, the smoother the face will be. Therefore, particleboard contains multiple layers of different sizes of particles in a reasonable length-to-thickness ratio and randomly mixed as is displayed in Figure 4 (Mullins and McKnight, 1981).

The typical particleboard has three layers with the larger particles in the core, and smaller, fiber-like particles on both faces (Bowyer et al., 2003; Cai and Ross, 2010). The American National Standard for Particleboard (ANSI, 1998) classifies

particleboard by density and is represented by the minimum values for each density category. The board density includes three levels with high density (0.80g/cm^3 or greater), medium density (0.64 to 0.80g/cm^3), and low density (less than 0.64g/cm^3) (ANSI, 1998).

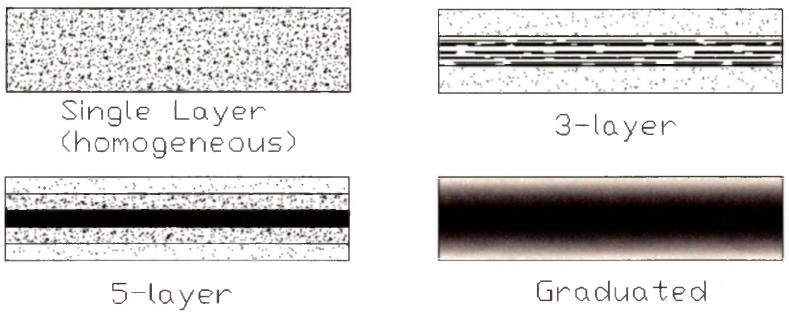

Figure 4. Different Types of Particleboard.

2.3.1 Manufacture Process

The general process for making particleboard is similar in many respects to other panel EWP where small particles of wood and adhesives are bonded together under heat and pressure in a hot press (Figure 5). Specific manufacturing processes may differ depending on the specific end use of the product (Bowyer et al., 2003).

Raw materials for manufacturing particleboard are variable. Several researchers have investigated particleboard production using wood residuals, sunflower stalks and needle litter, showing that most low valued wood residuals can be used as an alternative material in particleboard industries (Bektas et al., 2005; Mo et al., 2003; Nemli et al., 2008).

However, according to the literature, the quality of particleboard is rarely influenced by raw materials, rather the adhesive used, the specific processing parameters, and

the content of extractives in the raw material has a greater effect on particleboard quality (Ashori and Nourbakhsh, 2008; Lamason and Gong, 2007).

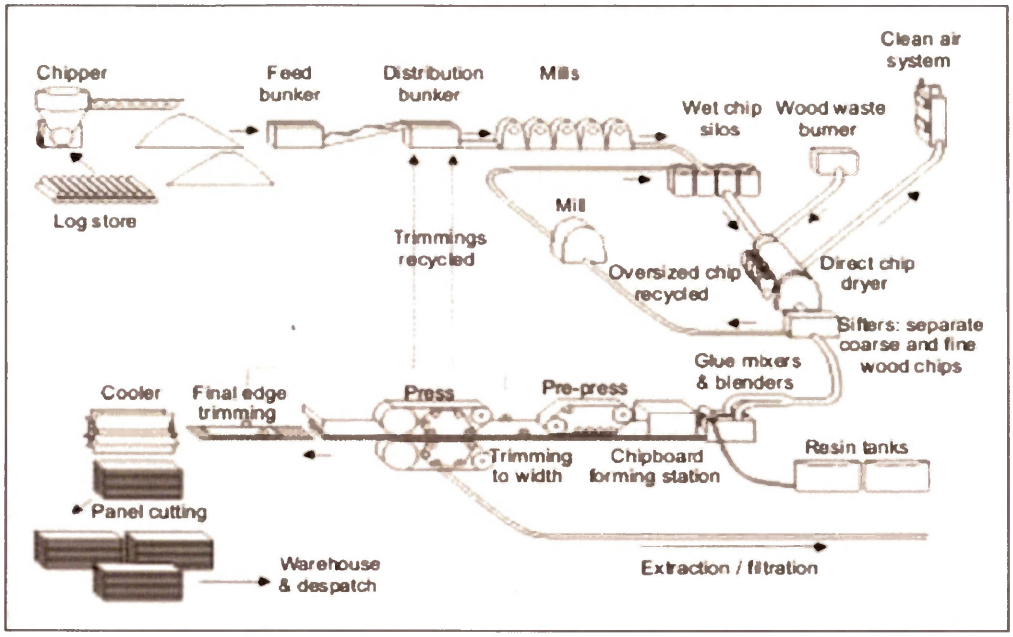

Figure 5. Figures of Particleboard Manufacture Process (Source: Board, 2006).

Specifically, press-closure rate and press cycle are two important variables when considering the stability of particleboard. For example, a rapid closure rate can improve particleboard's bond strength (IB) and dimensional stability without affecting hardness (Halligan, 1970); however, intermediate pressure-time cycles give the lowest thickness swelling (TS). Resin content and press time are the main factors influencing physical and mechanical properties. To be specific, mechanical properties are improved when the press time is increased from 4 min to 5 min, as a longer press time provides sufficient time to transfer the heat to the core section (Ashori and Nourbakhsh, 2008). Additionally, compression ratio, the ratio between board density and wood density, positively and significantly affect hardness, MOE, and nail withdrawal resistance (Lamason and Gong, 2007; Mendes et al., 2009).

2.3.2 Physical Properties

According to the literature, lower board density leads to higher board strength since the glue line contact is much easier and better under the pressure (Hrázský and Král, 2009). Thus, there is no need to produce higher density boards, as there is no improvement on strength; instead the board is just heavier (Bowyer et al., 2003). In addition, higher board density requires a higher compression set during pressing operations, which results in increased swelling when stress is relieved (Halligan, 1970). Additionally, lower density species reduce density variation within the mat; hence making it easier to obtain adequate inter-particle contact (Bowyer et al., 2003). In a 3-layer board, higher density surface flakes lead to an increase in TS while improving bending strength; whereas a higher density of core raw material contributes to lower TS and lower IB (Halligan, 1970). The extractives and potential of hydrogen (pH) of the raw material also affects the quality of particleboard, as the higher content of extractives creates difficulties using and curing resins and there is the possibility of internal rupture in the board (Ibrahim, 2010; Sernek et al., 2008). Moisture content determines the quality and life span of particleboard by affecting the combination of binder and particles during manufacturing as well as after the pressing operation (Halligan, 1970).

Dimensional stability is measured in the thickness and linear directions parallel to the long side of a sample. Two forms of TS include the swelling of the wood panel itself and the release of compression stress from the pressing operation, which is

non-recoverable, also known as "spring back" (Halligan, 1970). In a panel the linear direction easily absorbs moisture when exposed to a wet environment. Even though the changes are small, problems followed by changes are significant if boards are installed without protection from swelling (Bowyer et al., 2003). Therefore, particles should kept as dry as possible or even acetylated before making the board (Kalaycioglu et al., 2005; Pan et al., 2007), by using water resistant resin or adding wax to reduce TS (Lin et al., 2008), lower board density to reduce the possibility of "spring back"(Okino et al., 2004), or gluing the particleboard to the subfloor when used as underlayment to reduce dimensional changes (Hse et al., 2012).

2.3.3 Mechanical Properties

Mechanical properties for all structural boards that should be concerned include MOE, MOR, IB, and face screw-holding strength (FS). According to the literature, bond strength is more susceptible to resin content than bending strength (Lin et al., 2008). This is due to the fact that IB strength is strongly correlated to adhesive bond strength, which is a result of resin content (Grigoriou, 2000). Specifically, increasing resin content means increasing resin per unit surface area resulting in a higher adhesive bond strength (McNatt et al., 1989) Specific gravity has a strong positive relationship with FS and bending strength in particleboard (Cai et al., 2004; Eckelman, 1975; Wang et al., 2007). However, compared to solid wood, particleboard made from the same species has a lower FS (Eckelman, 1975). This can be explained by the reconstituted nature of the board compared to solid wood

(McNatt et al., 1989). To be specific, solid wood has all cells joined through middle lamellas and high lignin concentrations acting as a binding agent to create a strong bond between cells due to the nature of wood (Bowyer et al., 2003), whereas particleboard is gluing pieces of raw material together. Therefore, the consistency and strength of particleboard at the cellular level is not as high as that found in solid wood (Bowyer et al., 2003; McNatt et al., 1989). As mentioned before, the presence of bark and wax can improve the water resistance of particleboard, however, the high content of bark and wax can lower mechanical properties of particleboard (Lin et al., 2008), since the presence of bark results in a higher pH value, and hence, lowers the bond quality in Urea-formaldehyde resin (UF) boards (Pan et al., 2007). Therefore, the balance between these two properties should be carefully considered depending on end use. For example, high bark and wax are beneficial in a panel that is exposed to a moisture environment where there is no need for high mechanical properties (Zheng et al., 2006), while low bark and wax maybe required where high mechanical properties are needed such as in engineered I-joists (web material) and wall systems that are sealed so no moisture is allowed near the panels.

2.4 Oriented Strand Board

Oriented strand board was first produced in Canada in 1964, and developed rapidly and marketed as an improved form of Canadian wafer board in the early 1980s (Bowyer et al., 2003). It is unique because the long wood strands are oriented in one direction in each layer instead of randomly placed (OSB Guide, 2011). OSB has

replaced a portion of the plywood market gradually over the years due to its lower cost of raw material (Maloney, 1996), more efficient resource utilization by using lower-valued wood, good dimensional stability and is easy to handle and install (Wang and Xing, 2010). OSB is commonly used in traditional applications like sheathing, subflooring, and roof decking markets, as well as other areas such as structural insulated panels, furniture, and the webs for wood I-joists due to its superior performance (Bowyer et al., 2003; Ibrahim, 2010).

2.4.1 Manufacturing Process

Generally, OSB panels are made of strands, flakes or wafers sliced from small diameter, round wood logs and bonded with an exterior-type binder under heat and pressure (Bowyer et al., 2003). Raw materials used for producing OSB are usually low to medium density species like aspen (*Populus tremliodes*), yellow poplar (*Linodendron tulipifera*), and birch (*Betula spp.*) (Forest Products Laboratory, 1999). Particularly, OSB panels consist of layered mats where surface layers are composed of strands aligned in the long panel direction and inner-layers consist of cross- or randomly-aligned strands (Figure 6). These large mats are then subjected to intense heat and pressure to become a compressed panel, which are then cut to size (OSB Guide, 2011) (Figure 7). Strand dimensions are predetermined and have a uniform thickness of 0.75mm, and are usually 75- to 150-mm long and 25mm wide (Bowyer et al., 2003; Ibrahim, 2010; OSB Guide, 2011). Similar to particleboard, processing conditions of OSB for different end use products are changed and manipulated

depending on the specific application (Bowyer et al., 2003).

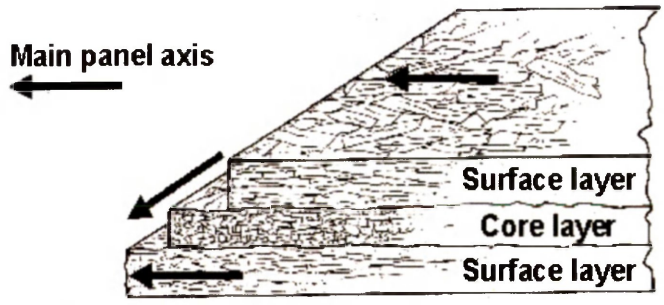

Figure 6. Diagram of General OSB Strands Orientation (Source: JP. Aucoin, 2014)

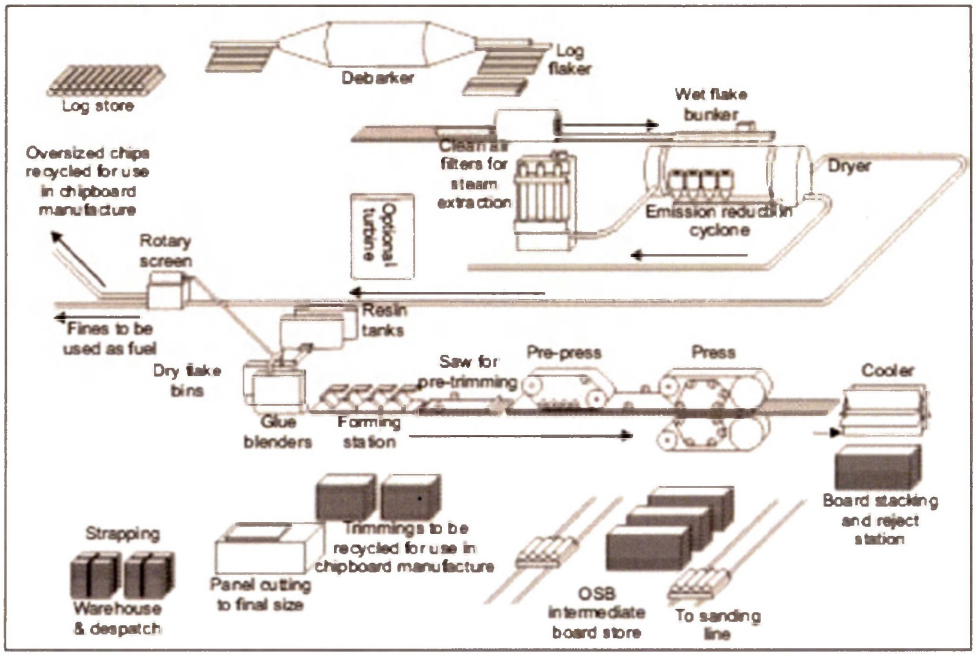

Figure 7. Figure of OSB Manufacture Process (Source: Board, 2006).

2.4.2 Properties of OSB

OSB performance is largely dependent on board density, strand geometry, resin type and its content, adhesive penetrations and processing parameters (Erdil and Zhang, 2002; Ibrahim, 2010). The continuous wood fiber, interweaving of the long strands and degree of strand orientation in surface layers provide OSB strong and unique strength properties (OSB Guide, 2011). Waterproof adhesives such as methylene-diphenyl-diisocyanate (MDI) are bonded together with strands yielding good IB,

rigidity, and creating superior moisture resistance for OSB (Forest Products Laboratory, 1999).

Specifically, with increasing density, MOR and MOE in both parallel and perpendicular directions are increased (Hrázský and Král, 2009), but result in a greater degree of TS (Ibrahim, 2010). For example, Hrázský and Král (2009) found that when board density was 579kg/m^3, the MOR and MOE were around 16% greater than those when the board density was 553kg/m^3 for a 15mm thick OSB. The adhesive content affects mechanical properties of OSB as well. For example, MOR and MOE in both parallel and perpendicular directions and IB are reduced as a result of decreased resin concentration (Hrázský and Král, 2009; Ibrahim, 2010). Specifically, Hrázský and Král (2009) found that when the resin concentration decreased from 3.3kg/100kg for surface layer and 3.6kg/100kg for central layer of polymeric isocyanate binder (pMDI) to 2.7kg/100kg and 30.kg/100kg respectively, there was an associated decrease in MOR (25.44 to 22.4N/mm^2 for parallel direction and 16.46 to 14.22N/mm^2 for perpendicular direction) and MOE (5102 to 4788N/mm^2 and 2409 to 2252N/mm^2, parallel and perpendicular respectively) values, as well as a decrease in IB from 0.33 to 0.28N/mm^2 in a 15mm thick OSB. In terms of the interaction effect between density and adhesive content, decreased density and slightly increased resin concentration can lead to a decreased MOR and MOE, whiles an increase in IB is seen (Hrázský and Král, 2009). This is due to the lower density allowing the board raw materials to access sufficient contact area

during the pressing operation (Ibrahim, 2010).

