Thermo-Hydro-Mechanical Densification of Western Hemlock (*Tsuga heterophylla*)

by

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Abstract

Thermo-Hydro-Mechanical densification (THM) is a controlled wood compression at high temperatures that results in improving some of its properties. This process has not been used until now to produce a commercial product, and still, remains a laboratory-scale process. Therefore, more research is needed to explore possible applications of THM with local species.

This thesis tests the hypothesis that THM will increase wood density and accordingly, improve mechanical properties such as hardness, strength, and abrasion resistance. Therefore, low-to-average density wood species could be proper candidates for densification. In addition, interactions among three important factors (pre-treatment, densification time, and temperature) on THM were examined to find the best combination of factors in process.

Western hemlock (*Tsuga heterophylla*) as one of the most common and important local timber species was selected for THM. Because this species is used mostly in construction, thus, the development of other uses could create new markets and extra profits to the industry. Kiln-dried hemlock boards were subjected to THM process. Two different specimen pre-treatments were selected before starting the compression of wood. The independent variables considered were 12% moisture content conditioned sample surfaces with and without hydration by water spraying, three densification times (5, 10, and 15 minutes), and three temperatures (120, 160, and 200°C). Tests performed on densified and control samples by means of a hot press to evaluate density, hardness, spring-back, color change, and abrasion resistance.

Data analysis shows that temperature, densification time, and moisture pre-treatment were significant factors. Compared to untreated samples, THM significantly improved density, hardness, and abrasion resistance of hemlock by 197%, 386%, and 437%, respectively. As a desired feature, this process darkened the hemlock around 200% as well. In addition, after 200 hours, spring-back reached to a steady state (less than 2% change). The optimum treatment took place for pretreated samples with water spray that were densified for 15 minutes at 160°C (WS-15-160).
Lay Summary

Thermo-Hydro-Mechanical Densification (THM) is an environmentally friendly thermal treatment method, which uses a hot press to compress wood boards. This method could consider just surface of wood rather than destroying the whole volume to increase their mechanical properties. Western hemlock is an important commercial tree in B.C. We selected this specie for THM since it rarely has been used for thermal treatment. The main goal of this study was to examine properties of densified western hemlock to find new possible markets, such as flooring, for it.
Preface

This dissertation is an original intellectual product of the author, Poorya Kooche Baghy under the supervision of Professor Stavros Avramidis. The proposed methodology in this manuscript is original, unpublished, and independent work by the author at the UBC Department of Wood Science.
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To my amazing wife: Elahe;

To my lovely daughter: Elena;

To Iranian people, especially women, who are fighting to reach toward freedom.
Chapter 1: Introduction

1.1 Background

Wood is one of the most widely used materials in the world that is natural, renewable, of reasonable cost, and requires relatively small amounts of energy for processing (Dogu et al. 2016, Sandberg et al. 2017). Wood is broadly used in construction where strength and lightness are required; properties that are due to its polymeric tubular structure (Winandy and Rowell 2013). However, because of its heterogeneous composition and natural growth patterns, wood is quite variable with additional drawbacks such as high hygroscopicity, dimensional instability, and biodegradability (Zobel and Van Buijtenen 1989, Winandy and Rowell 2013, Nourian 2018). Variability has a direct effect on the quality of various wood products, resulting in reduced application options and shorter service life, and thus, decreased industry profits (Moore and Cown 2015). However, structural modification may provide wood with a great potential for improvement and increased number of end uses by reducing the adverse effects of some of its natural defects (Fernandes et al. 2017).

Wood modification is defined as the action of one or combination of processes, leading to an improvement in a desired property. It can be categorized into four main groups, namely, (1) chemical, (2) biological, (3) physical, and (4) thermo-hydro (TH)/thermo-hydro-mechanical (THM), the latter is also called “surface densification” (Darwis et al. 2017, Sandberg et al. 2017).

Wood properties can be modified by means of chemical treatments. Most chemical treatments bring about some adverse effects and process concerns (Esteves and Pereira 2009). For example, the cost of most chemical modifications is high and the process by-products need to be recovered due to environmental concerns. Therefore, more environmentally friendly modifications are preferable to most traditional chemical treatments (Rowell et al. 2012). Thermal modification (TM), on the other hand, uses heat as a means for improving wood properties, such as density, hardness, and abrasion resistance, in an environmentally friendly way (Awoyemi and Jones 2010). Currently, there are different commercial variations of TM such as Plato, Rectification, Oil-heat treatment and Thermowood® (Esteves and Pereira 2009, Sandberg et al. 2017).
Thermo-hydro-mechanical densification (THM) is a form of thermal modification methods that combines thermally induced stability with increased density. Wood density is a critical property (Saranpaa 2003), that contributes to the quality of the final product and its applications. Furthermore, carbon cycle research considers wood density as an important variable, which also provides resistance of trees against wind, storms, and other environmental stresses (Rodriguez et al. 2016). It is highly correlated with its mechanical properties, and woods with a density lower than 500 kg/m³, have limited uses due to low strength (Hill 2006, Dogu et al. 2016, Sandberg et al. 2017).

In THM, the porous structure of wood is compressed between heated metal plates while it is simultaneously thermally modified (Laine et al. 2014). Wood densification is not a new technology; Esteves and Pereira (2009) report that the first attempt at wood densification, called “Lignostone”, occurred in 1936. Although densification has received numerous process alterations in the course of time, it is not yet a viable industrial process (Sandberg et al. 2017). THM performance is highly dependent on properties of selected wood due to its structure. Low-density wood species are appropriate candidates for the THM method. Research into improving density, strength and hardness of softwoods, such as Scots pine and Norway spruce, has been focus of most studies regarding surface densification (Neyses et al. 2015, Neyses and Sandberg 2016).

Western hemlock (*Tsuga heterophylla* Sarg.) is the dominant species on the west coast of North America and is the most plentiful tree species on the coast of British Columbia. Hemlock is used to produce pulp and timber with several applications such as paper industries, roof decking, laminating, buildings etc. Owing to its low density that is usually less than 500 kg/m³, hemlock is not suitable for applications that require high hardness and abrasion resistance. In addition, while its light-color is an appropriate feature for making newsprint, darker and harder woods are more preferable in applications such as flooring (Johnson and Gibbons 1929, Middleton and Munro 2001, Lazarescu and Avramidis 2012).

In light of the significant financial incentives and availability of western hemlock in British Columbia, improving its properties by THM densification was selected as the research focus of this thesis.
1.2 Hypothesis and Objectives

The overall objective of this study is to explore the thermo-hydro-mechanical densification of western hemlock. My specific objective is to optimizing pre-treatment, densification time, and temperature to improve the density, hardness, and abrasion resistance, and color of western hemlock.

The results are expected to provide flooring industries with some basic process and product information regarding the applicability of hemlock as a cheaper flooring alternative to hardwoods via THM densification.

1.3 Outline of Thesis

Chapter 1 of thesis briefly presents the topic, explains reasons of choosing the method and species. This chapter also provides a hypothesis. Chapter 2 reports background information on THM with an emphasis on selected factors and variables of interest in this study. Chapter 3 describes the methodology used for surface modification, preparing samples, and measuring the properties of densified samples; density, hardness, spring-back, color, and abrasion. In Chapter 4, the results of experiments analyzed, interpreted, and compared to peer-reviewed studies. Finally, Chapter 5 discusses the implications of results from Chapter 4 and shows how the results support the objective of the study. Lastly, in Chapter 6 recommendations for future research are presented.
Chapter 2: Literature Review

Wood is one of the oldest materials used by humans and in terms of utilization volume it is second after concrete (Navi and Heger 2004). Applications of wood will continue to be important because it has unique advantages such as widespread availability and renewability. In addition, wood has a high strength-to-weight ratio and outstanding workability. Nonetheless, wood has some disadvantages such as high variability of hygroscopicity, anisotropic behavior, and biodegradability. Changing these undesirable characteristics may lead to new applications and markets (Navi and Heger 2004).

2.1 Softwood Structure

Trees can be divided into two main classes as softwood and hardwood. The main difference between softwoods and hardwoods is that vessel elements just exist in hardwoods (Figure 2.1). The structure of softwoods is simpler and more homogeneous than hardwoods. (Hoadly 1990, Glass and Zelinka 2010). As THM methods usually consider softwood species, and our study focused on western hemlock, only structure of softwood is explained in this section.