The Canadian Standards Association (CSA) standard CAN/CSA O325.0 and the standard O437 Series (Structural Board Association and Willowdale, 2004) are the primary requirements of OSB manufactured for floor, roof and wall sheathing in Canada. Standard O437 contains two grades of OSB panels (Grade O-1 and Grade O-2) based on the different nominal thicknesses. Specifically, OSB in Grade O-1 is designed for thickness of 6.35, 7.9, 9.5, 11.1, 12.7, 15.9, 19.0mm; whereas Grade O-2 is a thickness collection of 6.0, 7.5, 9.5, 11.0, 12.0, 12.5, 15.0, 15.5, 18.0, 19.0mm. Table 5 shows the basic properties of OSB based on different grades (thicknesses).

The European Standard (EN 300, 2006) shows the basic requirements for OSB performance depending on the specific end-use-conditions (Table 6).

Table 5. Basic Properties of OSB based on CSA O325.0 and O437.0 OSB (Source: Structural Board Association and Willowdale, 2004).

Properties	Standard	Grade O-1	Grade O-2
Modulus of rupture-parallel (MPa)	O437.0	23.4	29.0
Modulus of rupture-perpendicular (MPa)	O437.0	9.6	12.4
Modulus of elasticity-parallel (MPa)	O437.0	4500	5500
Modulus of elasticity –perpendicular (MPa)	O437.0	1300	1500
Internal bond (MPa)	O437.0	0.345	0.345
Linear expansion, maximum 50-90% RH exposure (%)	O325.0	0.30 along major axis 0.35 across major axis	

Table 6. Properties Requirements for OSB based on End-use-conditions (Source: EN 300, 2006).

Board Type	Bending Strength MPa		Modulus of elasticity MPa		Internal Bond N/mm^2	Thickness Swelling (24 h immersion) (%)
	Major axis	Minor axis	Major axis	Minor axis		
OSB/1	18	9	2500	1200	0.28	25
OSB/2	20	10	3500	1400	0.32	20
OSB/3	20	10	3500	1400	0.32	15
OSB/4	28	15	4800	1900	0.45	12

Note: 1). All values in this table are valid for board thickness range between 10 – 18mm.

2). OSB/1 (non-load-bearing) and OSB/2 (load-bearing) are used in dry condition, whereas OSB/3 (load-bearing) and OSB/4 (heavy duty load-bearing) are used in humid conditions.

2.5 Adhesive Resin

Resin plays a crucial role in the whole process of making panels. The type and concentration of resin used in a product and how effectively it is mixed determines the strength and dimensional properties of the board (Ashori and Nourbakhsh, 2008; Bowyer et al., 2003). Therefore, resin should be cured to give the maximum bond strength, and any factors that lead to a more complete resin cure will reduce TS (Halligan, 1970). It has been noted that the strength and dimensional stability of a board will increase by increasing the resin solids yield (Bowyer et al., 2003; Mendes et al., 2009). This was further confirmed by Ashori and Nourbakhsh (2008) where they found the lowest TS was obtained when urea resin content was applied at 11% to the board compared to 9% and 10%. However, it is unnecessary to use a greater amount of resin (i.e. 11% compared to 9%) due to the high cost of the resin and the incremental improvement does not justify the higher resin content (Bowyer et al., 2003).

2.5.1 Urea-formaldehyde (UF) Resin

UF resin is commonly used in the production of particleboards. Curing of urea resin is affected by wood pH (Halligan, 1970), which has an important role in forming good bonding between resin and particles and therefore, determine the panel properties (Kalaycioglu et al., 2005). Specifically, UF resin cures in a relatively short press time and low curing temperature under acidic conditions (Chow, 1983; Zheng et al., 2006). In the United States, appropriate cost and short curing-cycle time of UF resins make them popular in the adhesive market (Bowyer et al., 2003). The principal disadvantages and obstacles of using UF resins are the lack of resistance to weather and water and its emissions of formaldehyde (Wang et al., 2004). Hence, a mixture of binding and impregnating phenolic resin should be used to reduce TS in urea boards.

2.5.2 Methylene-diphenyl-diisocyanate (MDI) Resin

MDI, one of the isocyanate binders, is used in several European mills as well as the United States. Due to its reaction with wood when put under intense heat, MDI has supreme chemical bonds with wood particles or stands (Chow, 1983; Ibrahim, 2010). Faster press cycles and increased dryer throughput are the two advantages of MDI resin. Hence, using MDI increases the productivity and saves energy for manufacturers (Bowyer et al., 2003; Wang and Xing, 2010). In addition, MDI resin can tolerate higher MC% when compared with other binders such as urea and phenolic resins (Chow, 1983; Wang and Xing, 2010). This is due to the reaction

between the hydroxyl groups (-OH) of wood surface and isocyanate groups (-N=C=O) of MDI resins (Roos and Sleeter, 1997; Wood Based Panels International, 2012). This therefore creates urethane linkages that help MDI-bonded boards perform better when exposed to a wet environment (Ibrahim, 2010). The widespread use of MDI is also due to the reduction in blender maintenance costs, frequency of cleaning required, lower formaldehyde emissions and lower drier energy requirements (Wood Based Panels International, 2012). Moreover, isocyanate is compatible with the waxy from the outer surface of straw in the case of wheat straw boards (Mo et al., 2003). However, the high cost, health risks and the reaction with metal (i.e. fasteners and connectors) of MDI itself are likely the main reasons hindering the expansion of the MDI market (Roos and Sleeter, 1997; Wang and Xing, 2010).

2.5.3 Phenol-formaldehyde (PF) Resin

PF is the primary adhesive in manufacturing structural panels. PF forms waterproof bonds, known as mechanical bonds, so that the product can be used in structural wood composites, however, PF panels are only intended for occasional, short-term exposure to moisture (Wang and Xing, 2010). Compared to MDI, PF is about one-fourth the cost of MDI, making its use more common. However, PF board shows a dark red to black color, and the cure time is longer for PF than that for MDI (Forest Products Laboratory, 1999). Therefore, in order to increase production and retain low cost, industries apply PF on the surface and MDI in the core for manufacturing

OSB panels (Forest Products Laboratory, 1999). However, more attention should be taken in order to minimize the exposure risks associated with both types of these uncured adhesives (Bowyer et al., 2003; Pizzi, c1994).

2.5.4 Utilization of Mixed Resin

As formaldehyde emission is an important concern for board products, researchers have tried to mix several adhesives together in order to get high bond strength and decrease formaldehyde emissions without increasing the cost (Roos and Sleeter, 1997). Grigoriou (2000) combined pMDI and UF resin in a straw-wood composite and found that both dry and wet strengths as well as swelling properties were improved significantly. Mixed adhesive, especially like MDI-UF and MDI-PF, are effective for difficult-to-bond wood veneer and noted for their adaptability to higher MC veneer (Pizzi, c1994). In addition, the effects of MDI-UF mixed adhesive without adding a hardener (NH_4CI) on the properties of particleboard (Wang et al., 2004) indicates that UF can react with MDI at lower temperatures, requiring less energy and reducing non-reacted UF when compared with pure UF resin boards. Grigoriou (2000) also found that UF-MDI particleboard has similar mechanical properties to that of pure UF particleboard, but with considerably lower formaldehyde emissions.

2.6 Thermal Treatment

Wood modification has been investigated for nearly a century already in order to protect wood from environmental effects such as changing humidity, weathering, and

rot or decay, and hence to achieve a longer life span of wood products in exterior use and more efficiently utilize the wood resource (Homan, 2004).

Researchers have shown that wood can be more durable and stable when treated at high temperatures compared to standard drying. There are 4 typical European heat treatments: Retiwood developed in France, Thermowood developed in Finland, oil heat treatment (OHT) developed in Germany and Platowood developed in the Netherlands (Esteves and Pereira, 2008; Homan, 2004). Specifically, retification operates in a nitrogen atmosphere and up to 210° C to 240° C wood temperature for pre-dried wood. Thermowood uses a water spray system to prevent the wood from burning under the temperature range from 150° C to 240° C wood temperature. The OHT process in Germany using hot oil provides good heat transfer and separates wood from oxygen between 180° C and 260° C wood temperature. The Plato process consists of hydro-thermolysis (160° C to 190° C), drying, and curing (170° C to 190° C) steps followed by a conditioning step (Homan, 2004; Militz, 2002).

Thermal modification lowers the pH value, MC, and wetting ability, and consequently, affects the bonding performance, especially when using PF adhesives (Sernek et al., 2008). It is worth noting that no toxic substances have been found during and after the thermal treatment process with the result of lower MC, lighter weight, chemical-free rot resistance, and higher thermal resistance, which conforms to consumer psychology and the environmental protection act (Finnish ThermoWood Association, 2003; Militz, 2008; Winandy and Smith, 2006). However, gas emissions

and waste-water from the process that contains the evaporated resin, formic acid, and other solid constituents should be carefully taken into account and disposed of or utilized (Militz, 2002).

2.6.1 ThermoWood Process

Generally, in Canada, the following processes showing in Table 7 are used for thermal modification, among these; the environmentally friendly Finnish ThermoWood process is used for this project. The process can be divided into three main phases (Finnish ThermoWood Association, 2003):

- Phase 1. Temperature increase and high-temperature drying

  The kiln temperature is raised to 130° C by using heat and steam. Simultaneously, the high-temperature drying takes place and the MC in wood decreases to nearly zero. Duration depends on the initial MC% of the wood, wood species and timber thickness.

- Phase 2. Heat treatment

  Temperature is increased to the set temperature for thermal treatment. When the target level has been reached, the temperature is held for 2–3 hours depending on the end-use application. Water steam is used as a protective vapor to prevent wood from burning during this high temperature phase.

- Phase 3. Cooling and moisture conditioning

  This stage lowers the temperature by using a water spray system. At the temperature of 80–90° C; Re-moisturizing and conditioning takes place to

bring the wood MC% to a useable level of between 4–7% depending on the end use and treatment temperature. Particular attention should be taken since the temperature difference between wood and outside air can easily cause both surface and inside splitting and checking.

Table 7. Thermal Modification Process in Canada.

Processes	Producers
ThermoWood	Les Industries I.S.A. Inc., Normandin, QC.
ThermoWood	ThermalWood Canada, Bathurst, NB.
Perdure	Kisis Technologies, Dolbeau-Mistassini, QC.
Perdure	Groupe Lebel, Cacouna, QC.
Mec torréfaction	Torrexpert, Ripon, QC.
Airex Industries	Torréfaction Plus, St-Gabriel-de-Brandon, QC.
Superior ThermoWood	Superior ThermoWood, Kakabeka Fall, ON.

2.6.2 Changes in Wood Chemical Structure

Wood chemical structure, which mainly refers to the wood polymer components, contains cellulose (40-50% of the dry wood) that is oriented axially in the wood cell offering the strength of wood, hemicelluloses (25-35% of the dry wood) and lignin (20-30% of the dry wood) that exist between cellulose and act as solidifying agents (Deka et al., 2002; Fengel and Wegener, 1983; Wikberg and Maunu, 2004). Other than this, a small quantity of low-molecular-mass compounds and extractives also provide wood unique properties like color, odor, and natural resistance to fungal attack depending on the species, which is different than other materials like metal or plastic (Wikberg, 2005). Specifically, the chemical degradation of wood is

permanently changed and observed as a result of exposure to high temperatures in the order of hemicelluloses, cellulose and lignin (Finnish ThermoWood Association, 2003).

Hemicelluloses degrade first when treatment begins, which is attributed to: 1) the low molecular weight and special branched structure (Fengel and Wegener, 1983), 2) the lack of crystallinity compared to cellulose (Tumen et al., 2010), and 3) the formation of less charred residue and more gaseous products in hemicelluloses (Kotilainen, 2000). As a result, the amount of active -OH groups is reduced and responsible for improved dimensional stability, whereas a decrease in the solidifying agents leads to a reduction in mechanical strength, particularly MOR (Hillis, 1984; Wikberg and Maunu, 2004). According to the literature, degradation of hemicellulose is more sensitive to the temperature than the duration of the treatment. Hence, with the increasing temperature, hemicellulose suffers a large degree of degradation, and wood structure changes with the increasing temperature (Paul et al., 2006).

Cellulose is thermally stable contributing to its crystalline nature, which degrades following the hemicelluloses (Esteves and Pereira, 2008). However, researchers found that cellulose crystallinity increases first attributing to the degradation of noncrystalline cellulose and hemicellulose (Hakkou et al., 2005; Militz, 2008; Yildiz et al., 2006), however, this decreases at higher temperatures due to thermal degradation in both the crystalline and noncrystalline regions (Bhuiyan et al., 2000).

Contrary to cellulose and hemicellulose, lignin displays the highest thermal stability (Finnish ThermoWood Association, 2003), the decomposition of which can be observed only at temperatures above 220° C, where the hemicellulose and cellulose have already decreased significantly and decomposed (Mburu et al., 2007). However, a manual from CTBA reported that cellulose displays the highest thermal stability (Chanrion, P., and Schreiber, J., 2002). Lignin content increases at the beginning of high temperature treatment (Yildiz et al., 2006) due to the reduction of other wood components like hemicellulose and cellulose, as well as the polycondensation reaction (Boonstra and Tjeerdsma, 2006). The increased lignin ratio can be explained by the higher amount of carbonyl groups found in lignin (Esteves and Pereira, 2008), which has a favorable effect on dimensional stability (Militz, 2002).

In terms of the chemical elements that make up wood, carbon (C), hydrogen (H), and oxygen (O) are the three main elements. During thermal treatment, both H and O are decreased with an increase of C (Boonstra and Tjeerdsma, 2006). This is because the two main reactions during high temperature drying are dehydration of the carbohydrates and decarboxylation (cleavage of acetic acid from hemicelluloses) (Militz, 2008), resulting in the reduction of O- and H-contents (Boonstra and Tjeerdsma, 2006). Additionally, lignin condensation reactions lead to a further decrease of H- and O-content (González-Peña et al., 2009).

Wood pH value decreases (from 5.0 to 3.5-4.0) induced by heat treatment as a result

of the formation of acetic acid that comes from thermolysis of the acetyl radicals linked to xylose in xylans and formic acid that associates with carboxylic groups of the glucoronic chains (Esteves and Pereira, 2008; Sernek et al., 2008).

Extractives differ from species to species, and most of them can evaporate easily or are captured by water at the end of the treatment by using the water spray system to cool down the wood (Militz, 2002). For example, a decrease from 5.2% to 1.6% of extractives quantity was observed in *G. robusta* heartwood following treatment (Mburu et al., 2007).

2.6.3 Changes in Physical Properties

Wood color is one of the most valuable characteristics for utilization from an aesthetic point of view. Thermally modified wood displays a darker color compared to its natural color (Militz, 2008). Research has shown that wood turns orange in high temperature environment and is irrelevant of wood species, however, closely related to all chemical components (González-Peña and Hale, 2009a). Therefore, the extent of changes in color depends on the treatment temperature and duration (Militz, 2008). Hence, color parameters can act as predictors for several physical properties (González-Peña and Hale, 2009b) and potentially some mechanical properties such as MOR and hardness (Bekhta and Niemz, 2003; Leitch et al., 2013). For example, González-Peña and Hale (2009b) found that the total color difference (ΔE^*) was a better predictor than the lightness difference (ΔL^*), with statistics of R^2 from 0.24 to 0.94 for most properties including anti-swelling efficiency (ASE),

nominal density, weight loss and strength parameters. In addition, Bekhta and Niemz (2003) found a strong linear relationship with R^2 of 0.99 between ΔE^* and bending strength in thermally modified spruce wood at 200°C wood temperature.

Fiber saturation point (FSP) is the MC% where the cell walls are holding as much water as they can. After cell walls are full of water, the additional water absorbed by the wood will go to fill up the cavities of cells (Elite Global Import Export (E.G.I.E.), 2000; Peck, 1957). Theoretically, most strength and elastic properties increase as wood dries below FSP, around 25 to 30% MC, but wood begins to shrink and swell at the same time (Bowyer et al., 2003). Contrary to this, decay can start only if the MC% of the wood is above FSP (Elite Global Import Export (E.G.I.E.), 2000).

During high temperature treatments, equilibrium moisture content (EMC) decreases with increasing temperature, due to the degradation of water-absorbing -OH groups of α-cellulose and hemicelluloses and formation of O-acetyl groups (Esteves and Pereira, 2008), as well as the increase in hydrophobic material - lignin (Mendes et al., 2013; Tumen et al., 2010). In addition, the formation of cross-linking between the wood fibers also contributes to the decrease in MC% since it increases wood hydrophobicity, and as a consequence, decreases the water sorption of wood (Militz, 2008; Tjeerdsma and Militz, 2005). The reduction in MC% leads to an improvement in dimensional stability since the TS and shrinkage was much lower in heat-treated wood than control wood when exposed to the same humidity (Finnish ThermoWood

Association, 2003; Winandy and Smith, 2006)

The treatment temperature affects weight loss more than the duration of the kiln run (Paul et al., 2007). For example, a study on *Eucalyptus grandis*, *Eucalyptus sallgna*, and *Eucalyptus citriodora* found that the weight loss is less than 5% at 180° C, between 5% and 17% at 220° C and more than 25% at 280° C under the same durations (Almeida et al., 2009). In terms of the mechanisms, water that is stored in the cell cavity, namely free water, starts to evaporate first even at the lower temperature (Deka et al., 2002; González-Peña et al., 2009). At a higher temperature, the physical bonds between water and the hydrophilic groups of wood, also known as bound water, is broken, and therefore, accelerates the movement of water (Hakkou et al., 2005). However, after the water is depleted, the rate of weight loss slows down in the second stage, which may be a result of the release of by-products during the degradation of wood components, primarily hemicelluloses (Deka et al., 2002; Hakkou et al., 2005; Mburu et al., 2007; Poncsák, 2006).

The fungal resistance of thermally modified wood has been shown to be improved (Mburu et al., 2007; Paul et al., 2007). Heat-treated wood displays that the degree of improved decay resistance is positively related to the heating temperature and duration at the temperature (Kim et al., 1998; Militz, 2008). However, the resistance to termites of thermally modified Scots Pine (*Pinus sylvestris*) was decreased, probably attributing to some compounds contained in untreated wood that inhibited termite attack (Shi et al., 2007).

There are several possible explanations for this improved durability: 1) the amount of fungi susceptible material, hemicelluloses that are the primary nutrition source of fungi, is lower (Paul et al., 2006), 2) the reduction of -OH groups lowers the potential target points for fungi such as brown and soft rot (Militz, 2008; Poncsák, 2006), 3) fungal enzymatic systems cannot recognize the modified wood as a substrate (Paul et al., 2006), and 4) creation of new free molecules act as fungicides caused by thermal modification (Weiland and Guyonnet, 2003). However, heat-treated wood cannot be used in ground contact applications without further protection (Finnish ThermoWood Association, 2003; Kamdem et al., 2002).

When wood is used for exterior construction, unprotected wood suffers a variety of degradations as a result of the sunshine, rainfall, and so on. Generally, the surface of weathered wood shows a gray color with checks and cracks (Nuopponen et al., 2004). Ultraviolet (UV) light is the main factor responsible for this change and leads to the reduction of the lignin content due to the de-polymerization of lignin in the wood cell and therefore, results in the degradation and discoloration of the wood surface (Wikberg, 2005). Compared to the untreated weathered wood, the condensed structure of lignin in heat-treated wood may inhibit the UV-light-induced free-radical reactions (Nuopponen et al., 2004), and hence, increase the resistance to natural weathering for thermally modified wood (Wikberg, 2005).

2.6.4 Changes in Mechanical Properties

Mechanical strength of thermally modified wood is inconsistent during the process

depending on the temperature, duration, heating rate and species. Some researchers observed a decrease in bending strength (Boonstra et al., 2007) and compression strength (Yildiz et al., 2006) after thermal modification, some have reported a slight increase in hardness (Leitch, 2009), tangential compressive strength (8%) and compressive strength parallel to the grain (28%) (Boonstra et al., 2007), while others displayed no significant difference in mechanical properties between thermally treated and untreated wood (Del Menezzi et al., 2009).

A reduction range in MOR from 0% (fir) to 49% (spruce) was observed depending on species and treatment process (Shi et al., 2007). Additionally, the rate of the reduction in bending strength is strongly linked to the treatment conditions, especially the duration of treatment, which may be due to the de-polymerization of the carbohydrate fraction (Kim et al., 1998; Poncsák, 2006). For example, the more severe the heat applied, the lower the bending strength, toughness (Boonstra et al., 2007), compression strength of spruce (Yildiz et al., 2006) and the resistance against screw withdrawal (Poncsák, 2006). The larger amount of hemicellulose degradation and the crystallization of amorphous cellulose have been suggested as the cause for larger decreases in MOR (Boonstra et al., 2007; Curling et al., 2001).

Contradictory to this, some researchers are of the opinion that breaking chains of hemicellulose does not reduce the strength of the wood as much as cellulose would, due to the amount of cellulose in wood compared to hemicellulose having a greater influence on strength properties (Salim et al., 2008). Therefore, the relatively minor

degradation of cellulose could be linked to a minor decrease in the strength of wood (Tjeerdsma et al., 1998).

The reduction rate of MOE is not as rapid as MOR (Curling et al., 2001). Specifically, MOE increased during low temperature treatments at 180° C and 200° C but decreases dramatically during treatments at 220° C wood temperature (Esteves and Pereira, 2008), which corresponds to the changes in lignin, especially with the increase of cross-linking to resist internal stresses (Boonstra et al., 2007); and the contributions of the increased amount of crystalline cellulose at the beginning of the treatment at lower temperatures (Curling et al., 2001).

When comparing the difference between softwood and hardwood in terms of strength change induced by high temperature drying, literature shows softwood displays better strength properties than hardwood (Kamdem et al., 2002), which is probably due to the large degree of decomposition in hardwood (Militz, 2008). It is explained by the condensation of lignin in softwoods (mainly composed of guaiacyl units); whereas hardwood lignin consists of guaiacyl and syringyl units and does not form carbon-carbon bonds between syringyl units (Wikberg, 2005).

2.7 Thermal Treatment of OSB

The lower dimensional stability of OSB plus the lower durability as well as the high potential of weathering by the environment have been the main limitations when compared with plywood (Del Menezzi et al., 2006; Mendes et al., 2013). Therefore, in order to enhance the properties of OSB, researchers have applied different

processes to OSB, and found thermal treatment is the most effective. There are two ways to thermally treat OSB: pre-treatment, which means applying the temperature to the strand particles before making panels, and post-treatment, applying high temperatures to the consolidated panels (Del Menezzi et al., 2006). Dimensional stability increased in both pre-treatment and post-treatment of OSB panels, and the reason for the former is chemical degradation of particle constituents; whereas for the later it could be the result of liberation of the compression stress, also known as "spring back" (Mendes et al., 2013).

The irreversible thickness swelling (ITS) of panels is more useful than TS when considering panel performance in service (Paul et al., 2006), since the panels will be exposed to a frequent moisture environment if used in outdoor applications (Del Menezzi et al., 2006), and as expected, a lower ITS at a temperature of 240° C of pre-treated strands was observed (Paul et al., 2006). Furthermore, wet-heat treatment produces boards with higher dimensional stability and bonding performance compared to hot-dry pressing treatments, due to the degradation of hemicellulose, which can release the stresses stored in microfibrils and the wood matrix (Homan et al., 2000; Kamdem et al., 2002; Winandy and Smith, 2006).

Considering the end use of OSB, IB, MOR, MOE and hardness are the properties requiring attention. It has been found that a significantly lower IB resulted in panels produced from pre-treated strands, which was attributed to the movement of extractives to the surface of particles during heat treatments, and hence providing

less penetration for adhesives (Mendes et al., 2013). In addition, the inactivation of the particle surface as a result of high temperatures, results in a loss of bonding ability, and as a consequence, lowers bond strength among the particles (Paul et al., 2006). However, values of IB had an increasing trend during post-treatment, due to the increasing number of adhesive joints from the polymerization reactions and lignin during thermal treatment (Chow and Pickles, 1971). For the bending properties, both MOE and MOR of OSB panels were reduced after pre-treatment, which depend on duration of the treatment and species (Militz, 2008; Paul et al., 2006).

2.8 Cost and Environmental Benefits of Thermally Modified OSB

OSB prices have been increasing since 2011 and sustained this level for the first time since 2006 except a sharp fluctuation during 2010 (Figure 8). According to some analysts, this price will remain strong through 2013 and will have a little to go before it hits the top (VandenBosch, 2012). Additionally, the increasing price of OSB can be largely due to the improved demand in housing market by more than 20% between 2013 and 2014 (Natural Resources Canada, 2013). Therefore, the development of OSB products and the high cost of OSB could reach a saturation point in the near future, resulting in the demand for innovation in these products such as treated OSB and thermally modified OSB.

According to Silverwood (2014), people prefer to use treated lumber versus the

thermally modified right now because of the cheaper price of treated lumber. However, thermal modification is different from the treated process, which add nothing into wood and the product can be made from local and under-utilized wood rather than imported exotic hardwoods, providing thermally modified OSB an effective more environmentally friendly product than treated products (Finnish ThermoWood Association, 2003; Winandy and Smith, 2006).

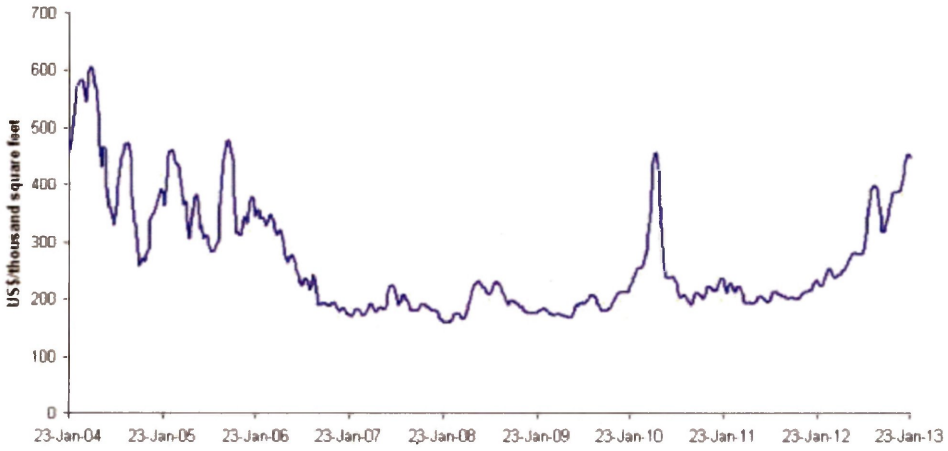

Figure 8. Yearly OSB Composite Price (Source: Natural Resources Canada, 2013).

Energy consumption, waste water, and gas emission of the treatment process are the main factors when comparing thermally modified and treated OSB in the aspect of environmental influence (Militz, 2002). Specifically, according to the Finnish ThermoWood Association (2008), ThermoWood treatment has a higher impact on resource depletion as a result of the demand for natural gas and the energy consumptions compared to the treated wood (Figure 9); however, for the environmental impact such as toxicity, ThermoWood is comparable or even superior to preservative treated wood. Additionally, Militz (2002) found a 25% increase in the total energy consumption of thermal treatments compared to that of the ordinary

timber drying process, and most of this consumption is used for drying, which is as high as 80%.

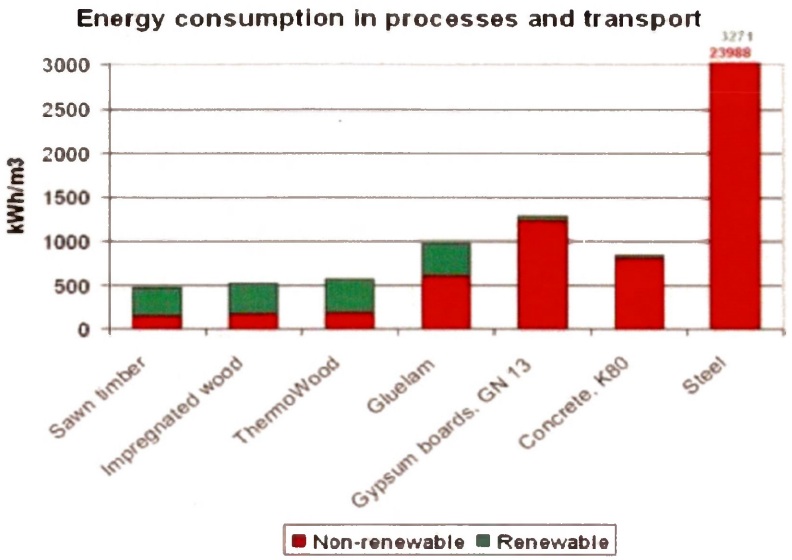

Figure 9. Energy consumption of several building materials in processes and transportation (Source: Finnish ThermoWood Association, 2008).

Even Militz (2002) mentioned that thermal treatment can create gas emissions and waste water that contains the evaporated resin, formic acid, and other solid constituents, which can be disposed of or utilized. For example, the solid components of waste water can be separated in a special clarification basin so that the water can be recycled and reused in a closed loop system (Benetto et al., 2009), the resulting gases can be burned with a special purpose-built burner and used as part of the heat-production process (Militz, 2002), and therefore, reducing the fuel demand for heat production (Benetto et al., 2009).

The emission of volatile organic compounds (VOCs) during the drying stage is a known problem in an ordinary OSB production process. However, an innovative vapor drying technology called "ecodry" process, which is successfully operated at

Kronospan Luxembourg S.A. and Superior ThermoWood in Thunder Bay, Ontario, as well as the normal heat-treated process were expected to reduce the VOCs (odorous) emission and provide a significant environmental added value, in terms of reduced contributions to environmental impacts and damages (Benetto et al., 2009; Hyttinen et al., 2010; Manninen et al., 2002; Superior Thermowood, 2014). For example, a reduction of 30% in odorous emissions, a decreased by 15-20% of climate change, and a 50-75% reduction of human health damage were found as a result of using the ecodry process, attributing to the lower CO_2 emissions and the lower VOCs and particulate emissions (Benetto et al., 2009).

To sum up, in the perspective of environmental benefits, it is important to emphasize that the ThermoWood process only uses high temperature and steam without toxic substances and reduces the VOCs emissions during the thermal treatment process, which conforms to consumer psychology and the environmental protection act (Finnish ThermoWood Association, 2003; Militz, 2008; Winandy and Smith, 2006). According to Grönroos and Bowyer (1999) around 36% and 24% of surveyed homebuyers in Chicago and Minneapolis/St. Paul indicated that they would preferentially pay for wood products that had been environmentally certified, in their home. Therefore, it will be possible and necessary to design and manufacture products, including their utilization, recycling and disposal, in such a way that the environmental burdens are minimized and reduced to levels that are competitive (Rivela et al., 2006).

CHAPTER 3

METHODOLOGIES AND MATERIALS

3.1 Materials and Experimental Design for Particleboard

Trees

Six mature (90 year-old) and six juvenile tamarack trees (30 year-old) from the Thunder Bay area, with 27.32- and 17.6-cm DBH, respectively were selected. The selected trees were cut into logs and labeled as juvenile whole tree (JW), mature heartwood (MH) and mature whole tree (MW), and then transported to the Lakehead University Wood Science and Testing Facility (LUWSTF) for further chipping and sorting.

Processing Raw Material

Material was chipped to a dimension of 10mm by 30-40mm (width by length), and some was re-chipped and grind using a portable chipper (electric garden shredder, Yardworks; Figure 10 left) and a portable grinder (Wiley Mill, Model No.2; Figure 10 right) in order to achieve smaller particles and fines (Figure 11) and then all was differentiated into piles using a screen selection (Figure 12) (Hatton, 1975). All material was kept in an environment of 35% relative humidity (RH) and 20°C to maintain the material at approximately 3-4% MC (Figure 13).