The structure of wood that is visible by naked eye is known as macrostructure, which contains several distinct zones (Mouritz 2012). The main macroscopic parts of wood are bark, pith, sapwood and heartwood, annual ring, rays, and resin canals (Navi and Sandberg 2012). Bark as the outer layer protects inner sections of wood (xylem) against extreme temperatures, mechanical injury, insects, and other organisms. Pith is located in the center of a tree, and is formed in the first year of growth and its shape varies between species. As a tree grows, the function of living cells in the center part starts to decline and the heartwood is formed. In several species, there is no clear boundary between these parts. However, the portion of sapwood is greater than heartwood in softwoods. While sapwood has a very high moisture content, heartwood is denser and stronger, and supports trees against mechanical loads. Annual ring is a ring of wood indicating one years' growth and has two parts: earlywood produced in spring, and latewood is formed in summer. In coniferous species (softwoods), earlywood is lighter in color, and has lower density. Wood rays contain nutrient-storing cells in the transverse direction from the bark toward the pitch at a right angle to the annual rings. In most softwoods, rays have a simple structure with only one
or two cells wide, which are known as uniseriate and biseriate, respectively. Rays have a significant effect on wood properties such as strength, and they are the main reason of transverse hygroexpansion anisotropy in wood. Resin canals are in softwoods are elongated, tube-shaped intercellular space, and lined with specialized parenchyma that protect wood against insects. These canals exist only in some softwood species. (Glass and Zelinka 2010, Navi and Sandberg 2012, Burgert et al. 2020).

Figure 2.1. The main differences between structure of softwoods and hardwoods (Burgert et al. 2020).

Microstructurally, wood consists of long void cells squeezed together like drinking straws (Figure 2.2). In softwoods, axial cell system mainly is made up of tracheids. Arrangement in tracheids is in order with neat rows. These long and thin cells conduct the water and provide most of the structural support. In the materials engineering context, microstructure of wood is often called as a unidirectional fiber-polymer composite. Wood fibers (tracheids) usually are roughly parallel with the longitudinal axis, and this is known as the grain direction, which is correlated with mechanical properties of wood (Kohler 2007, Mouritz 2012, Burgert et al. 2020).
The walls of wood cells consist three polymers: cellulose, hemicelluloses and lignin, which are the main chemical components of wood. Extractives are other components, which are deposited in the cell walls during the formation of heartwood (Table 2.1) (Navi and Sandberg 2012).

Figure 2.2. The microstructure of softwood (Scots pine (*Pinus sylvestris*)) (Ansell 2015).

<table>
<thead>
<tr>
<th>Component</th>
<th>Composition (%)</th>
<th>Polymeric nature</th>
<th>Basic monomer</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>45-50</td>
<td>Linear molecule semi-crystalline</td>
<td>Glucose</td>
<td>Fiber</td>
</tr>
<tr>
<td>Hemicelluloses</td>
<td>20-25</td>
<td>Ramified amorphous Molecule</td>
<td>Sugar essential non glucose</td>
<td>Matrix</td>
</tr>
<tr>
<td>Lignin</td>
<td>20-30</td>
<td>Three-dimensional amorphous-bonded</td>
<td>Phenolpropane</td>
<td>Matrix</td>
</tr>
<tr>
<td>Extractives</td>
<td>0-10</td>
<td>Polymerized molecule</td>
<td>Polyphenol</td>
<td>protection element</td>
</tr>
</tbody>
</table>
Cellulose is the major constituent of the cell wall and is the main responsible of mechanical properties and hygroscopicity in wood (Siau 1995). Cellulose has both amorphous and crystalline regions (Figure 2.3). The crystallinity in wood is defined as the weight fraction of crystalline cellulose (Andersson et al. 2003). Cellulose is more resistance against high temperatures compared to hemicellulose due to high degree of polymerization and crystallinity. Hemicellulose has polysaccharides with similar composition with cellulose but lower molecular weight. It has only amorphous structure, and the first thermal degradation in wood occurs in hemicellulose (Bourgois and Guyonnet 1988, Siau 1995). Lignin is a complex amorphous material, and highly branched phenolic polymer. It is the most stable wood component against temperature and the least hygroscopic component of cell wall (Sanderman and Augustin 1963). Extractives include several number of organic compounds that most of them evaporate in a heat treatment (Siau 1995).

Wood is an orthotropic material, and has independent properties in the directions of three perpendicular axes (Figure 2.4). "The longitudinal axis $L$ is parallel to the fiber (grain); the radial axis $R$ is normal to the growth rings and perpendicular to the grain in the radial direction; and the
tangential axis $T$ is perpendicular to the grain but at tangent to the growth rings" (Green et al 1999, Alves et al. 2015).

![Diagram of wood axes](image)

Figure 2.4. Three axes of wood with respect to grain direction and its growth rings (Olorunnisola 2018).

### 2.2 Water in Wood

The concentration of water absorbed in air is commonly referred to as absolute humidity ($AH$) and it is measured in grams of water per cubic meter of moist air. The ratio of $AH$ to the maximum amount of water which air is able to hold at a particular temperature, is known as relative humidity ($H$) that can range between 0 and 100% (Siau 1995).

Wood also absorbs water and that amount is called moisture content ($M$) and is expressed as a percentage of the oven-dry weight of wood. The level of its $M$ is always a strong function of air $H$ and temperature ($T$) and a plot of that relationship called a sorption isotherm. Numerically, $M$ may range from 0% (oven dry or bone-dry wood) to levels over 200% (Skaar 1988).

Freshly cut wood from a recently felled tree is referred to as green wood and the water contained in it exists in three forms: liquid water that partially or completely fills the cell cavities (lumens); water vapor that is in empty cell cavities; and molecular water absorbed into the cell wall material (Skaar 1988, Dubey 2010). The liquid water in lumens is called free water and the water absorbed in the cell walls is referred to as bound water. Bound water is bonded to the polymeric structure of wood and specifically, the so-called sorption sites (-OH) via hydrogen bonds, as compared to free
water that is only held by capillary forces (Dubey 2010). The majority of sorption sites are in the hemicelluloses followed by cellulose and lignin. Two-thirds of the hydroxyl groups are bound between and within cellulose chains, which are mostly inaccessible (Engelund et al. 2013).

Due to energetic state of the two water-types, when green wood dries, free water is the first to evaporate. The wood $M$ at the point where all free water has left is called the Fiber Saturation Point ($M_{fsp}$) and typically corresponds to a moisture content between 25 to 35% depending on the species. Below $M_{fsp}$, wood begins to shrink as it starts to lose its bound water (Skaar 1988). This dimensional instability is what makes wood a problematic candidate for many applications.

Owing to its hygroscopic nature of wood, water molecules are continuous exchanged with those in the surrounding atmosphere. $M$ change (adsorption or desorption) has an important influence on wood properties and performance. Water exchange ceases at a certain point where $M$ reaches a dynamic equilibrium with its surrounding environment. This balance point is called the equilibrium moisture content ($M_{emc}$). $H$ and $T$ are effective parameters for determining $M_{emc}$ (Glass and Zelinka 2010).

Wood in service is continuously subjected to environmental humidity changes. Wood picks up water from air (adsorption) when $H$ increases, and gives water off (desorption) when $H$ decreases for constant $T$. Increasing air $T$ forces wood to lose water whereas decreasing $T$ results in water gain, assuming same $H$. The relationship between $M$ and $H$ for various $T$ is given by the sorption isotherm is a sigmoid curve usually referred to as a type II sorption (Figure 2.5). (Glass and Zelinka 2010).

Sorption is a common term used to address both absorption and adsorption phenomena. It is an important fact that the sorption isotherm achieved when wood is gaining moisture (absorption isotherm) does not coincide with desorption isotherm, namely, when wood is losing moisture. The difference between these two isotherm curves for the same $H$ is called hysteresis (Glass and Zelinka 2010). The sorption behavior of wood is affected by $T$, $H$ and by its immediate history (Time 1998, Shi 2017). Elevating the temperature of wood reduces $M$ at a given $H$, which is a temporary and reversible effect. High temperatures can also permanently reduce the hygroscopicity of wood even after the wood returns to normal temperatures (Skaar 1988, Liu et al. 2015).
Figure 2.5. Typical wood sorption isotherm showing also the phenomenon of hysteresis.

2.3 Dimensional Changes of Wood

The dimensional stability of wood is defined as its ability to withstand changes in its dimensions when its $M$ changes (Dubey 2010). Water adsorption and desorption result in wood cell wall dimensional changes that manifest as gross wood swelling and shrinkage, respectively. Both $M$ and wood dimensional stability can be controlled by $H$ (Skaar 1988, Ahmed 2006).