Figure 10. Electric Garden Shredder (Left) and Wiley Mill Grinder (Right).

Figure 11. Diagram of Sorted Tamarack Particles (Left) and Fines (Right).

Figure 12. Diagram of Chip Screening Apparatus.

Figure 13. Diagram of Sorting Conditions for Different Tamarack Particles and Fines.

Particleboard Production

Wood particles and fines were transported to Natural Resources Research Institute's (NRRI) Center in Duluth, MN for making particleboard. The fines and particles were completely coated with PF resin by using a batch blender (custom built; Figure 14 left) and an atomized resin spraying system (custom built; Figure 14 right). A mattress was laid up with three layers, putting the particles in the middle and the fines on both surfaces, which was fed into a single-opening, electrically-heated press (custom built; Figure 15) where the glue was cured under pressure (500 psi) and heat (approximately 380F (190^{0}C)) for a few minutes (2min) per panel with the nominal board density of 0.64g/cm^{3}. Particleboard was then labeled with MW, MH, and JW, and then dried to obtain the target MC of approximately 8% in an environment of 20 ^{o}C and 50% RH before cutting testing specimens (ASTM D4933 - 99, 2010).

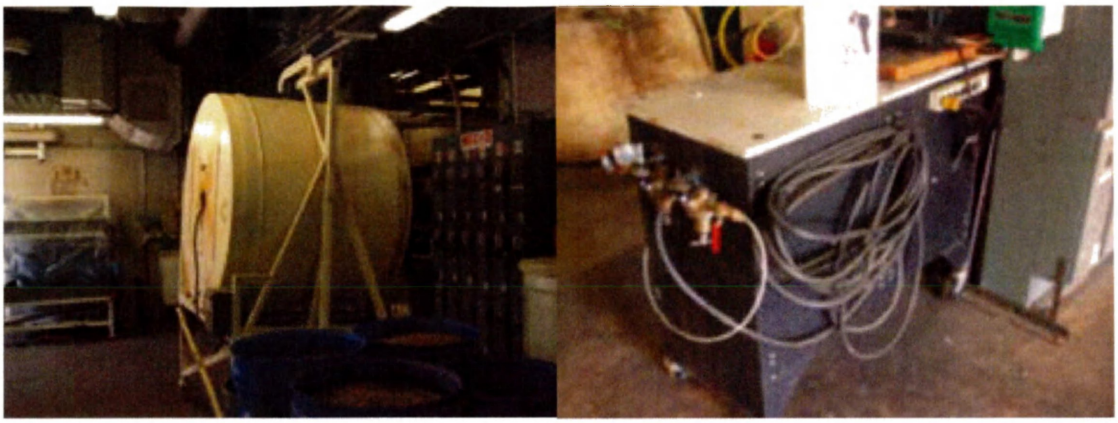

Figure 14. Diagram of Small Batch Blender (Left) and Atomized Resin Spraying System (Right).

Figure 15. Diagram of Single-opening, Electrically-heated Press.

Panel Sample Processing

Experimental design was made up of three types according to the three different raw materials by using PF resin (Table 8). Two panels (610 x 610 x 12.5 mm) were produced from the JW, MH, and MW raw material type with a nominal density of 0.625g/cm^3 for mature trees and 0.600g/cm^3 for juvenile trees (Major, 2013). All boards were cut into 610 x 305 x 12.5 mm sub-samples to increase the replicates to four for each board type.

Table 8. Experimental Design for the Production of Particleboard.

Treatments	Types of Particleboard	Resin
T1	Juvenile Whole Tree	PF Resin
T2	Mature Whole Tree	
T3	Mature Heartwood	

Sample Tests

After conditioning, test samples were cut (Figure 16) by using a band saw (General MFG CO. LTD. Model 390; Figure 17). The dimensions, numbers, and procedures of test specimens for each property, namely board density, MC, water absorption by weight and by volume after 2 plus 22 h of water immersion (WA.W2, WA.W24, WA.V2, WA.V24, respectively), thickness swelling after 2 plus 22 h of water immersion (TS2 and TS24), and linear expansion (LE), MOE, MOR, IB, FS and hardness, were decided according to standards (ANSI, 1998; ASTM D1037-12, 2012).

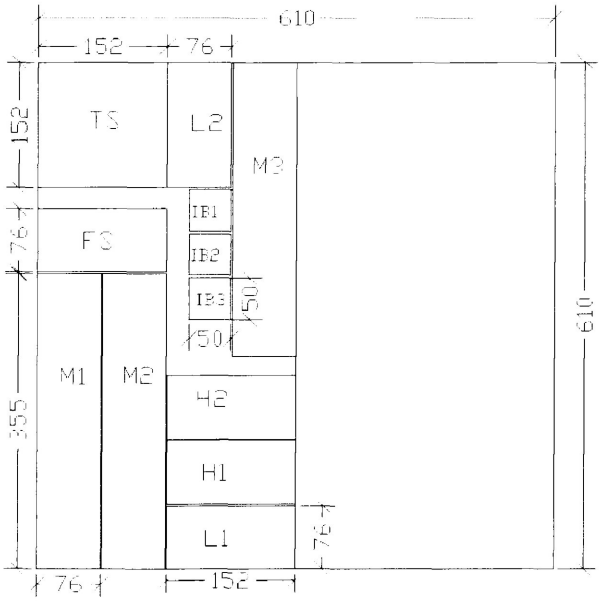

Figure 16. Samples Cut-up Pattern (mm).

Figure 17. Diagram of Band Saw.

3.2 Materials and Experimental Design for OSB

There were 12 OSB sheets using MDI resin, which came directly from one company for this project, with the dimension of 1.22 m by 2.44 m by 12.5mm (width by length by thickness).

The effects of post-thermal treatment on OSB properties were evaluated in this study. Experimental design was made up of four types including two levels of temperatures (T1 and T2) and two corresponding references (C1 and C2) (Table 9). Samples for T1 and C1 were cut from the same sheets, whilst samples for T2 and C2 were cut from the same sheets in order to reduce the variance between different sheets.

All 12 OSB sheets were labeled and randomly classified into two levels of treatment by Excel (version 2010) using the random number generator (Appendix I). Three boards (0.34 m x 2.44 m) per sheet with the thickness of 12.5mm were cut in order to achieve the required dimensions of the thermal kiln (Moldrup SSP Pilot Hydro-

Thermo Treatment Plant, AT-700/2600; Figure 18) from the NRRI Center. Labeling was completed at every stage including the sheet number, location within a sheet and treatment level (Appendix II). Boards were dried again to obtain the target EMC of approximately 8% and stored in an environment of 20° C and 50% RH before thermal treatments (ASTM D4933 - 99, 2010).

Table 9. Experimental Design for the Production of Thermally Modified OSB.

Treatments	Thermal Treatment	
	Temperature (° C)	Effective Duration (min)
Low Cook (T1)	160	60
Control 1 (C1)	–	–
High Cook (T2)	175	60
Control 2 (C2)	–	–

Thermal treatments occurred at the NRRI in Duluth using a thermal kiln at a temperature of 160° C (Table 10) and 175° C (Table 11) for an effective time of 1 hour.

As water spray system was used to cool down during the cooling and moisture conditioning stage, cover boards were used for the top and bottom to prevent treated boards from absorbing water vapor at this stage.

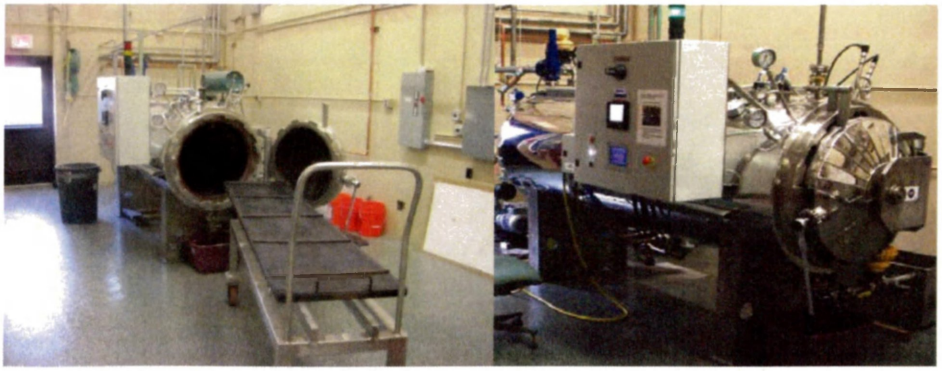

Figure 18. Diagram of the Thermal Kiln (Inside (Left) and Outside (Right)).

Table 10. OSB Treatment Cycle at 160° C

Step	Temp (°C)	P (bar)	Time (min)	Spray (s)
1	70	1.0	5	0
2	70	0.1	20	0
3	120	1.5	20	0
4	140	1.5	20	0
5	160	2.0	60	0
6	140	1.5	20	5
7	120	1.0	20	5
8	105	1.0	20	5

Table 11. OSB Treatment Cycle at 175° C.

Step	Temp (°C)	P (bar)	Time (min)	Spray (s)
1	70	1.0	5	0
2	70	0.1	20	0
3	120	1.5	20	0
4	140	1.5	20	0
5	160	1.5	20	0
6	175	2.0	60	0
7	160	1.5	20	5
8	140	1.0	20	5
9	120	1.0	20	5
10	105	1.0	20	5

After boards were treated and conditioned to obtain a constant MC, test samples were cut (Figure 19) according to ASTM standards (ASTM D1037-12, 2012).

Properties evaluated for dimensional stability were board density (ASTM D2395, 2007), MC, WA.W2, WA.W24, WA.V2, WA.V24, TS2, TS24, and linear expansion parallel and perpendicular to the long axis (LE (//) and LE (⊥)). For the mechanical properties, MOE and MOR perpendicular to the long axis of a board (MOE (⊥) and MOR (⊥)), IB, FS and hardness were evaluated (ASTM D1037-12, 2012). Small sized sample such as MC and FS were cut from the broken MOE samples.

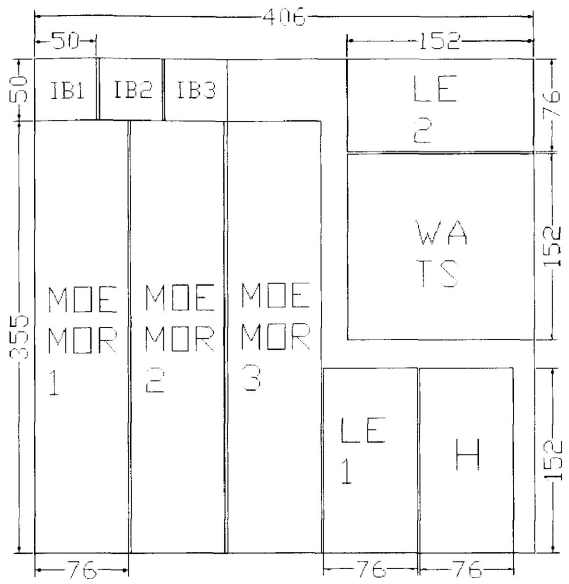

Figure 19. Sample Cut-up Pattern (mm).

3.3 Test Process

3.3.1 Dimensional Stability

Moisture Content (MC):

Moisture content implies the water content of a board in an equilibrium RH condition (Ibrahim, 2010) and is expressed as a percentage based on oven-dry mass by using Method B that can be calculated from (ASTM D4442 - 07, 2007):

MC % = (A – B)/B *100

Where A is the original mass (g) of specimen and B (g) is the corresponding oven-dry mass.

Water Absorption (WA) and Thickness Swelling (TS):

Water absorption is a board's ability to absorb water after soaking into water for 2 and 24 hours at room temperature (Ibrahim, 2010). Thickness swelling is the thickness change after immersing in water after 2 and 24 hours at room temperature.

Method A, the specimen after 2-plus-22-h submersion, was used in this test. Four-point method was used for the thickness determination. After immersion, samples were dried in an oven (Hotpack Corp. Model 206220) to determine the MC%. The amount of water absorbed by the specimen during the immersion was calculated based on the increase in weight and expressed as the percentage by volume and by weight. The TS was reported as a percentage of the conditioned thickness (ASTM D1037-12, 2012).

Linear Expansion (LE):

Linear expansion is a measure of the change of length of a sample caused by RH% change. Specifically, specimens were first conditioned to practical equilibrium at a RH of 50% and a temperature of 20°C in a conditioning chamber (Thermal Scientific 3851/3940M) and the length of each specimen were measured. Then specimens were conditioned to practical equilibrium at a RH of 90% and a temperature of 20°C and the length was measured again. For each conditioning and measurement the specimen was oriented in the same way (ASTM D1037-12, 2012). The results were reported as the percent change in length based on the length at 50%RH.

3.3.2 Mechanical Properties

A Tinius Olsen H50kt universal wood testing machine was used for testing IB, MOE (⊥) and MOR (⊥), hardness, and FS.

MOE and MOR

Elasticity means that deformations caused by low stress are completely recoverable

after loads are released. MOR displays the maximum load-carrying ability of a specimen in bending (Cai and Ross, 2010; Forest Products Laboratory, 1999).

The supports and span distance (305mm span) were determined by the standard (ASTM D1037-12, 2012). Specimen was loaded at the center of the span with a continuous load applied to the top surface of the specimen at a uniform loading rate of 6mm/min (ASTM D1037-12, 2012).

Tension Strength Perpendicular-to-surface (IB):

Internal bond Strength is the maximum stress of a specimen from a test with tension forces applied perpendicular to the surface (EN 319, 1993).

Two 50-mm square and 25-mm thick loading steel blocks (Figure 20 left) were effectively bonded with hot melt glue to the square faces of the specimen. The loading fixtures (Figure 20 right) were attached to the heads of the testing machine. The load was applied continuously throughout the test with a uniform rate of 1.016mm/min for thickness of 12.7mm samples until failure occurred (ASTM D1037-12, 2012).

Internal bond strength was calculated from (ASTM D1037-12, 2012; EN 319, 1993)

$IB = P_{max} / (ab)$

Where "a" is the width (mm) of a specimen, "b" is the length (mm) of the specimen, and "P_{max}" is the maximum load (N) recorded by the testing machine.

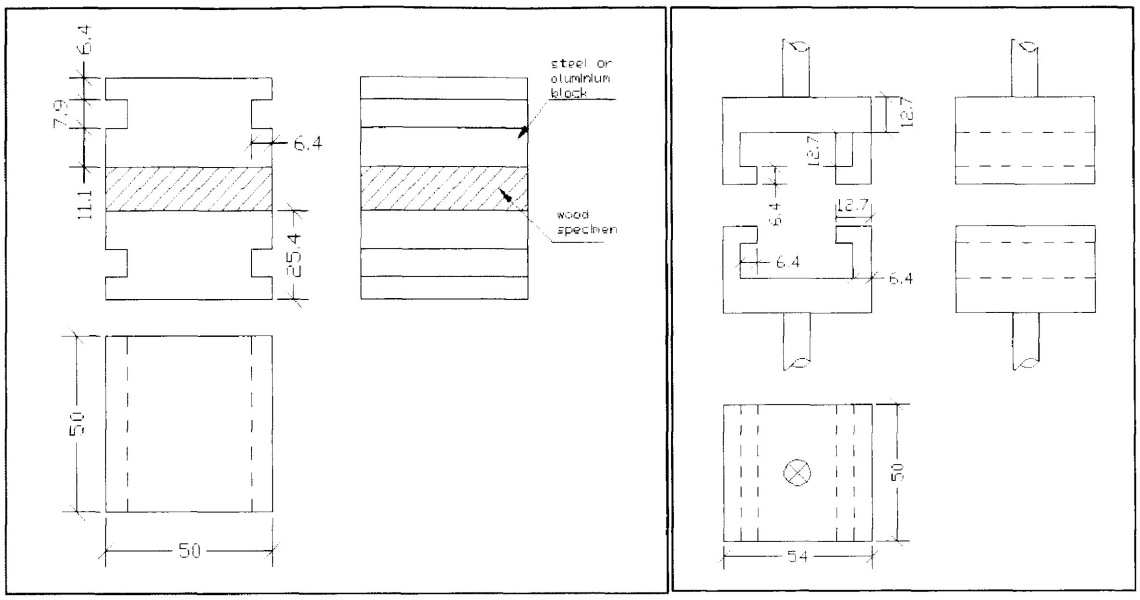

Figure 20. Details of Bonded Specimen and Blocks (Left) and Loading Fixtures (Right) (mm).