Wood cells exist as long tubes with the length of these tubes being much longer that the diameter of the tube. The long axis is referred to as the grain direction and usually corresponds to the longitudinal direction of the wood sample. The changes in the thickness of the cell walls that make up these tubes results in the density of the wood changing over the course of a growing season and leads to the annual growth rings commonly seen in a cross section of a stem or branch. A result of the cell aspect ratio and growth rings is that wood is anisotropic and has different properties in the longitudinal, radial and tangential directions (Ritter 1990, Green et al 1999).
Wood anisotropic behavior strongly affects mechanical properties such as stiffness, strength. For instance, wood has high compressive strength (resistance to squeezing) when is loaded in the same direction as the grain. Although wood properties differ in each direction, differences between the tangential and radial directions are mostly negligible compared to their huge differences with the longitudinal direction. Therefore, most wood properties for structural applications are presented only for directions parallel to grain (longitudinal) and perpendicular to grain (radial and tangential) (Ritter 1990).

Dimensional change depends on grain direction as well. Wood shrinks or swells the most in the tangential direction (6% to 12%), then, in radial (3% to 6%) and longitudinal (0.1% to 0.3%), respectively (Figure 2.6) (Skaar 1988, Siau 1995, Dubey 2010). For instance, these values for western hemlock (from green to oven dry condition) in tangential, radial and longitudinal directions are 7.8%, 4.2%, and 0.2%, respectively. (Glass and Zelinka 2010). Shrinking and swelling in wood can lead to warping, checking, splitting, and, it can create gaps in strip flooring (Simpson and TenWolde 1999).

![Figure 2.6. Approximate shrinkage values for wood species (Workshop Companion 2009).](image)

Wood cell wall contains free hydroxyl groups, which form hydrogen bonds between matrix components and water (Dubey 2010). When water evaporates from the cell wall, the matrix shrinks and the microfibrils move closer together. In longitudinal direction, the dimensional change is
much smaller than in other directions because fiber cell walls are more apart (the distance between fiber cell walls are 100 times higher than that of in transverse direction) (Time 1998). This implies that dimensional changes in wood are different in each direction, and depend on density and growth characteristics of wood (Carll and Wiedenhoeft 2009).

Dimensional change is proportional to density, and less dense woods shrinks or swells less than denser ones. A simplistic explanation about density–shrinkage relationship is that solid wood shrinks but empty space does not shrink. As a high-density wood has more cell walls and less lumen (void) spaces, it shrinks and swells more than a low-density wood (Schulgasser and Witztum 2015). Anisotropic anatomy of wood makes the relation between density and shrinkage more complicated, and several researches investigated to find an appropriate model for each species (Schulgasser and Witztum 2015, Christoforo et al. 2016). For instance, Alfas et al. (2005) found that there is a negative correlations between wood density and longitudinal shrinkage and positive correlations between density and transverse shrinkage.

Any modification to wood that lowers its $M_{emc}$ will improve its dimensional stability. A treated sample with a lower $M_{emc}$ will absorb and release less water than an untreated sample for a given change in $RH$. This will result in smaller changes in the sample’s dimensions and reduces swelling and shrinkage (Bonigut et al. 2014, Mitchell 2018, Shukla 2019). Therefore, heat treatment, which decreases $M_{emc}$, is one means of improving the wood stability (Glass and Zelinka 2010).

### 2.4 Moisture Effects on Wood Properties

There is variability in $M$ in green wood even within individual pieces cut from the same tree. As several properties of wood are strongly related to its $M$, this variability could be an effective indicator of its properties, such as dimension and strength (Glass and Zelinka 2010).

In terms of biological degradation, a moisture content that exceeds $M_{fsp}$ encourages degradation by insect and particularly fungi. Even after drying wood and reaching an appropriate level of $M$, moisture fluctuation should be maintained within a reasonable range ($M$ of 20% or less has been recommended) (Carll and Wiedenhoeft 2009).

By decreasing $M$ below $M_{fsp}$, almost all mechanical properties of wood increase (Table 2.2). $M_{fsp}$ is a descriptor of wood properties as below $M_{fsp}$, increase in moisture content causes decreases in
most strength properties and beyond $M_{sp}$, there is no significant change in mechanical properties and dimensions of wood (Gerhards 1982, Patterson 2010, Korkmaz and Buyuksari 2019).

Table 2.2. Effects of $M$ on mechanical properties of clear wood at about 20°C (Gerhards 1982).

<table>
<thead>
<tr>
<th>Relative change in property from 12% $M$</th>
<th>At 6% $M$</th>
<th>At 20% $M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Modulus of elasticity parallel-to-the-grain</td>
<td>+9</td>
<td>-13</td>
</tr>
<tr>
<td>Modulus of elasticity perpendicular-to-the-grain</td>
<td>+20</td>
<td>-23</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>+20</td>
<td>-20</td>
</tr>
<tr>
<td>Bending strength</td>
<td>+30</td>
<td>-25</td>
</tr>
<tr>
<td>Tensile strength parallel-to-the-grain</td>
<td>+8</td>
<td>-15</td>
</tr>
<tr>
<td>Compressive strength parallel-to-the-grain</td>
<td>+35</td>
<td>-35</td>
</tr>
<tr>
<td>Shear strength parallel-to-the-grain</td>
<td>+18</td>
<td>-18</td>
</tr>
<tr>
<td>Tensile strength perpendicular-to-the-grain</td>
<td>+12</td>
<td>-20</td>
</tr>
<tr>
<td>Compressive strength perpendicular-to-the-grain</td>
<td>+30</td>
<td>-30</td>
</tr>
</tbody>
</table>

$M$ is an important parameter affecting the progressive deflection over time (creep) of wood members, under load during their service life. Especially, $M$ fluctuation can accelerate viscoelastic creep (Huang 2016) and result in unwanted deflection of wood members. In addition, the function of mechanical connections is affected by elevated $M$ (Carll and Wiedenhoeft 2009).

Density plays an important role in mechanical properties, and it varies with $M$ (Glass and Zelinka 2010), and differs from species to species (Ahmed 2006). Typically, high $\rho$ species are preferable for engineering applications compared to low $\rho$ ones due to their higher mechanical properties. For instance, density has a positive correlation with hardness and wearing resistance. Most high-density species are more expensive and less available (Fang et al. 2019). Therefore, treatment methods that increase the density of lighter and normally cheaper species, have gained increasing interest during recent years (Senol and Budakci 2016, Schwarzkopf et al. 2018, Lykidis et al. 2020).
2.5 Western Hemlock

Western hemlock (*Tsuga heterophylla*), (Figure 2.7.a) was once considered a “weed species” before the late 1930s due to excessive warp during drying. This softwood covers the entire coast of British Columbia and occurs in humid regions of the interior on the western slopes of the Rocky Mountains where it ranges from the Prince George to parts of northern Idaho and Montana (Figure 2.7.b) (Natural Resources Canada 2015). Fortunately, development of new drying schedules that minimized warping led to the successful use of this species for several applications (Jozsa *et al.* 1998). Today, hemlock is one of the important domestic species in British Columbia.

The word *Tsuga* is derived from a Japanese hemlock species, and the word *heterophylla* means various-sized leaves (Johnson and Gibbons 1929). A secondary western hemlock tree is defined as a tree that has re-grown after a prime timber harvest. According to many tests, the properties of second growth western hemlock are equal to, or even better than, old growth western hemlock. There is no clear difference in color between heartwood and sapwood of green western hemlock. However, dry heartwood, which is the largest portion, is slightly lighter than sapwood. In terms of \( M \), the moisture content of sapwood (170%) is usually greater than that of heartwood (85%) (Middleton and Munro 2001, Glass and Zelinka 2010).

![Figure 2.7. (a): Western hemlock tree. (b): Distribution of western hemlock in B.C (Natural Resources Canada 2015).](image)

Green western hemlock wood has a sour odor; the dried one is non-resinous, and odorless. Wetwood, which is a result of moisture variation in heartwood, has a higher moisture content and
density compared to adjacent areas, leading to uneven drying and dimensional instability of hemlock timbers. (Hartley et al. 1961, Schroeder and Kozlik 1972, Hoadly 1990). In terms of properties, western hemlock is moderately light in weight and of moderate strength, hardness, and stiffness (Table 2.3) (Alden 1995, Green et al. 1999).

Table 2.3. Mechanical properties of western hemlock grown in Canada.

<table>
<thead>
<tr>
<th>Moisture content</th>
<th>Specific gravity</th>
<th>Modulus of rupture (kPa)</th>
<th>Modulus of elasticity (kPa)</th>
<th>Compression parallel to grain (kPa)</th>
<th>Compression perpendicular to grain (kPa)</th>
<th>Shear parallel to grain (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green 12%</td>
<td>0.38</td>
<td>48,000</td>
<td>10200</td>
<td>24700</td>
<td>2600</td>
<td>5200</td>
</tr>
<tr>
<td></td>
<td>0.41</td>
<td>81,000</td>
<td>12,300</td>
<td>46700</td>
<td>4600</td>
<td>6500</td>
</tr>
</tbody>
</table>

Hemlock has a comparatively narrow latewood band, and there is no sharp contrast between summer and spring portion of growth rings, leading to a relatively uniform hardness within annual rings, which hemlock falls between hard and soft pines regarding hardness (Johnson and Gibbons 1929).

Regarding applications of hemlock, it has been a crucial component of the traditional 'post-and-beam', called Zairai, Japanese house for 1,300 years. It is mainly used for doors, windows, parts of staircases, ladders and structural timbers. It could be used in other applications such as flooring after using various treatment methods to improving its properties (Edgington 2003, Canadian Wood 2019). Hemlock has a uniform and fine textured wood, which is an important factor for flooring companies. However, this species has a low decay resistance, which this undesirable factor for in ground applications (Johnson and Gibbons 1929). Some studies have shown that the decay resistance of wood can be increased by thermal densification. One potential mechanism is that denser wood has a lower risk of wounding as a suitable medium for infectious agents (Schwarze and Spycher 2005, Larjavaara and Muller-Landau 2010, Pelit and YalcIn 2017).

Another concern with hemlock, especially for the flooring industry, is its poor resistance to marring and denting. Generally, Industry would prefer to use hardwoods than softwoods because the former are harder and more abrasion resistant (Table 2.4). Nonetheless, industries may find hemlock easies to lay compared to some of the woods commonly used for flooring (Johnson and
Gibbons 1929). Density of hemlock is even throughout the wood, which results in good machining properties. However, the density of green hemlock is usually between 470 to 490 kg/m$^3$, which is too low for using in flooring applications (Ross 2010, Laskowska 2017). As a result, a modification method with an ability to increase the density could add value to this domestic species.

Table 2.4. Janka hardness of some common wood species in flooring industry (Ross 2010).

<table>
<thead>
<tr>
<th>Species</th>
<th>Hardness (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazilian Walnut</td>
<td>16.4</td>
</tr>
<tr>
<td>Brazilian Cherry</td>
<td>8.1</td>
</tr>
<tr>
<td>Acacia Collection</td>
<td>7.6</td>
</tr>
<tr>
<td>Red Oak</td>
<td>5.7</td>
</tr>
<tr>
<td>Red Maple</td>
<td>4.2</td>
</tr>
<tr>
<td>Handscraped Aspen</td>
<td>4.1</td>
</tr>
<tr>
<td>Phoenix Birch</td>
<td>3.5</td>
</tr>
</tbody>
</table>

2.6 Wood Modification

Wood modification is a method of improving the properties of wood. Although wood modification has been the subject of research for over the past century, significant commercial developments have occurred only decades (Hill 2006).

In a recent comprehensive review about wood modification, Sandberg et al. (2017) classified all current commercial modification methods into three groups: 1- Chemical processing, 2- Thermo-hydro processing (thermal modification (TH), 3- thermo-hydro mechanical processing (thermal densification (THM). The classification of non-chemical methods is shown in Figure 2.8. By considering the properties of modified wood and the complexity of each process, each of these methods has its advantages and disadvantages (Hill 2011).
2.6.1 Chemical Modification

Chemical modification (CM) is defined as any chemical reaction of wood polymeric components (hemicelluloses, cellulose, and lignin), with a chemical reagent, with or without a catalyst, that results in forming a stable bond between the reagent and the cell-wall polymers (Rowell 1983, Varma et al. 1989, Sandberg et al. 2017). This method is considered as an active modification due to its ability to change the chemical structure of wood. Industrial wood chemical modification can be categorized into two main methods, namely, acetylation and furfurylation (Sandberg et al. 2017).

In acetylation, the reaction of acetic anhydride with wood polymers leads to the esterification of accessible hydroxyl groups in cell walls and formation of a by-product, namely, acetic acid. Since the human nose is sensitive to the odor of acetic acid, it should be removed from modified wood (Sandberg et al. 2017). Acetylated wood exhibits high dimensional stability and good decay resistance and has negligible impacts on mechanical properties (Hill 2011, Sandberg et al. 2017).
In the furfurylation process, firstly, a mixture of furfuryl alcohol and catalyst is impregnated into wood. Then, a heating process leads to polymerization of the resin. Furfuryl alcohol used for furfurylation method is derived from corncobs or sugar cane residues from agricultural wastes (Sandberg et al. 2017). Furfurylation is able to increase physical-mechanical properties of wood such as indentation modulus, hardness and durability (Li et al. 2016). However, the chemical process is complicated and there are unanswered questions about the polymerisation of furfuryl alcohol in wood (Sandberg et al. 2017).

### 2.6.2 Thermal Modification

Heat treatment uses water and heat to modify wood properties. In fact, no additives are used in the processes except water in combination with wood, heat, and external forces to form the wood (Sandberg et al. 2017). The idea of using heat for modification of wood is not new. For instance, in 1920, the equilibrium moisture content of wood samples was decreased by drying at high temperature. However, interest in using the heat treatment methods increased recently. The main reason for this increase stems from increasing a high demand for sustainable building materials and governmental restrictions regarding using chemical treatments due to their consequences on human health and environment (Esteves and Pereira 2009).

There are several thermal modification methods. The Plato treatment (from Netherland) is a hydrothermal modification process that takes place on a pre-dried timber in four stages where steam plays a key role in both heating and conditioning stages. The Plato-treatment combines a hydrothermolysis step with a dry curing step. Hydrothermolysis results in different chemical transformations. At the first step of process (hydrothermolysis), a green or an air-dried wood is treated at temperatures between 160°C and 190°C under a super atmospheric pressure for 1-5 hours. In the second stage, a conventional drying process heats the wood to reach a low moisture around 10%, which it takes 3-5 days. In the curing stage, the wood is heated again at temperatures around 170 -190°C for 14- 16 hours. At the end of the process, conditioning occurs for 2-3 days. Depending on the species and thickness of wood, the duration for each process is different. Both steam and heated air can be used as heating medium in this process (Sahin 2017, Nourian 2018).

The Rectification method (from France) uses a nitrogen atmosphere in an oven where wood is heated to between 180°C and 250°C. At the beginning of this process, wood is dried to 12%
moisture. Next, the wood is heated slowly in a chamber by using a nitrogen atmosphere when the oxygen amount should be less than 2%. The process is sensitive to even a slight change of temperature (Sahin 2017, Nourian 2018).

The Oil-heat treatment (OHT) (from Germany) uses a hot oil bath instead of an inert gas to modify wood. The wood is treated in a closed system and the hot oil circulates all over the vessel with same condition and provides the wood with fast heat transfer. In addition, oil plays an important role to separate oxygen from wood, and gives it rubbery condition. The hot oil is kept at a high temperature when it is circulating around the wood. At the end, the oil is pumped back, and then, wood is picked up from the system. The temperature is between 180°C and 200°C in this process (Sidorova 2008, Sahin 2017, Nourian 2018).

In ThermoWood® method (from Finland) there are three steps. Firstly, heat and steam increase the temperature around 100°C. Then, the temperature is gradually increased to 130°C, and the moisture content in the wood reaches close to zero. In the second step, temperature is raised up to 185-230°C for 2-3 hours. Finally, cooling and conditioning take place using water to decrease the temperature to 80-90°C (Sahin 2017, Nourian 2018).

The Thermo-hydro-mechanical (THM) process is fully explained in 2.8 section, and uses one or combination of temperature, water, steam, and oil accompanies with mechanical forces to modify (densify) wood (Sandberg et al. 2017).

2.7 Effect of Modification on Wood Properties

Wood modification alters the molecular structure of cell wall components. Wood properties can be improved considerably when hydrophilic OH-groups are converted into larger more hydrophobic groups. Cell wall itself changes to a permanently swollen state that can attract no or very little water, allowing wood to reach a dimensionally stable condition. The modified wood is no longer a potential nutrient medium for fungi or the lowered $M_{enw}$ no longer promotes decay. Wood modification can improve important properties of the wood including biological durability, dimensional stability, hardness and strength (Homan and Jorissen 2004).