Face Screw-holding Ability (FS):

This test required a minimum thickness of 25mm, so two samples were glued together by using hot-melt glue to meet this requirement. Number 10 Type AB screws (root diameter of 3.51±0.1mm and a pitch of 16 threads per inch) were used. A lead hole was predrilled using a drill of 3.16mm and the screw was threaded 17 mm into the lead hole in the specimen at a right angle to the face of the panel. A continuous load at a uniform rate of 1.5mm/min was applied (ASTM D1037-12, 2012).

Hardness for Particleboard:

The hardness modulus method was used for determining hardness of particleboard panels, which is applicable for panels greater than 3mm in thickness (Lewis, 1968). A uniform rate of 1.3 mm/min was applied until the penetration was 2.5mm. On each of two faces of each specimen, at least two penetrations were made. Each penetration

was at least 25mm away from each other and the edges of the specimen (ASTM D1037-12, 2012).

Hardness for OSB:

The modified Janka-ball (11.3mm in diameter) test method was used for determining hardness of OSB. Extra specimens were prepared as a backing material during the test. The load was applied continuously at a uniform rate of 6 mm/min until the "ball" penetrated to one-half its diameter (5.65mm) into the sample. The location of penetrations was at least 25mm away from each other and the edges of the specimen (ASTM D1037-12, 2012).

3.4 Statistic Analysis

3.4.1 Statistical Design for Particleboard:

For comparing the material effects on the properties of particleboard, three factors of juvenile wood, mature heartwood, and mature whole tree were enforced on testing variables with 4 replicates for each.

The null hypothesis for this study was that there would not be a significant difference in particleboard properties with changes in the type of raw material.

3.4.2 Statistical Design for OSB:

In order to analyze the effects of thermal modification on the properties of OSB, four groups of analysis were employed in this part. Specifically, the variances within two control groups with 39 replicates for each, the comparison between low cook (160°

C) and control 1 with 39 replicates for each, high cook (175° C) and control 2 with 44 replicates for each, as well as the parallel and perpendicular to long direction of MOE and MOR within one board with 22 replicates for each.

The null hypothesis was that there would be no significant difference in OSB properties with changes in temperature levels and boards.

3.4.3 Statistic Analysis:

Test results were collected and statistically analyzed using the LUWSTF WoodScience app, SPSS (version 19), and R (version R Studio) software (Appendix III). Analysis of variance (ANOVA) and t-test were used to test for significant difference between factors. A Tukey HSD's post hoc test at 95% probability was applied when the ANOVA indicating a significant difference, particularly for the material effects on particleboard. Over 200 test specimens were analyzed for particleboard and more than 2500 (2588) of test specimens for OSB in total for this study.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Particleboard Results

Since the minimum standard values of low density (LD), grade 1, from ANSI (1998) are obtained from particleboard regardless of the species and material types (no sort by juvenile or mature), the results gained from MW board (no sort by juvenile and mature) should be the proper one to compare when considering the feasibility of utilizing tamarack as a raw material for particleboard.

Except MOR of MW (2.67MPa), which is lower than the minimum value (3.0MPa), other selected mechanical properties like MOE, IB, and FS all exceeded the minimum values required by ANSI standard (1998), LD-1 (Table 12), showing that tamarack has the potential to be used as a raw material in particleboard industries. Specifically, the MOE value of MW (882.05MPa) was 1.6 times higher than the standard value of LD-1 class (550MPa). The IB value was almost twice the minimum required value by the same class, which is 0.10N/mm^2. Approximately 1.4 times higher value of FS was obtained from MW than the standard.

Table 12. Selected Values of Standard and Experimental Particleboard (Source: ANSI, 1998).

	MOR (MPa)	MOE (MPa)	IB (N/mm^2)	FS (N)	LE (max) (%)
ANSI Standard (LD - 1)	3.0	550	0.10	400	0.35
Mature Whole Tree	2.67	882.05	0.19	587.46	0.45

However, 0.45% LE of MW was higher than the minimum value required by ANSI (1998) standard, class LD-1, which is 0.35%. The weak performance of tamarack particleboard is probably a result of absence of hydrophobic materials like wax. For example, Lin et al. (2008) found that with every 0.5% increment of wax (from 0% to 1.5%) in a 0.7 g/cm^3 and 6% resin content board, the value of TS was decreased from 19%, 18%, 17.3% to 17%, specifically.

In terms of the raw material effects, tamarack particleboard made from JW, MH, and MW were compared and analyzed. Results show that JW particleboard (0.63g/cm^3) displayed a lower density board than the MH (0.69g/cm^3) or MW (0.69g/cm^3) (Table 13). This is consistent with the literature that juvenile tamarack has lower specific gravity (Major, 2013; Yang et al., 1986). Even though the JW board displayed a lower density, it was not significantly different than the MH or MW board values according to statistical analysis (Table 13). Furthermore, when comparing the tamarack tree density values presented by Major (2013), 0.60 kg/m^3 for juvenile trees and 0.625 kg/m^3 for mature trees, the particleboard process improved the density for both juvenile and mature boards, 0.63g/cm^3 and 0.69g/cm^3,respectively.

The JW displays a significantly higher value of MC% (7.3%) than the MH (6.53%). In addition, the lowest MC% in heartwood (6.53%) is in accordance with the findings that tamarack displays higher MC% in sapwood than the heartwood (Srinivasan et al., 1999). This is explained by Bowyer et al. (2003) that the extractives tend to take the place of water molecules during the transition of a tree

from sapwood to heartwood and thus, the amount of moisture in the cell wall of heartwood may be decreased as a result of extractive deposition.

Table 13. Physical Properties of Tamarack Particleboard Using PF Resins.

Properties	Raw Material Type		
	JW	MH	MW
BD (g/cm3)	.63 a	.69 a	.69 a
MC (%)	7.30 a	6.53 b	7.29 a
WA.W2 (%)	89.30 a	73.19 b	88.03 a
WA.W24 (%)	98.66 a	83.82 b	95.48 a
WA.V2 (%)	55.33 a	46.73 b	55.85 a
WA.V24 (%)	61.14 a	53.57 b	60.49 a
TS2 (%)	35.12 a	31.64 a	36.36 a
TS24 (%)	41.13 a	39.29 a	45.01 a
LE (%)	1.03 a	.82 a	.45 b

Note: Values within the same row followed by different letters (a-b) are significantly different at $P< 0.05$.

Statistical analysis indicates that dimensional stability of tamarack particleboard is significantly affected by chip type (Table 13); particularly in all WA properties (Figure 21), which is consist with the study by Dix and Roffael (1994), who found that boards made from heartwood of tamarack were always of lower water absorption and thickness swelling than tamarack sapwood boards. This is probably due to the larger microfibril angles in juvenile wood and therefore, result a higher shrinkage than mature heartwood with smaller microfibril angles (Zobel and Buijtenen, 1989). Additionally, the extractives in heartwood may be another factor that act as waxes and help improve water resistance (Lin et al., 2008; Pan et al., 2007). For example, Nemli et al. (2006) found that particleboard made with 5%

extractive concentration of *Pinus brutia* bark improved the TS24 (17.54%) significantly compared to the 0% extractive concentration (28.32%) board. In all absorption and swelling tests, MH board displayed significantly superior values over the JW and MW samples (Table 13, Figure 21).

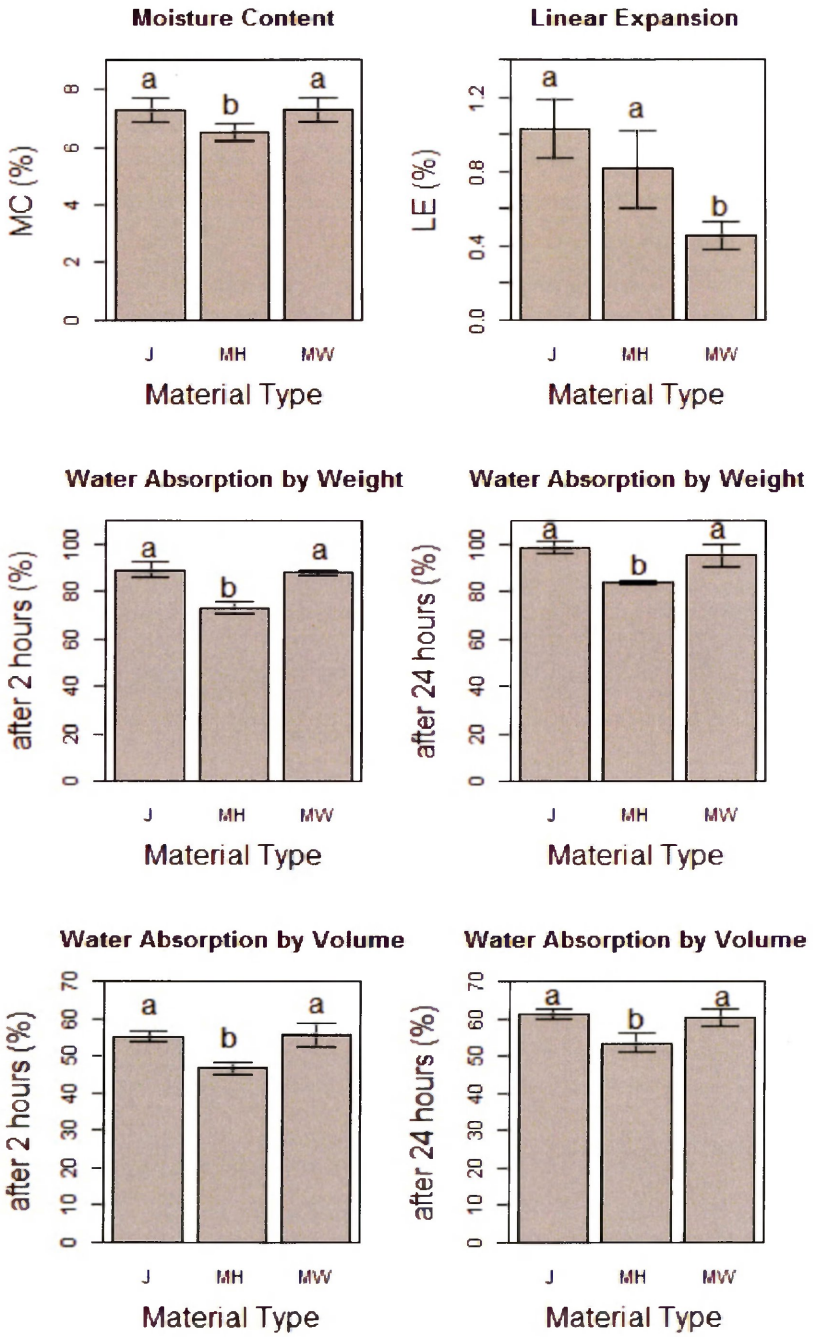

Figure 21. Dimensional Stability of Different Type of Tamarack Particleboard Using PF Resin.

JW sample boards displayed the highest LE% (1.03%) (Figure 21 right top), proving that the higher content of JW leads to a higher LE% (Pugel et al., 2004). A similar finding was reported by Pugel et al. (2004) where he found the LE% of southern pine (*Pinus taeda* L.) was increased with the increased percentage of JW (fast-grown) in the sample boards, for example, 100% pure JW board displayed more than 65% LE value whereas around 45% LE was found in the board made from 50% JW, and as low as 30% LE for the board made from 25% JW.

Other than physical properties, raw materials only had a significant effect on IB according to the statistical analysis (Table 14) where the MH (0.24N/mm^2) displayed the highest IB over the JW (0.18 N/mm^2) and MW (0.19 N/mm^2) samples.

Table 14. Mechanical Properties of Tamarack Particleboard Using PF Resins.

Properties	Raw Material Type		
	JW	MH	MW
MOE (MPa)	965.68 a	966.62 a	822.05 a
MOR (MPa)	2.66 a	2.47 a	2.67 a
Internal Bonding (N/mm^2)	.18 b	.24 a	.19 b
Face Screw Withdrawal (N)	597.10 a	572.85 a	587.46 a
Hardness (N)	1561.52 a	1179.91 a	1537.38 a

Note: Values within the same row followed by different letters (a-b) are significantly different at $P< 0.05$.

For the MOE, MOR, hardness and FS, there was no significant difference between the samples (Table 14). The result agrees with the findings by Lin et al. (2008) who found that bonding strength is affected more by resin content than bending strength. Therefore, the highest IB value found in the MH (0.24N/mm^2) is probably a result of the high extractives content in heartwood (Table 14, Figure 22), which may be acting

as extra resins to accelerate the connection between particles and resins, leading to a better IB (Halligan, 1970).

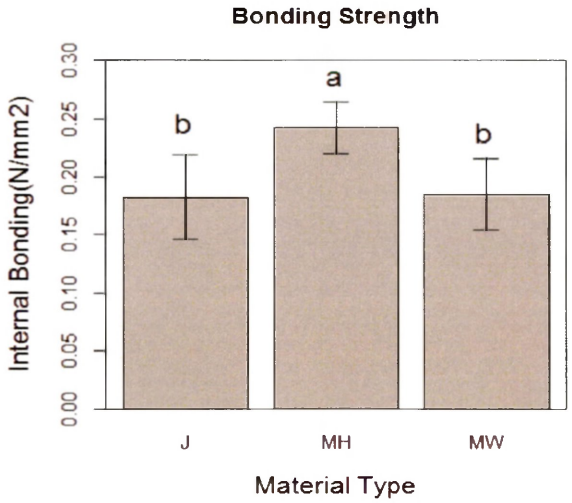

Figure 22. Bonding Strength of Different Type of Tamarack Particleboard Using PF Resin.

As mentioned above, there was no significant difference in MOR according to the statistics; however, JW sample board displayed a slighter higher mean value of MOR (2.66MPa) than that of MH board (2.47MPa), agreeing with the conclusion that pure JW panels were slightly higher in bending strength (MOR) than the pure MH panels, which has been reported in the literature (Pugel et al., 2004). In addition, the slightly lower strength of MH sample boards in terms of MOR (2.47MPa), FS (572.85N), and hardness (1179.91N) are a result of high extractive content since this can increase gluing difficulties, and hence, negatively affect board strength as was reported by Ibrahim (2010).

In conclusion, raw materials, especially those displaying high extractive contents, have effects on the properties of particleboard, particularly dimensional stability

properties. Therefore, we can suggest that the MH appears to display on average the best overall physical and mechanical properties with JW displaying certain mechanical properties that are higher, however, not significantly. So the MH can be considered the best overall raw material for panel production.

4.2 OSB Results

4.2.1 Variation within Controls for OSB

In order to verify the variance between OSB boards, two control groups collected from different OSB boards were studied. An outlier of board density was noticed in C2 with the value 0.45g/cm^3 (Figure 23 left). The emergence of this outlier was probably due to some void spaces in the sample resulting in a decreased density, however, no change in volume. Considering the influence of the outlier, the average density was calculated without this outlier during analysis. The variance of board density after removing the outlier is shown in Figure 23 (right).