Regarding thermal modification (TM), these methods are able to improve equilibrium moisture content, dimensional stability, durability against decay, and color of wood. However, most of the
treatments decrease the density and flexibility of wood. According to research, thermal treatments lower the density by 5-10%. TM increases hardness as the processing temperature increases, but the relative change is very small due to decreasing density. Thermal treatments also produce a darker wood. (Thermo-treated wood handbook 2010, Sandberg et al. 2017).

Among all thermal modification methods, THM is reported to increase density, hardness, and strength properties of wood, simultaneously (Sandberg et al. 2017).

2.8 Thermo-Hydro-Mechanical Densification (THM)

Heat treatment methods are widely used for modification of wood properties. However, in most heat-based processes, in spite of improving the physical properties, decrease in mechanical properties of wood are reported (Navi and Heger 2004, Sandberg et al. 2013). THM is an abbreviation for as a combination mechanical-thermal treatment, which is able to enhance the mechanical properties of wood as well as its dimensional stability. Simplicity of method, all that is a hot press is another advantage. This treatment increases the density of wood, which is directly related to several mechanical properties. Surface densification is a new approach of TM that just addresses surface layers rather than modifying the whole structure of wood such as most treatment methods (Navi and Heger 2004, Sandberg et al. 2013).

Wood densification can be defined as compressing the material (board for example) in its transverse direction in order to decrease void volume (cell cavities), and thus, increase its density (Figure 2.9) (Kultikova 1999). During THM, heating changes the wood from a glassy form to a soft and rubbery structure (Kutnar and Sernek 2007, Ulker et al. 2012, Petric 2013).
Generally, a hot press (Figure 2.10) has been used in THM processes as a compression machine (Laine 2014). However, some researchers have employed different machine types instead of a hot press. For instance, Navi and Sandberg (2012) used a friction-welding machine and Neyses et al. (2016) developed a continuous wood surface densification method using a roller-pressing technique. In addition, Sadatnezhad et al. (2017) showed that a common high-capacity continuous pressing technique could increase the density of poplar (Populus spp.) in the region beneath the surface.

Figure 2.10. Hot press for THM of wood (Pelit et al. 2014).
There are two different THM methods, namely, whole volume (bulk) densification and surface densification. In bulk densification, the wood material is usually water saturated and subjected to a long processing time. Surface densification starts with relatively dry wood around 12% \( M \). Therefore, the densification process is faster than the bulk densification (Rautkari et al. 2010). There is no clear boundary between reductions in dimension for the two methods. However, around 50% reduction has been achieved by surface densification and more reduction can occur during whole densification. In some applications such as flooring, wood just needs to be densified at the surface, which means that surface densification is preferable (Laine et al. 2013, Gasparik 2015, Zhou et al. 2019).

Changing the shape of wood is another major problem for bulk densification, which leads to volume loss (Gaff and Gasparik 2015). In addition, surface densification uses less energy compared to the bulk densification. After densification, wood has a tendency to recover its original shape, which is an undesired behavior and is called spring-back or shape memory (Dhamodaran, and Afzal 2012). Because surface densification addresses this adverse effect, it produces a lower compression strain recovery compared to bulk densification due to the lower percent of thickness reduction (Laskowska 2017). In addition, lower compression for the surface densification creates lower residual stresses in comparison with bulk densification (Laine et al. 2016).

Wood has low thermal conductivity material, which helps to thermal densification mainly takes place just on surface layers (Gaff and Gasparik 2015). In fact, surface densification is based on two distinct behaviors of wood: 1- the influence of the moisture content on the glass transition temperature \( (T_g) \) of the wood, which is the temperature region where a polymer (wood) transitions from a hard material to a soft one, and 2- the poor thermal conductivity of wood (Navi and Sandberg 2012).

The first step for THM is pre-treating the surfaces of samples with a material, before starting the treatment. As there are growing concerns to use chemical materials for pre-treatment, softeners such as water are preferable. However, some researchers have used chemical softeners, especially when small samples were compressed since the chemical process takes huge amount of time (Neyses et al. 2017).
Although densification brings about several improvements for wood species, it also has some disadvantages. For instance, densified wood is susceptible to spring-back (Navi and Sandberg 2012, Hill et al. 2012). Several researchers attempted to decrease the negative effect of this undesirable effect. For instance, Rautkari and Hughes (2009) reported that the cell wall does not break under compression above the glass transition point due to rubbery condition. They proposed a post-treatment at a high temperature using saturated steam to release inner stresses in the microfibrils during the thermal densification. They reported that a high temperature around 180°C-200°C could partially eliminate spring-back, particularly in a closed press system under humid conditions.

Furthermore, Navi and Sandberg (2012) reported that post-treatment could eliminate the stored elastic strain by heating wood in saturated steam at 200°C (in a closed system) for about 4 minutes, or heating at a temperature of 160°C for 60 minutes or 180°C for 20 minutes. Gong et al. (2010) improved dimensional stability of densified Aspen (*Populus tremuloides* Michx.) by post-heat treatment, while the mechanical properties decreased to some degree. However, the mechanical properties of heat-treated densified aspen were still higher than those of non-densified. Regarding spring-back elimination, (Norimoto et al. 1993, Laine et al. 2013) reported that alongside post treatment, formation of cross-linkages, isolation of wood polymer, and relaxation of stress are main prevention methods. As a result, while post-treatment methods decrease the adverse effects of spring-back, they lower the positive effects of densification, especially regarding mechanical properties.

Aside from the possible environmental concerns regarding chemical treatments, other methods, such as combination of heating and compression, are more successful for improving the density of wood (Cai and Blanchet 2011, Fang et al. 2019). From an environmental viewpoint, by using a larger portion of wood products and extending service life, as two consequences of the wood densification method, carbon is stored over a longer period. Based on life-cycle assessment (LCA), densified wood presents a low emission of carbon dioxide with less adverse effects on the environment (Sandberg et al. 2013). While the main target of wood densification is low-density species, densification of high-density wood is also considered as a way of achieving higher mechanical properties, particularly in terms of hardness (Laskowska 2017). Generally, wood with a density below 500 kg/m³ is considered as a low-density species, which can be treated to obtain
higher density. The highest reported density by means of densification is 1500 kg/m³, which is generally not needed for current applications of wood (Laskowska 2017). Therefore, three fold improvement of density can be achieved in an ideal densification process. Mostly, surface densification can densify a thin region of the wood surface by much more than 50% through the compression of cell lumens (Navi and Sandberg 2012).

2.9 Important Parameters in THM

THM involves control of several factors, including species, pressure, reduction percentage, moisture content, densification time and temperature. Interactions among these factors play an important role in producing a suitable treated wood. At first, the wood species is selected mostly based on achieving higher density material from a low-density species, preferably looking to position a domestic species for a new market. However, wood densification can also be used for high-density wood to gain even higher levels of hardness (Laskowska 2017).

The percentage of reduction in thickness and pressure are selected before densification. As mentioned in Section 2.8, the reduction percentage determines the type of densification. Pressure parameter is amount of the pressure that a press imposes on untreated samples to achieve target densification. Pressure ranges reported for various densification methods vary from less than 5 Mpa to more than 150 Mpa, which are related to the purposes of densification and more importantly, capacity of the press (Ulker and Hiziroglu 2017, Yu et al. 2017). However, using a lower pressure during densification leads to better control of mass loss, and compression rate (Xu and Tang 2012, Bao et al. 2016).

The initial moisture content before densification is an important parameter on softening progress (Ulker and Hiziroglu 2017, Yu et al. 2017). As a low value, Tu et al. (2014) used 3-5% moisture content to densify White poplar (Populus tomentosa P. sect. Leuce Duby). In addition, Kadivar et al. (2019) reported that $M$ less than 10% resulted in micro cracks, and when $M$ exceeded 20%, uneven thickness throughout the length and width was observed due to steam expanding the wood structure. However, Navi and Girardet (2000) reported that the moisture content of wood should be limited to 13% to eliminate risk of steam-induced explosion. In addition, several papers mentioned that the best moisture content for surface densification is around 12%. This low
moisture content eliminates the danger of explosion, and provide enough moisture for densification of surface layers (Pizzi et al. 2005, Rautkari et al. 2010b).

In terms of using water spray before densification, higher moisture content brings about lower glass transition point ($T_g$) for both lignin and hemicellulose and leads to better softening of wood layers (Lenth and Kamke 2001, Xu and Tang 2012). However, as mentioned above, higher moisture content increases risk of explosion. Hence, for a short time densification process, water spray on surface helps the softening process and also lowers the possible risk of densification with a high moisture content such as steaming methods (Lenth and Kamke 2001, Xu and Tang 2012). For instance, Xu and Tang (2012) used a hand-sprayer to add 10-gm of water to a surface area of 300 mm by 50 mm. They stated that water spray is able to fix the surface layers, and decreases the loss of wood volume. Sadatnezhad et al. (2017) showed that using 50 g/m² water spray on both surfaces of poplar (Populus deltoides Bartr. ex.) wood with dimensions of 100 mm width x 300 mm length was as an effective pre-treatment before densification.