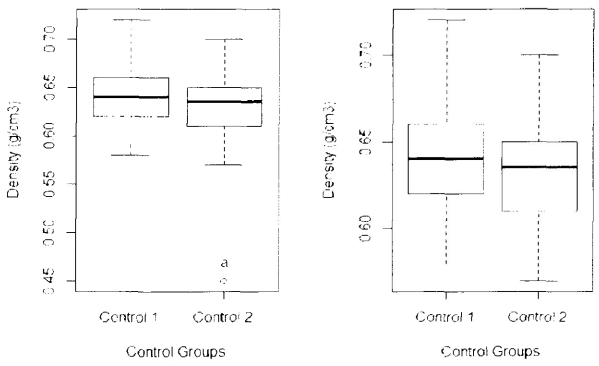

Figure 23. Box Plot of Control Groups Board Density.

Table 15 shows the mean values of physical properties from C1 and C2. No significant difference was found in board densities (0.64g/cm^3 of C1 and 0.63g/cm^3

of C2). This is consistent with the reality that board density is depended on the set up parameters during the process, especially pressure and duration (Bowyer et al., 2003). As long as they were coming from the same production batch, their density should be homogenous.

Table 15. Physical Properties of Two Control Groups.

Properties	Control Groups	
	C1	C2
BD (g/cm^3)	.64 a	.63 a
MC (%)	8.79 b	9.34 a
WA.W2 (%)	11.19 a	7.84 b
WA.W24 (%)	44.69 a	33.04 b
WA.V2 (%)	7.01 a	4.93 b
WA.V24 (%)	28.01 a	20.80 b
TS2 (%)	5.03 a	3.49 b
TS24 (%)	21.43 a	16.24 b
LE// (%)	.09 a	.08 a
LE⊥ (%)	.15 a	.13 b

Note: Values within the same row followed by different letters (a-b) are significantly different at $P< 0.05$.

Other than density, MC% and dimensional stability are significantly different from each other, showing the variable nature of wood (Zobel and Buijtenen, 1989) (Table 15, Figure 24). Specifically, the mean value of MC of C2 is 9.34%, which is higher than 8.79% MC of C1. Mean values of all WA and TS are lower in C2 compared to C1 (Table 15, Figure 24). For the LE, results from different directions are varied. For example, no significant difference was found in LE (//), 0.9% for C1 and 0.8% for C2, respectively, whereas for LE (⊥), a lower value of 0.13% for C2 was found to be statistically different than 0.15% for C1 (Table 15, Figure 24).

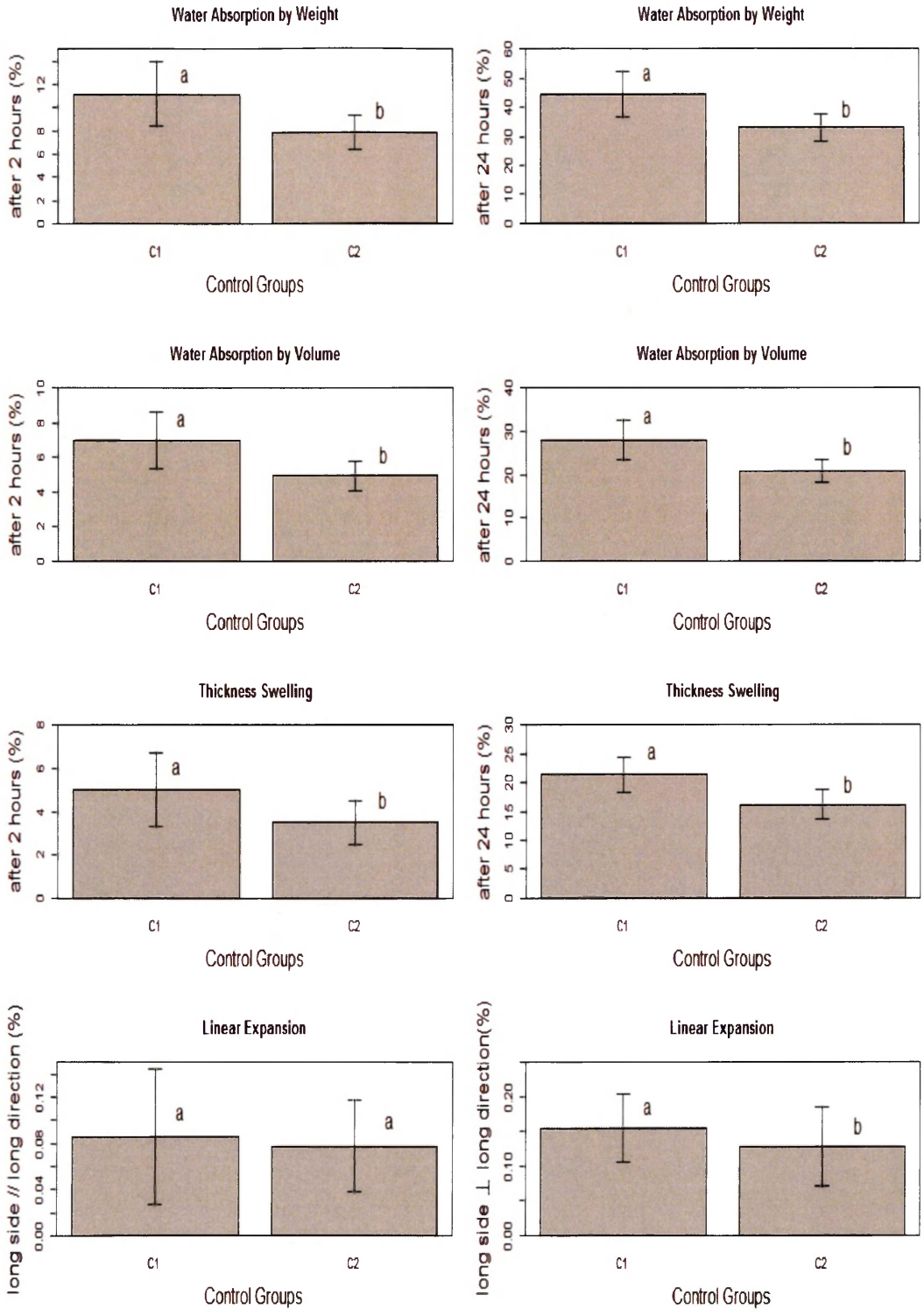

Figure 24. Dimensional Stability of Two Control Groups.

As wood is a natural material and tree is subject to many constantly changing influences such as weather and soil conditions, and growing space, wood properties vary considerably, even in clear material (Forest Products Laboratory, 1999).

Additionally, fiber length and specific gravity are the two main physical properties that occupy higher variability of wood, and therefore, affect the performance of wood (Zobel and Buijtenen, 1989). According to Bowyer et al. (2003), the shrinkage values from green to oven dry MC are varied from radial to tangential within a tree. For example, the radial shrinkage value of tamarack is 3.7% whereas as much as 7.4% in the tangential direction.

In contrast to the physical properties, lower variances were observed in mechanical properties. No significant differences were found in MOE ($\perp$), MOR ($\perp$), and FS (Table 16). However, the mean value of IB for C1 is 0.33N/mm^2, statistically higher than 0.30N/mm^2 of C2 (Table 16, Figure 25 left). Quite the contrary, hardness mean value of C2 (2724.05N) is statistically higher than that of C1 (2496.83N) (Table 16, Figure 25 right). Similar research was carried by Thompson et al. (2002) who indicated that the strength variability exists across each OSB board with ±14.0% standard deviations of bending strength, which displayed the greatest variation compared to the chipboard (±9.0% standard deviation) and the MDF (±8.4% standard deviation). This variation is probably a result of the varied microfibril angle with a single tree (range from 0^0 to 50^0) according to Groom et al. (2002), who investigate the effect of the microfibril angle on the mechanical strength and elasticity of spruce wood and reported that the elastic modulus was sensitive to the mcrofibrils angle, with the changes from 17GPa at 0^0 angle to 10GPa at 50^0 angle.

Table 16. Mechanical Properties of Two Control Groups.

Properties	Control Groups	
	C1	C2
MOE ⊥ (MPa)	2136.32 a	2127.25 a
MOR ⊥ (MPa)	12.64 a	12.65 a
Internal Bonding (N/mm^2)	.33 a	.30 b
Face Screw Withdrawal (N)	1114.90 a	1061.40 a
Hardness (N)	2496.83 b	2724.05 a

Note: Values within the same row followed by different letters (a-b) are significantly different at $P< 0.05$.

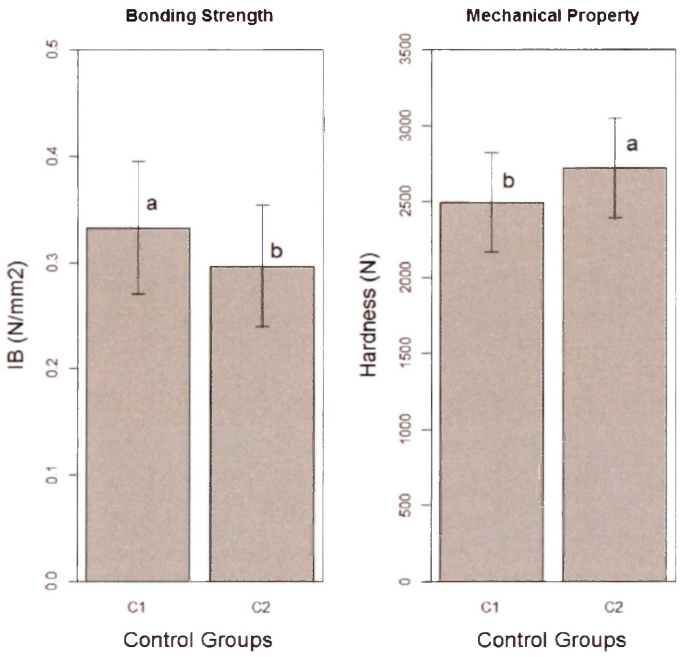

Figure 25. Internal Bond Strength and Hardness of Two Control Groups.

Bonding strength depends largely on the efficiency of the mixing of wood strands and adhesives together, which is largely dependent on the manufacture processes and the changes of wood particles' property during heat and pressure (Vick and Adherends, 1999). For example, some void space may result from insufficient blending and arrangement of wood strands, therefore, leading to varied values of IB. As described by Vick and Adherends (1999), the wettability of the surface of wood products is much poorer than that of freshly cut, polar wood surface. This is because

during hot pressing, adhesives on the outer surfaces of particles cure, whereas extractives stored in wood cells migrate to the surface and release agents that remain on surfaces, all of which inactive surfaces from being fully wetted by adhesives and therefore, the strength of bonds to the surfaces of wood products is limited.

The variance of hardness is probably dependent on the conditions of the penetration area where the test occurs. Unlike solid wood or particleboard, the surface of OSB is made up of long wood strands that are aligned in the long direction, with shorter strands that are cross- or randomly-aligned (Bowyer et al., 2003). Therefore, it is hard to find a clear area for the Janka-ball to penetrate consistently from test to test, not knowing what is just under the surface of the sample. According to the testing standard (ASTM D1037-12, 2012), the location of penetration is the same for each sample, and therefore, some penetrations were on the cross of two strands, and some were on the surface of one strand, leading to the varied hardness values.

In summary, variance is naturally found in wood (Zobel and Buijtenen, 1989), even though the composite board is meant to minimize variation across the board, its physical and mechanical properties still differ from one board to the next due to wood natural variation and then how this variation is arranged in an individual board made of pieces of wood (Erdil and Zhang, 2002). Therefore, in order to reduce the variance between boards, testing samples for C1 and T1 were cut from the same board; similarly, samples for C2 and T2 were cut from the same board.

4.2.2 Comparison of the Low Cook and Control 1 for OSB

Table 17 shows the mean values of physical properties for T1 and C1. Despite the insignificant difference in LE (//) and LE (⊥), results of dimensional stability of T1 show statistically lower values than that of C1 except for MC% (Figure 26).

Table 17. Physical Properties of the Low Cook (160°C) and Control 1.

Properties	Control Groups	
	C1	T1
BD (g/cm^3)	.64 a	.62 b
MC (%)	8.79 b	9.13 a
WA.W2 (%)	11.19 a	9.22 b
WA.W24 (%)	44.69 a	40.98 b
WA.V2 (%)	7.01 a	5.47 b
WA.V24 (%)	28.01 a	24.33 b
TS2 (%)	5.03 a	1.89 b
TS24 (%)	21.43 a	11.13 b
LE// (%)	.09 a	.09 a
LE⊥ (%)	.15 a	.14 a

Note: Values within the same row followed by different letters (a-b) are significantly different at $P< 0.05$.

The lower values of all WA and TS properties indicate a higher dimensional stability as a result of the low temperature treatment than that of C1 as expected (Figure 26). This result confirms the conclusion from previous studies that even in the low temperature cook, dimensional stability can be improved significantly (Militz, 2008) as a result of reduction in free water and hydrophilic materials (Cai and Cai, 2012; Peck, 1957). For example, Popper et al. (2005) found that a noticeable reduction of the EMC was observed only at 100°C for several wood species (*Pinus radiata* D. Don, *Pseudotsuga menziesii* Franco, *Laurelia sempervirens* (R. et Pav) Tul.,

Castanea sativa Mill. and *Quercus robur* L) attributed to the void volume and cross linking of the holocellulose. Similarly, Cai and Cai (2012) found lower values of volumetric swelling at 4.29% for air-conditioned and 13.05% for water- soak samples after treated for 1.5hours at 195° C compared to control groups of 5.38% and 15.08%, respectively.

However, a MC of 9.13% found in T1 was statistically higher than the 8.79% MC in C1, which was an unexpected result (Figure 26 right top). This unexpected value may be a result of treatment processes. Specifically, we used a water spray system in the final step to cool down the kiln, which is described in the Finnish ThermoWood Association Handbook (2003). It is possible that some parts, which happened to be the MC% specimens, of the testing boards absorbed the steam water and swelling occurred leading to a higher MC% in those samples. The fact that there were several slightly swelled specimens in the MC% samples noticed in the thickness direction does not remove them from the sample set, as the standard does not describe acceptable and unacceptable specimens based on swelling. Therefore, testing results should not be abandoned unless obvious defects or swellings were observed.

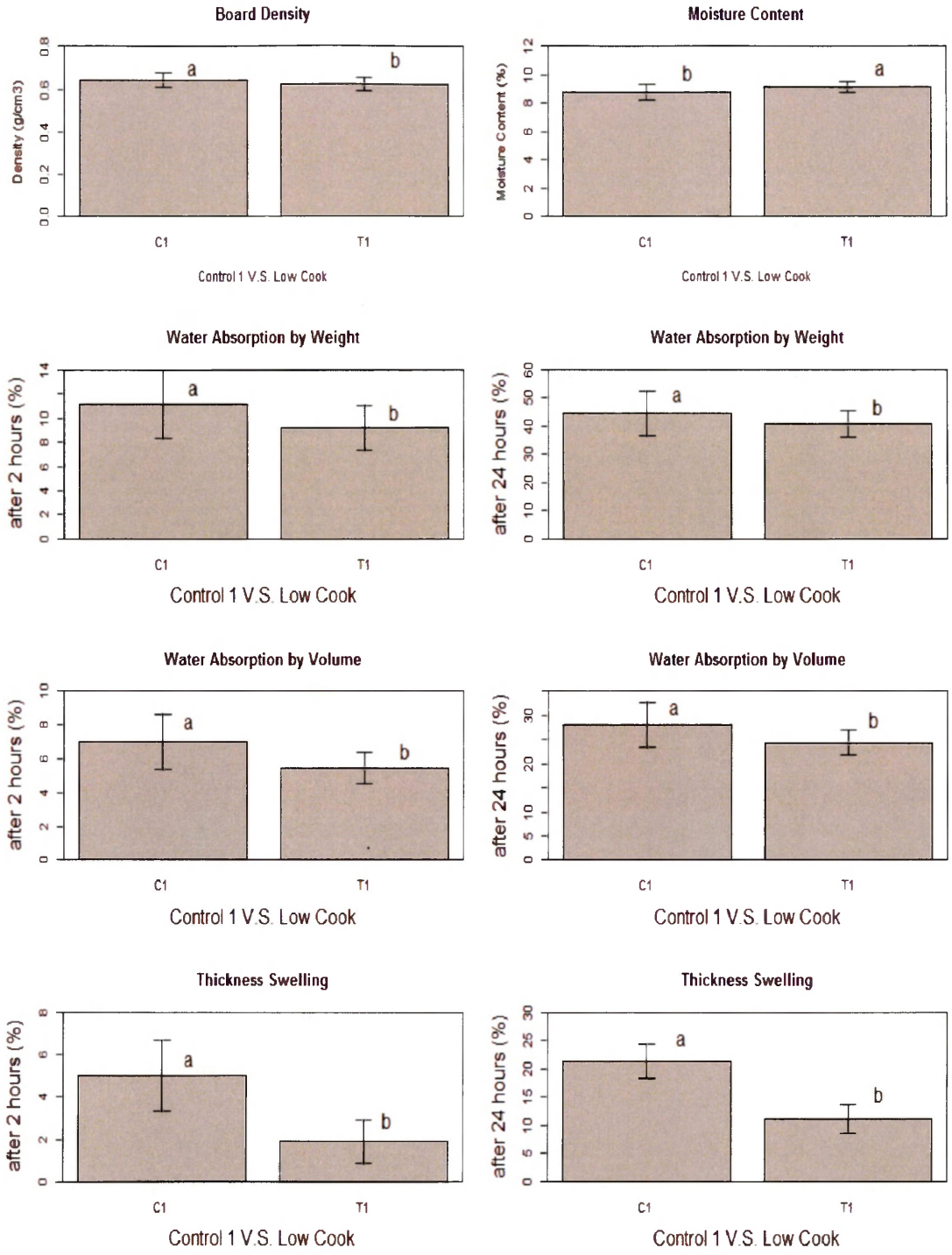

Figure 26. Dimensional Stability of the Low Cook (160°C) and Control 1.