Densification time starts from the moment that pressure is imposed on the surface of samples, and ends when the target thickness is achieved. Based on amount of desired softening and capacity of the press, densification time could vary from one minute to more than one hour (Navi and Sandberg 2012). $T$ is the most important parameter affecting the softening of wood, and prepares it to pass from a glassy to a rubbery structure. Softening the wood helps to decrease the $T_g$, and gets the rubbery state of wood at a lower temperature. By considering the $T_g$ effect in wood densification, the temperature of THM varies from 85°C to around 200°C (Sandberg et al. 2013, Fang et al. 2019).

### 2.10 Effects of THM on Wood Properties

According to the literature, density, hardness, color, spring-back, and strength/stiffness ($MOR/MOE$) are the most important properties during THM (Bao et al. 2016, Kariz et al. 2017, Cruz et al. 2018). In this study, I chose density, hardness, color, spring-back and abrasion resistance as my variables of interest.
2.10.1 Density

Most mechanical properties are related to the density of wood (Kamke 2006, Senol and Budakci 2019, Mania et al. 2020). More dense layers lead to enhanced mechanical properties (Chen et al. 2020). Moreover, wood species employed in flooring industries are limited by density value (Fang 2012b). The density profile indicates density variation across the thickness of wood. This profile is formed during the densification process and strongly depends on the softening stage during compression time. In addition, density can be controlled by processing parameters, such as closing time and temperature (Laine 2014).

Madhoushi et al. (2010) increased density of eastern cottonwood (Populus deltoids W.Bartram. ex Marshall) from 370 kg/m$^3$ to 740 kg/m$^3$, by using three different temperatures (120, 140 and 160°C), and 10 minute densification time. Belt et al. (2013) used a temperature range from 100°C to 200°C for surface densification of Scots pine (Pinus sylvestris L.), and by increasing the temperature, the density of wood gradually increased. A study by Laskowska (2017) showed that increasing the temperature from 100°C to 200°C caused a gradual increase in density of birch (Betula pendula Roth). In another study, needle fir (Abies nephrolepis L.) was densified at 160°C and 180°C, and the density increased from 350 kg/m$^3$ to 800 kg/m$^3$ (Zhan and Avramidis 2017). Ulker and Hiziroglu (2017) worked on THM of Eastern red cedar (Juniperus virginiana L.) at four different temperatures (100°C, 120°C, 150°C, 180°C). They reported that by increasing the temperature during THM, the density increased up to 930 kg/m$^3$ at 180°C, which was about two times greater than the density of untreated wood (460 kg/m$^3$).

Higher temperatures during THM result in higher density. However, based on different species, increasing the temperature beyond a certain zone results in engaging more layers (shift from surface to core) instead of having a surface densification. Thus, temperature should be selected wisely based on desired outcomes for process (Zhou et al. 2019).

Rautkari et al. (2011) and Wu et al. (2019) reported that temperature, time, and their interaction are main parameters affecting the density profile of densified wood. Laine (2014) mentioned that during surface densification, the deformation takes place in the earlywood cells close to the heated plate and there is no significant damage to the cell wall during densification. In fact, the density of
wood can increase in two ways: filling the void sections or compression. However, the combination of filling and compression methods should be taken into account.

2.10.2 Hardness

Hardness is one of the most important mechanical properties of wood (Bekhta et al. 2014). National Wood Flooring Association (NWFA) ranks and categorizes flooring species based on value of Janka test (Fang 2012b). According to peer studies, THM is able to improve hardness, and researchers have addressed different densification parameters to find the maximum hardness increase. Rautkari et al. (2013) reported that surface densification increased the Brinell hardness of Scots pine by more than 90%. Gasparik et al. (2016) compared hardness of two different species after densification and reported that the hardness for densified European beech (Fagus sylvatica L.) was three times greater than that of European aspen (Populus tremula L.). By using 50% compression rate, Laine et al (2016) increased the hardness of Scots pine about two times that of control samples. Laskowska (2017) examined the effects of temperature and time of treatment on density profile, and hardness of surface-densified birch wood (Betula pendula Roth). According to their results, as temperature increased, the maximum density of wood gradually increased, and hardness of the surface-densified birch became 1.4 to 2.2 times greater than the hardness of non-densified wood. In a study by Zhou et al. (2019), while the hardness of untreated Poplar (Populus tomentosa Carr.) was 1.89 kN, the value of densified samples increased to 3 and 3.5 kN at 100°C, and 180°C, respectively. They claimed that densified poplar could be an appropriate substitute for more expensive species such as red oak, which is used by the flooring industry. Chen et al. (2020) investigated THM of poplar wood at 150°C, and improved hardness from 1.76 kN to 4.32 kN.

Temperature is reported as an important factor to increase hardness. However, the correlation is not always positive. In a study on aspen species (Lamason and Gong 2007), hardness saw a slight decrease when temperature of hot press increased from 145 to 175°C, and again an increase from 175 to 205°C. However, based on statistical analysis, temperature had no significant effect on hardness. In addition, there was no significant effect on hardness when press closing time changed from 4 to 7 minutes. In some studies, (Fang et al. 2012b, Li et al. 2013, Fu et al. 2016) hardness decreased when temperature increased to a high temperature close to 200°C. Ulker and Hiziroglu (2017) reported that by increasing temperature up to 150°C, hardness increased. However, by
increasing temperature to 180°C, hardness decreased. Degradation of lignin and hemicellulose was mentioned as a major reason for negative correlation between temperature and hardness. In fact, the release of acetic acid during the degradation of hemicellulose results in degradative changes in amorphous regions of cellulose microfibrils (Fang et al. 2012b, Fu et al. 2016).

Budakci et al. (2016) investigated the effect of THM and post-treatment on hardness of three different species. They used different temperatures and compression rates. The hardness of Uludag fir (Abies bornmulleriana Mattf.), linden (Tilia grandifolia Ehrh.), and black poplar (Populus nigra L.) species improved up to 121%, 110%, and 147%, respectively. However, the post treatment reduced the hardness. In terms of wood anatomy, they found that using the lower temperature with higher compression rate leads to more deformation of cell wall.

### 2.10.3 Spring-back

Alongside all advantages of thermo-hydro-mechanical densification methods, researchers always mention spring-back as a concern, and work to reduce it. Although post-treatment methods mostly can decrease spring-back, these methods decrease mechanical properties, such as hardness and abrasion, as well. The reason for this adverse effect is a tendency of a surface to become more brittle after a post-treatment (Gong et al. 2010). For instance, sharp recovering was reported in the first 24 hours after densification. However, by increasing both temperature and densification time, the amount of spring-back decreased (Xu and Tang 2012).

Laine et al. (2016) densified Scots pine with three different compression rates at 200°C, and used a steam injection system. They found that a lower compression rate led to lower spring-back. Fu et al. (2016) used three different temperatures (180, 200, and 220°C), and short densification times (450, 900, and 1350 seconds) for densification of sugar maple (Acer saccharum Marsh.). Spring-back decreased as temperature increased, and the effect of temperature was more important than densification time. However, increasing the temperature beyond 200°C led to significant decrease in density and hardness of treated sugar maple due to increased mass loss. Kariz et al. (2017) studied the influence of temperature on surface densification of spruce (Picea abies L. Karst.). Firstly, they thermally pre-treated samples at 170, 190, 210, and 230°C with an initial vacuum method, which was developed in their laboratory. Then, the treated samples were heated to 150°C with the aim of surface densification. Spring-back decreased with temperature of thermal
treatment, and untreated samples had the highest spring-back. Lykidis et al. (2019) reported that a post-treatment at high temperature and under high humidity is able to decrease the adverse effects of spring-back.

2.10.4 Color

Color change could be a criterion to indicate changes during a thermal densification process, because the wood degradation is related to color change. Therefore, color change has been used as an indicator of degradation during thermal modification processes (Guller 2012, Mitani and Barboutis 2014). In addition, color aspect is important from an aesthetic point of view, and a darker wood is more desirable for some materials (Mitani and Barboutis 2014, Candelier et al. 2016).

Some researchers found that color change could be used as a predictor of mechanical properties. However, there are controversial results in this regard, and prediction is only valid based on similar parameters and conditions (Bekhta and Niemz 2003, Todorovic et al. 2012, Cristescu et al. 2015). For instance, Johansson and Moren (2006) reported that since the color change is not homogeneous across the surface of a treated wood, color cannot be used for quality control.

Based on literature, samples darkened after THM. The main reason for color change is degradation of the hemicelluloses causing a relative increase in lignin content, and having more phenolic substance (Huang et al. 2012, Bekhta et al. 2014, Cruz et al. 2018).

CIE L*a*b* is the most common system to describe color changes during the THM. Lightness (L*) varies from black (0%) to white (100%), and chromatic coordinates a* range is from green (-a) to red (+a), and for b* this value is from blue (-b) to yellow (+b) (Johansson 2008). In a study (Fang et al. 2012) on densification of Sugar maple, at 200°C, lightness (L*) reduced significantly, (a*) increased significantly, and (b*) increased slightly. Bekhta et al. (2014) examined the effect of pressure and temperature on color change. They found that the effect of temperature was more important than pressure factor. In addition, the color change mainly took place after pressure and temperature were increased to 8 MPa and 150°C, respectively. Cruz et al. (2018) did not observe significant changes in the lightness (L*) at lower temperatures between 100°C and 150°C. Laskowska (2018) reported that the color change of heartwood was two times that of sapwood in THM of Scot pine. In addition, the color change at 200°C was two times more than the change at
100°C. Shi et al. (2020) densified the fir (Abies spp.) at 160°C. They saw decreases in brightness (L*), and (b*). However, a slight increase took place for (a*).

2.10.5 Abrasion

The abrasion resistance of wood is an important factor in many applications such as wooden floors, decks, and staves (Aytin et al. 2015). It is difficult to measure the abrasion resistance of wood that is related to in-service use of it. There have been few studies on the abrasion of modified wood. However, by relying on other properties of wood such as weight loss, surface roughness, volume changes, and amount of energy consumption, the abrasion behavior can be predicted (Brischke et al. 2004, Aytin et al. 2015).

Wearing resistance is highly dependent on the density of wood. There is no significant difference in abrasion resistance of treated and untreated wood when the density is unchanged (Gong et al. 2010).

Although abrasion is one of the most important parameters for the flooring industry, there are few studies that measured the abrasion rate of THM wood. The weight loss during wear test is considered as one of the effective parameter to show the level of abrasion. For instance, Coelho et al. (2017) showed that thermomechanical treatment is able to improve abrasion resistance of Pinus wood. They used wood samples with 12% moisture content modified at two different temperatures (160°C and 190°C). Wood modified at the highest temperature (190°C) had the lowest value, which was 0.6 of abrasion rate for untreated samples.

2.11 Anatomical and Chemical Characteristics of THM Wood

Although most TM methods, such as wood densification involve physical processes, basic components of wood are affected during the THM depends on densification conditions. Cellulose, hemicelluloses, and lignin structures change during a thermal densification (Boonstra 2016, Pelit and Yorulmaz 2019).

The macroscopic structure of surface densified wood is similar to the structure of popular composites, which are used widely in different industries. However, unlike the structure of wood panel composites such as oriented strand board (OSB) that require the use of materials like glue
or resin for joining different layers, in surface densification, there is a natural fiber joint that keeps the original structural features of wood (Bekhta et al. 2018, Wang et al. 2018 Chen et al. 2020).

Rautkari et al. (2010) studied the chemical behavior of surface densified Norway spruce (Picea abies L.), and found that there was no significant chemical changes caused by surface densification. Xu and Tang (2012) mentioned that there is no significant chemical change during short-time densification. However, heating of lignin and hemicellulose may help the softening stage of densification. During thermal treatment, softened lignin and hemicellulose are associated with plasticizing and re-shaping the wood. However, these two wood components turn to their rigid structure after cooling down, and help to fixation of process. Laine et al. (2014) investigated the effects of temperature and press closing speed on the micromorphology of cell walls in densified wood. They reported that by increasing both temperature and closing time target deformation can be achieved. Based on their results, the effect of temperature on deformation was more important than closing time. (Laine 2014) showed that at the lower temperature (below 75°C) the level of moisture content is the most significant parameter in wood softening, which affects hydrogen bonding of cellulose and hemicellulose, while at higher temperatures (above 75°C), the heat plays a key role in softening and flowing of lignin. From a wood anatomy perspective, Bekhta et al. (2016) examined alder wood on short densification time (4 min) at three different temperatures: 100, 150, and 200°C. Scanning electron microscope (SEM) showed that by increasing the temperature, the reducing of cell lumen volume and deformation of cell were more evident. Cruz et al. (2018) studied the relationship between chemical components and the physical and mechanical properties of densified radiata pine (Pinus radiate D. Don). They found that lower initial lignin content led to a greater rate of increase in hardness. Chen et al. (2020) mentioned that reduction in cell lumen volume as the major anatomical change in wood subjected to densification. Degradation of hemicelluloses and cellulose occurs during the wood modification, and this leads to an increase the apparent lignin content of wood (Klarhofer et al. 2010, Televise et al. 2020).

2.12 Summary

In recent years, densification has been considered to modify the wood in several studies. However, there is still a lack of knowledge to evaluate densified properties of many species. For instance, there is no densification on western hemlock as a locally abundant species in British Columbia.
In commercial flooring, Canadian wood species compete with much denser tropical species as the market wants wood flooring, which is hard wearing. Therefore, developing a cost effective process based on wood modification is necessary for Canadian wood species. Wood densification should be able to increase the density and hardness of wood as an environmentally friendly process.

It is predicted that each 1% gain in flooring sector market share represents potential sales of $200 million in Canada (Bouffard 2017). As a result, addressing THM in this study can lead to a new market by replacing tropical hardwoods with an abundant local species such as western hemlock.
Chapter 3: Materials and Methods

3.1 Preliminary Study

The objective of the preliminary study was to select the most appropriate parameters for densification, by considering the variables of interest. As a result of this section, among all aforementioned in Chapter 2, three parameters, namely, pre-treatment, densification time, and temperature, were selected based on their importance as reported in literature and preliminary experiment. The conditions of used material for preliminary experiment were the same as those for the main experiment, which are fully described in Section 3.2.

The preliminary study was effective in finding some important information before running the main experiments. For instance, as a pre-test attempt, two different annual ring orientations (ARO) that includes horizontal (flatsawn - Fₖ), and vertical (quartersawn - Qₖ) were densified, and results showed that only the flatsawn samples were appropriate for densification since the quartersawn samples split in half and were not suitable for flooring applications (Figure 3.1).

In addition, the number of level for each factor was determined based on results of several pre-tests. For instance, the pre-test densification showed that carbonization of wood took place when
densification time and temperature were longer than 15 minutes, and higher than 200°C, respectively. Finally, the most important features of the treated wood, which were altered by the THM method, were selected as density; hardness; spring-back; color; and abrasion resistance.

3.2 Main Experiments

Freshly cut second-growth Western hemlock (3000 × 100 × 55 mm and 120% M) were obtained from Interfor Acorn Sawmill, and shipped to UBC in mid-January 2019. Timbers were kiln-dried in a laboratory dry kiln to a target moisture of 12%. A mixed drying method (time and moisture-based drying) was used, without seasoning, equalization, and conditioning.

After kiln-drying, thirty defect-free (12 ± 5% moisture) Fₜ, hemlock timbers with dimensions of 1200 × 100 × 55 mm were selected. One hundred and fourteen samples (114) with dimensions of 260 × 100 × 55 mm, and the average density of 445 kg/m³ were cut, and placed in a walk-in conditioning room at 65 ± 5% relative humidity and 20 ± 1°C temperature in order to reach an equilibrium moisture content of about 12 ± 2%. One hundred and eight (108) randomly selected samples were used in the densification experiments and the six left for control samples.

The initial thickness of samples before densification was 55 mm (Figure 3.2.a), and the target reduction in thickness was 30% to achieve the final thickness of 38.5 mm. When densification was completed, samples were removed from the press and returned to the walk-in conditioning room, for 10 days.

There were six (6) replications for each treatment. Therefore, the total number of densified wood was: (2 pre-treatments) x (3 temps) x (3 closing times) x (6 replications) = 108 samples.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Species</th>
<th>Pre-treatment</th>
<th>Temperature (°C)</th>
<th>Closing time (minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Western hemlock</td>
<td>None (N)</td>
<td>120</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water spray (WS)</td>
<td>160</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>15</td>
</tr>
</tbody>
</table>
After THM, according to Figure (3.2.b), all densified specimens were cut into two different sizes to measure variables of interest: part A was used for hardness, spring-back; and Part B was used to evaluate density, color, and abrasion resistance.