Mean values of MOE (⊥), MOR (⊥), IB, FS, and hardness are shown in Table 18. Unlike the favorable physical properties produced by T1, mechanical properties displayed a few trends. The mean values of MOE (⊥), MOR (⊥), and IB gathered from T1 are lower than that of C1, with 1860.81MPa, 11.18MPa, and 0.29N/mm^2

compared to 2136.32MPa, 12.64MPa, and 0.33N/mm^2, respectively (Figure 27). This is an unexpected result for these properties as it has been reported that low temperature treatments do not decrease mechanical properties when compared to control treatments as was described by Del Menezzi et al. (2009) in a study on post-treated OSB, where higher values of MOR (⊥) and MOE (⊥) were obtained (24MPa and 2700MPa, respectively) and no significant difference in IB (0.56N/mm^2) was observed after treated at 190° C for 12min when compared to controls (22MPa, 2500MPa, and 0.54N/mm^2, respectively). The explanation of this low impact on the mechanical properties of treated boards was probably due to the mild conditions, such as the short duration, low temperature and pressure, as well as the lignin polymerization reactions and adhesive behavior during the treatments (Del Menezzi et al., 2009). Fortunately, face screw withdrawal and hardness show no statistically difference between C1 and T1 as expected (Table 18, Figure 28).

Table 18. Mechanical Properties of the Low Cook (160°C) and Control 1.

Properties	Control Groups	
	C1	T1
MOE ⊥ (MPa)	2136.32 a	1860.81 b
MOR ⊥ (MPa)	12.64 a	11.18 b
Internal Bonding (N/mm^2)	.33 a	.29 b
Face Screw Withdrawal (N)	1114.90 a	1046.46 a
Hardness (N)	2496.83 a	2392.23 a

Note: Values within the same row followed by different letters (a-b) are significantly different at $P< 0.05$.

Though the mechanical results of T1 are not as good as we expected, the changes in mechanical properties between C1 and T1 are not obvious, especially for MOR (⊥)

and IB, and additionally no statistical change was seen in hardness (2496.83N for C1 and 2392.23N for T1) and FS (1114.90N for C1 and 1046.46N for T1). These results suggest the potential that increasing dimensional stability without changing or at least not largely negatively affecting mechanical properties by using a low temperature treatment is possible.

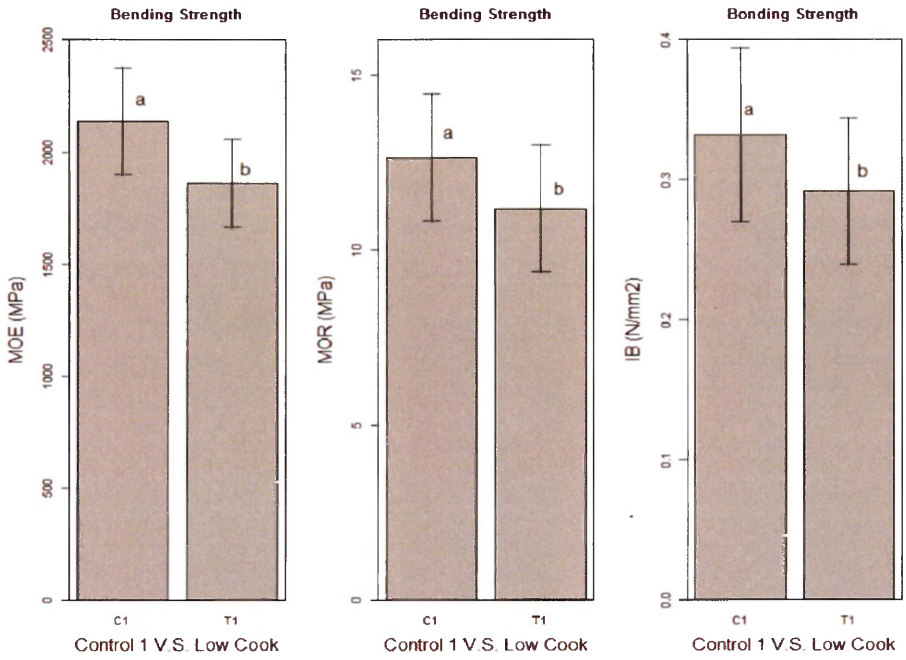

Figure 27. Bending and Bonding Strength of the Low Cook (160°C) and Control 1.

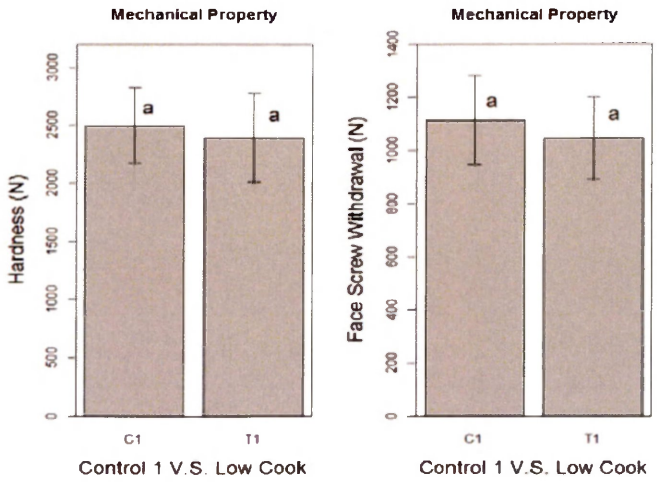

Figure 28. Hardness and Face Screw Withdrawal of the Low Cook (160°C) and Control 1.

4.2.3 Comparison of High Cook and Control 2 for OSB

The test results of physical properties for T2 and C2 are presented in Table 19. No significant difference was found in LE (//) and LE (⊥) according to the statistical analysis, however, T2 displayed a lower LE value (0.07% (//) and 0.12% (⊥)) when compared with C2 (0.08% (//) and 0.13% (⊥)). Other than this difference, density, MC% and dimensional properties, especially the TS properties (TS2 and TS24), displayed significantly lower values than that of C2 (Table 19, Figure 29), confirming that thermal modification increases dimensional stability with increasing temperatures (Cai and Cai, 2012; Del Menezzi et al., 2009; Militz, 2008). For example, Welzbacher et al. (2007) found that with the increasing treatment temperatures from 180° C to 240° C, the value of ASE was increased from 20% to approximately 40%, indicating that a higher heat-treatment temperature caused a higher ASE value and hence, a greater effect on dimensional stability. This is attributed to less -OH and large degradation of hemicelluloses of high temperature modified specimens compared with untreated controls (Boonstra and Tjeerdsma, 2006). Additionally, the lower ITS induced by higher thermal treatment, indicating a higher dimensional stability, was explained by the reduction of compression stresses (Del Menezzi et al., 2009).

Mechanical properties of T2 show significantly lower values than that of C2 for all properties measured (Table 20, Figure 30 - 31). The most significant decrease in

single property was found in hardness (Figure 31 left), which was found to be nearly half that of C2 (1672.60N versus 2724.05N, respectively).

Table 19. Physical Properties of the High Cook (175°C) and Control 2.

Properties	Control Groups	
	C2	T2
BD (g/cm^3)	.63 a	.59 b
MC (%)	9.34 a	7.42 b
WA.W2 (%)	7.84 a	6.31 b
WA.W24 (%)	33.04 a	29.99 b
WA.V2 (%)	4.93 a	3.58 b
WA.V24 (%)	20.80 a	17.02 b
TS2 (%)	3.49 a	.65 b
TS24 (%)	16.24 a	5.18 b
LE// (%)	.08 a	.07 a
LE⊥ (%)	.13 a	.12 a

Note: Values within the same row followed by different letters (a-b) are significantly different at $P< 0.05$.

Table 20. Mechanical Properties of the High Cook (175°C) and Control 2.

Properties	Control Groups	
	C2	T2
MOE // (MPa)	2127.25 a	1769.52 b
MOR ⊥ (MPa)	12.65 a	9.26 b
Internal Bonding (N/mm^2)	.30 a	.25 b
Face Screw Withdrawal (N)	1061.40 a	902.80 b
Hardness (N)	2724.05 a	1672.60 b

Note: Values within the same row followed by different letters (a-b) are significantly different at $P< 0.05$.

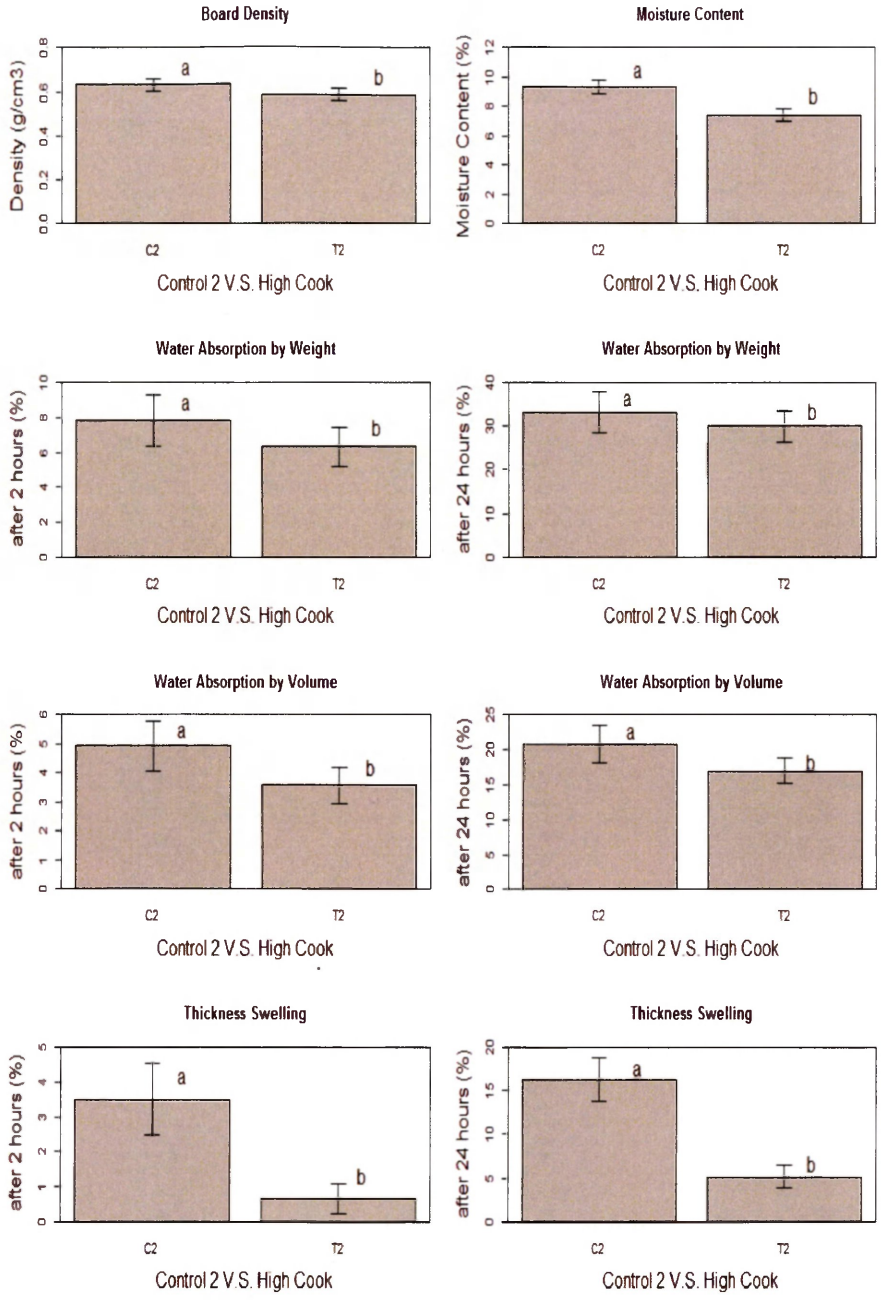

Figure 29. Dimensional Stability of the High Cook (175°C) and Control 2.

It is clear that T2 negatively affected the boards more than T1 did for mechanical properties. It has been described that this result can be attributed to the large degradation of chemical components during T2 at the molecule level (Cai and Cai, 2012). For example, Del Menezzi et al. (2009) indicated that unchanged content of glucan, xylan and Klason lignin was related to the unaffected MOE in low

temperature treatments, whereas the large degradation of arbinan and galactan was responsible for the decreased MOR according to their study. Similarly, Poncsák (2006) indicated that the lower MOR of higher treated samples was attributed to a large degree of the break-up of the hemicelluloses and cellulose polymers. Additionally, Cai and Cai (2012) found that the decreased wood flexibility was a result of the replacing of flexible bonds (hemicelluloses-cellulose-hemicelluloses) by rigid bonds (cellulose-cellulose) during thermal treatment.

Therefore, compromising mechanical properties is the main drawback of T2 even though dimensional stability is improved. This result conforms to the findings by Goroyias and Hale (2002) where they tested treated wood strands for OSB production and found that high temperature treatments resulted in significant reductions in TS but reduced MOE and MOR by up to 20% at the same time.

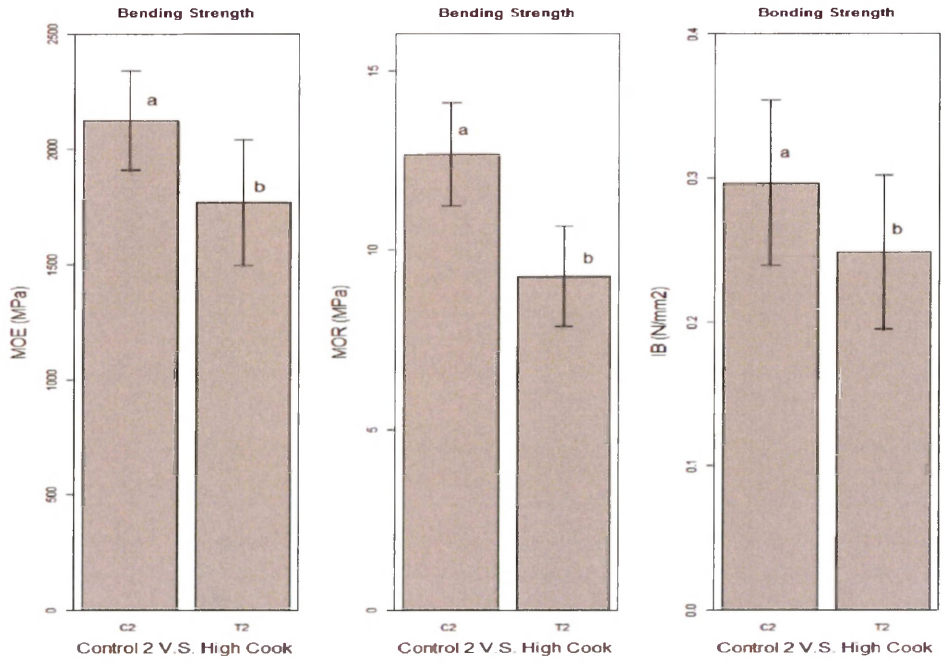

Figure 30. Bending and Bonding Strength of the High Cook (175°C) and Control 2.

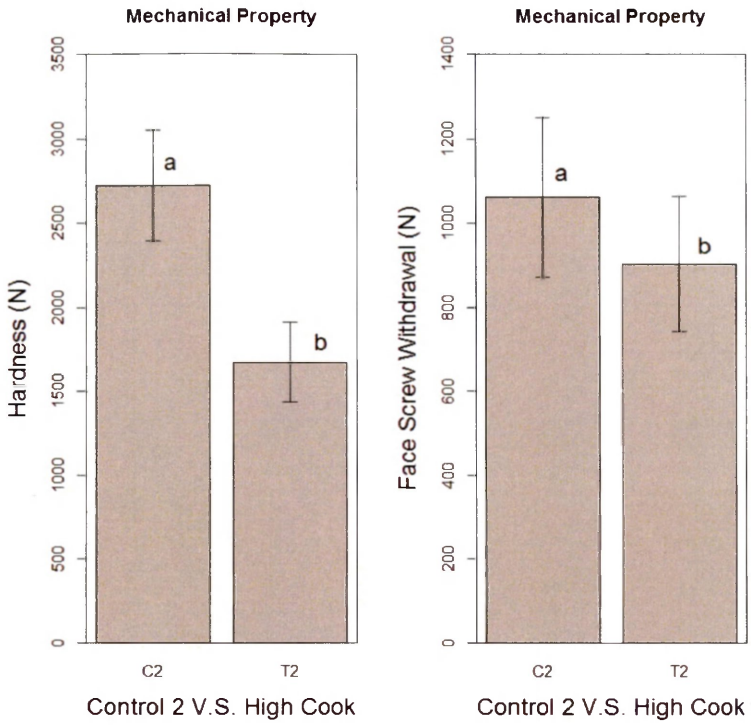

Figure 31. Hardness and Face Screw Withdrawal of the High Cook (175°C) and Control 2.

4.2.4 Comparison of Perpendicular and Parallel to the Long Axis of the Board MOE and MOR in OSB

Due to the manufacturing process, mechanical properties of OSB differ from one direction to the other direction. For example, the strength parallel to the long direction of a panel is higher than that in the perpendicular direction, especially for MOE and MOR (Structural Board Association, 2004). During the comparison analysis between T1, T2, C1, and C2, MOE (⊥) and MOR (⊥) results were collected from the perpendicular direction as a result of the cutting process (Appendix IV). Therefore, the comparison between parallel and perpendicular MOE and MOR were studied in this section.

The mean values shown in Table 21 provide a brief view of the differences on the basis of direction. No significant difference was found in board density and MC%. However, MOE (⊥) and MOR (⊥) values, 2131.71MPa and 12.55MPa, respectively, are half that MOE (//) and MOR (//), 5707.72MPa and 27.29MPa, respectively (Figure 32), proving that the long axis of OSB is the strength direction (Ibrahim, 2010), and hence, panels should be cut in the long direction when used for structural purposes (Bowyer et al., 2003).

Table 21. Physical and Bending Strength of Control Groups in Both Directions.

Properties	Control Groups	
	Parallel to Long Direction (//)	Perpendicular to Long Direction (⊥)
BD (g/cm^3)	.65 a	.64 a
MC (%)	9.30 a	9.08 a
MOE (MPa)	5707.72 a	2131.71 b
MOR (MPa)	27.29 a	12.55 b

Note: Values within the same row followed by different letters (a-b) are significantly different at $P< 0.05$.

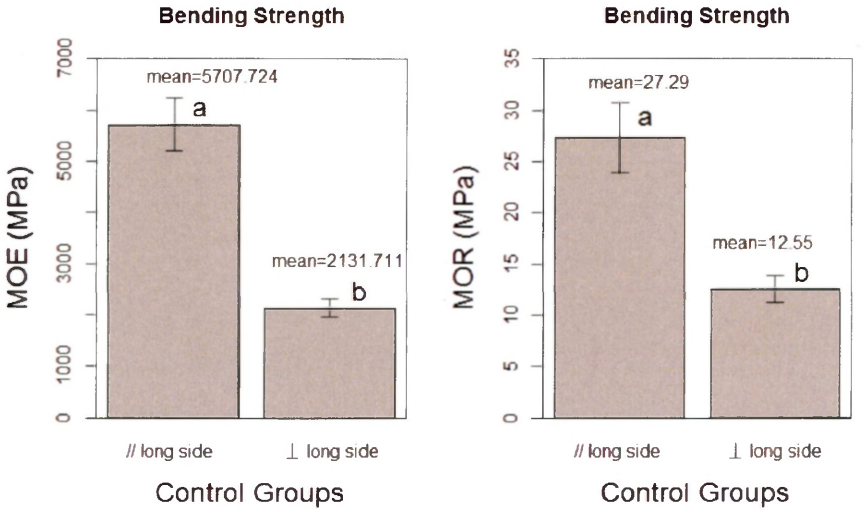

Figure 32. Bending Strength in Both Directions of Control Groups.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions for the Particleboard Study

The first part of this thesis studied the feasibility of using tamarack, an under-utilized species, for manufacturing particleboard and the effect of raw materials (juvenile wood, mature heartwood, and mature whole tree) on the physical and mechanical properties. The results show that tamarack has the potential to be used as the raw material for particleboard manufacturing, and raw materials do have effects on the properties of particleboard.

Specifically, particleboard made from mature whole tree tamarack performed better on most properties than the minimum values required by the standard in the same category. Particleboard made from mature heartwood of tamarack displays better dimensional stability compared to particleboard made from juvenile and mature whole tree in a wet environment, as well as a higher internal bond strength in the mature heartwood samples. The favorable water resistance and stronger internal bond strength of mature heartwood boards are mainly a result of: 1) the smaller microfibril angle in S2 layers of heartwood than juvenile wood; and 2) the higher extractive content in the heartwood, which is acting as: i) adhesives to help improving water resistance and ii) binders for accelerating the connection between particles to increase bond strength.

In summary, under-utilized wood species like tamarack, especially the heartwood of tamarack can be used as an alternative source of fiber for the particleboard industries. In addition, wood that contains higher extractives like heartwood leads to a more desirable dimensional stability.

5.2 Conclusions for the OSB Study

The second part of the experimental research investigated variance between OSB sheets, the effects of thermally modified temperatures (160° C and 175°C) on the properties of OSB, and differences between the parallel and perpendicular MOE and MOR values of OSB.

Based on the results presented in this study, the following conclusions can be drawn:

i. Wood variance is the nature of wood that cannot be eliminated. Even if the variance of some properties like density can be reduced during production processes, the variance still exists, especially in the physical properties.

ii. The low temperature treatment (160°C) displays a favorable dimensional stability. Hardness and FS remain the same as Control 1 according to statistical analysis as expected. However, MOE (⊥), MOR (⊥), and IB display a statistical significantly decrease compared to Control 1.

iii. High temperature treatment (175°C) leads to a greater effect on the water resistance property as expected, however, selected mechanical properties are negatively affected with no exceptions.

iv. OSB is not as homogenous a board as particleboard; MOE and MOR are varied depending on directions due to its manufacturing process. Long wood strands align in the long direction of a panel displaying higher values of MOE and MOR, which is almost twice that of values found in the perpendicular direction.

In summary, properties of OSB differ from board to board due to the nature of wood. The long axis of OSB is important to clarify when panels are used in structural applications since it is the strength direction. Low temperature treatment appears to be the ideal treatment because it increases dimensional stability as is the case for the higher temperature treatment; however, no compromise on FS and hardness in the low temperature treatment while there is a large decrease in mechanical properties of the high temperature treatment. Additionally, though MOE ($\perp$), MOR ($\perp$), and IB display a statistical significantly decrease in low cook treatment compared to Control 1, the difference between MOR ($\perp$) and IB were not as large as the high temperature treatment.

Therefore, thermal treatment in low temperature (160^0C) on OSB of this study is not as cost effective as we expected; however, for the sake of environmental and life cycle benefit, it is reducing the VOCs emission and improving dimensional stability without significantly affecting mechanical properties, such as FS and hardness.

5.3 Recommendation for Future Work

A number of research areas should be examined for further studies on both parts of this thesis.

Specifically, other under-utilized species should be tested using waterproof resin for manufacturing particleboard with large-scale replicates under a modified process (e.g. industry process) to analyze raw material effects. As a consequence, this could expand the usable wood species in the particleboard industries.

Thermally modified OSB in the low temperature treatment (around 160°C) requires better process control to protect samples from absorbing steam water during processing. The study should be redone to test property changes induced by the low temperature treatment as some samples were lost due to this moisture sitting on the panels following treatment. Instead of investigating the perpendicular direction as was done in this study, MOE and MOR parallel to the long direction should be the focus in order to have an accurate evaluation of thermally modified OSB when utilized in structural purposes.

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APPENDIX I. Random Selection for Thermal Treatment Level of OSB.

12 sheets (48" X 96")			Randomize Treatments by Group			
Original label	Relabeled			Random Data Generator	Temperature Level	Abbreviation
7	sheet 1					
12	sheet 2					
2	sheet 3	group 1	group 2	0.079531	160℃	T1
10	sheet 4					
11	sheet 5					
1	sheet 6					
8	sheet 7					
3	sheet 8					
9	sheet 9	group 2	group 1	0.2172	175℃	T2
5	sheet 10					
4	sheet 11					
6	sheet 12					

APPENDIX II. Board's Location before Thermal Modification and Their Conditions after Treatment.

label and cut into 16" X 16"

		1			2			3			4			5			6		
		16"	16"	16"	16"	16"	16"	16"	16"	16"	16"	16"	16"	16"	16"	16"	16"	16"	16"
group1 T2 175 ℃	16"	T2.1	C2.1	T2.7	C2.7	T2.13	C2.13	T2.19	C2.19	T2.25	C2.25	T2.31	C2.31	T2.37	C2.37	T2.43	C2.43	T2.49	C2.49
	16"	T2.2	C2.2	T2.8	C2.8	T2.14	C2.14	T2.20	C2.20	T2.26	C2.26	T2.32	C2.32	T2.38	C2.38	T2.44	C2.44	T2.50	C2.50
	16"	T2.3	C2.3	T2.9	C2.9	T2.15	C2.15	T2.21	C2.21	T2.27	C2.27	T2.33	C2.33	T2.39	C2.39	T2.45	C2.45	T2.51	C2.51
	16"	T2.4	C2.4	T2.10	C2.10	T2.16	C2.16	T2.22	C2.22	T2.28	C2.28	T2.34	C2.34	T2.40	C2.40	T2.46	C2.46	T2.52	C2.52
	16"	T2.5	C2.5	T2.11	C2.11	T2.17	C2.17	T2.23	C2.23	T2.29	C2.29	T2.35	C2.35	T2.41	C2.41	T2.47	C2.47	T2.53	C2.53
	16"	T2.6	C2.6	T2.12	C2.12	T2.18	C2.18	T2.24	C2.24	T2.30	C2.30	T2.36	C2.36	T2.42	C2.42	T2.48	C2.48	T2.54	C2.54

		7			8			9			10			11			12		
		16"	16"	16"	16"	16"	16"	16"	16"	16"	16"	16"	16"	16"	16"	16"	16"	16"	16"
group2 T1 160℃	16"	T1.1	C1.1	T1.7	C1.7	T1.13	C1.13	T1.19	C1.19	T1.25	C1.25	T1.31	C1.31	T1.37	C1.37	T1.43	C1.43	T1.49	C1.49
	16"	T1.2	C1.2	T1.8	C1.8	T1.14	C1.14	T1.20	C1.20	T1.26	C1.26	T1.32	C1.32	T1.38	C1.38	T1.44	C1.44	T1.50	C1.50
	16"	T1.3	C1.3	T1.9	C1.9	T1.15	C1.15	T1.21	C1.21	T1.27	C1.27	T1.33	C1.33	T1.39	C1.39	T1.45	C1.45	T1.51	C1.51
	16"	T1.4	C1.4	T1.10	C1.10	T1.16	C1.16	T1.22	C1.22	T1.28	C1.28	T1.34	C1.34	T1.40	C1.40	T1.46	C1.46	T1.52	C1.52
	16"	T1.5	C1.5	T1.11	C1.11	T1.17	C1.17	T1.23	C1.23	T1.29	C1.29	T1.35	C1.35	T1.41	C1.41	T1.47	C1.47	T1.53	C1.53
	16"	T1.6	C1.6	T1.12	C1.12	T1.18	C1.18	T1.24	C1.24	T1.30	C1.30	T1.36	C1.36	T1.42	C1.42	T1.48	C1.48	T1.54	C1.54

Note: Pink and green: different sheet

Orange: part of board damaged (board size < 16"X16")

Grey: missed board (untreated in Duluth)

Blue: moldy board

1 inch = 0.41 meter

APPENDIX III. R Syntax for Particleboard and OSB (Template).

```
getwd()
data <- read.csv("File Name.csv", header = T)          ##File Name##
data$AA <- as.factor(data$AA)                          ##AA: Independent Variable##
data$BB <- as.numeric(data$BB)                         ##BB: Dependent Variable##

str(data)
attach(data)

install.packages("sciplot")
library(sciplot)
install.packages("agricolae")
library(agricolae)
install.packages("multcomp")
library(multcomp)
install.packages("car")
library(car)

boxplot(BB ~ AA, xlab= "Name",
        ylab="Value (unit)")
summary(BB)

data_ BB.aov<-aov(BB ~ AA)
resid_ BB <-resid(data_ BB.aov)
shapiro.test(resid_ BB)                                ##Check Normality##
hist (resid_ BB)                                       ##Histogram##

bartlett.test(BB~ AA)                                  ##Check Homogeneity##
par(mfrow=c(1,1))                                      ## QQ plot ##
qqPlot<-function(x, ...){
 qqnorm(x)
 qqline(x)
}
qqPlot(BB)

data_BB.aov<-aov(BB ~ AA)
summary(data_ BB.aov)                                  ##ANOVA Test##

PosHoc_BB <-TukeyHSD(data_BB.aov)
```

```
PosHoc_BB
significant


BB.M <- tapply (data$ BB, INDEX = data$ AA,
                    FUN = mean)
BB.sd <- tapply(data$ BB, INDEX = data$ AA,
                    FUN = sd)

bp1 <- barplot(BB.M, xlab = "Name",
                   ylab = "Value (unit)")
arrows(bp1, BB.M, bp1, BB.M + BB.sd, lwd = 1.5,
         angle = 90, length = 0.1)
arrows(bp1, BB.M, bp1, BB.M - BB.sd, lwd = 1.5,
         angle = 90, length = 0.1)
text(locator(1), "a", cex= 1.5)

box()
```

```
##PosHoc Test when

  difference occur##


##Mean Value##

##Standard Deviation ##


##Bar Plot##



##Text Caption##
```

APPENDIX IV. Description of Sample Direction.