![Diagram of dimensions before and after THM](image)

Figure 3.2. (a): Dimensions before THM, (b): Cutting protocol after THM.

Three indicators were used for the eighteen (18) treatments and each indicator is separated by a dash (-) sign. These three parts are represented the three factors, namely, pre-treatment, time, and temperature. For instance, WS-5-120 refers to a sample pre-treated with water spray that was densified for 5 minutes at 120°C (Table 3.2).

Table 3.2. Labeling all 18 possible treatments.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Non water spray pre-treatment (N)</th>
<th>Water spray pre-treatment (WS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Densification time (minute)</td>
<td>Densification time (minute)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>120</td>
<td>N-5-120</td>
<td>N-10-120</td>
</tr>
</tbody>
</table>
In terms of pre-treatment, based on recent studies (Xu and Tang 2012, Pelit et al. 2015, Sadatnezhad et al. 2017), 50 gr/m² of distilled water was sprayed on both surfaces of 54 samples (half) just prior to hot pressing; the other half did not receive water spray.

The densification took place in a customized Pathex® hot press (Figure 3.3). There was a remote control program (PressMan), which was linked to the press hardware that made it possible to set the final desired thickness, total time of process (closing time), and temperature.

For each treatment, once the temperature of the platen reached a desired value (120, 160, and 200°C), the samples were placed on the lower platen which moved up so that the top surface of the sample touched the upper flat surface of the press without any pressure. Then, the pressure was applied in the radial direction. All 108 samples were allocated to three different times (closing time) of 5, 10, and 15 minutes (Table 3.1).

Figure 3.3. Customized Pathex® hot press.
3.3 Assessment of THM Treated Properties

3.3.1 Density

In accord with ASTM D2395-17 Standard, the density of THM treated and non-treated samples was measured. Each sample was cut lengthwise into five sections in such a way that two 6 mm thick sections were cut from each surface, and the leftover was the fifth core section.

The density of each section was measured using a digital balance (precision ±0.001 g) for weight, and their dimensions were measured by a caliper with ±0.01 mm accuracy (Okeke et al. 2011). The density of each portion was calculated based on the equation at 12% moisture content:

\[
\rho_m = \frac{w_m}{V_m}
\]

where \(\rho_m\) is density (kg/m\(^3\)), \(w_m\) is the weight (kg), and \(V_m\) is the volume (m\(^3\)) of sample.

3.3.2 Hardness

The Janka method was used to measure hardness according to ASTM and using a Universal testing machine (ASTM Intl. 2012, ASTM Intl. 2014). The machine was the Instron\textsuperscript{®} model 4204 that was a computer controlled electro-mechanical system. The load frame set on a compression type to run hardness test. The system was controlled from its control board, and a computer, which automatically controlled the process. The testing machine (Figure 3.4) was employed a modified Janka-ball test method with a ball 11.3 mm in diameter. The load was recorded when the ball penetrated to one-half of its diameter with a penetration rate of 6 mm/min.

Two penetrations were considered on each of the two densified surfaces of the wood. The locations of the penetration points were more than 25 mm from the edges, and ends of the samples, and located away from testing points on the surface. A computer software recorded hardness (kN) load. An average of four tests was considered for hardness of each control and treated sample.
3.3.3 Spring-back

The spring-back for all THM samples was measured 1, 24, 200, 240 hours after densification. All samples were kept in the same conditioning room at a relative humidity of 65 ± 5% and a temperature of 20 ± 1°C prior to spring-back was measurement. Five different points on each treated sample were marked to follow changes in thickness, and the average of all points was used to calculate of spring-back (SB) based on equation (2) (Pelit et al. 2016).

\[
SB = \frac{\lambda(t) - \lambda}{\lambda}
\]  

(2)

where SB is spring-back (%), \(\lambda\) is thickness after densification (mm), \(\lambda(t)\) is thickness (mm) after densification and passing the time of t (hours)

3.3.4 Color

Color measurements were recorded for performed on both THM and control samples with a colorimeter Minolta Chroma-Meter (Figure 3.5.a). Percentage of reflectance was converted into the CIELAB color system (Figure 3.5.b), where (L*) illustrates the lightness, (a*) and (b*) show the chromatic coordinates on the green-red and blue-yellow axis, respectively (Bekhta and Niemz, 2003). The lightness (L*) ranges is from black (0%) to white (100%), and chromatic coordinates (a*) ranges from green (-a) to red (a), and (b*) ranges from blue (-b) to yellow (b). The similarity
between the CIELAB system and human vision makes it suitable for camera or scanner imaging editing (Johansson 2008, Nourian 2018).

The color parameters were measured at three different points (in the middle, and 25 mm from both ends) on both surfaces for each sample. A Minolta spectrophotometer (Model #CM-2600d) with a 6 mm sensor head and using a D65 illuminant and a 10-degree Standard observer was employed to measure all color parameters based on the ASTM D2244-16 (ASTM Intl. 2016). Two parameters, namely, SCI (specular component included) and SCE (specular component excluded) were achievable (Konica Minolta 2007). For this study, the SCI option was used based on the fact that SCI measures the true color of an object without considering the surface conditions, and also peer studies regarding wood heat treatment have used this parameter rather SCE (Johansson 2008, Nourian 2018).

By measuring the L*, a*, b* parameters, the difference in the lightness (ΔL*), chroma coordinates (Δa* and Δb*), and finally the total color difference (ΔE) were calculated using the following formulae (Bekhta and Niemz, 2003).

\[
\Delta L^* = L^*_{t} - L^*_{c} \\
\Delta a^* = a^*_{t} - a^*_{c} \\
\Delta b^* = b^*_{t} - b^*_{c} \\
\Delta E^* = \left[ (\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2 \right]^{1/2}
\]

where \(L^*_{t}, a^*_{t}, b^*_{t}\) belong to densified specimens; \(L^*_{c}, a^*_{c}, b^*_{c}\) belongs to the control specimens.
3.3.5 Abrasion

The ASTM D4060-95 standard was followed for abrasion tests (ASTM Intl. 2019). The tests were conducted on a Taber® Rotary Abraser, model 5150 (Figure 3.6), which included the grinding (abrasive) wheels, model CS-0 (Taber Industries, 2019) (Figure 3.7.a), placed over the sample surface. The rubber wheels were weighed with a 500 gr load, and each covered with a S-42 sandpaper strip (Emmler et al. 2004) (Figure 3.7.b).
To prevent the excessive accumulation of abrasion waste, the grinding wheels were cleaned and the sandpaper strips were replaced after 300, 600, 1000, and 1500 cycles (DFT Tech, 2016). Flat specimen approximately 100 mm square were placed on a turntable that rotates on a vertical axis at a fixed speed. The amount of material lost provides the abrasion value; a lower rate is desirable which shows that the material has a higher resistance abrasion. Sample dimensions were 100 by 100 by 6 mm\(^3\), in length, width, and thickness respectively, and the weight losses after 300, 600, 1000, and 1500 cycles were recorded.

In terms of evaluation of abrasion resistance, mass loss \((L)\) was used to measure how much material was removed by the abrasion wheels, and is reported in milligrams (mg). The abrasion rate \((AR)\) for each cycle was calculated based on the weight loss value (equation 8):

\[
L = A - B
\]

\[
AR = \frac{L}{A}
\]

where \(L\) is weight loss (mg), \(A\) is weight (mass) of specimen before abrasion (mg), \(B\) is weight (mass) of specimen after abrasion (mg), and \(AR\) is the abrasion rate value (\%).

The Taber Wear Index \((I)\) is another method for abrasion evaluation, which indicates rate of wear, and is calculated by measuring the loss in weight (in milligrams) per thousand cycles of abrasion. The lower the wear index, the better the abrasion resistance.

\[
I = \frac{[(A - B) \times 1000]}{C}
\]
where $I$ is wear index (mg), and $C$ is number of test cycles.

### 3.3.6 Statistical Analysis

R and Genstat software were used to carry out the statistical analysis. Firstly, data were analyzed by means of R software. The analysis was based on a factorial design by considering a completely randomized design (CRD) model with three factors, which were pre-treatment, time, and temperature as below:

$$y_{ijkl} = \mu + \tau_{Aj} + \tau_{Bk} + \tau_{Cil} + \tau_{ABjk} + \tau_{BCkl} + \tau_{ABCjkl} + \varepsilon_{ijkl} \quad (10)$$

where $y_{ijkl}$ is a function of the response variables (hardness, density, spring-back, color, and abrasion) measured on experimental unit $i$ and factors $A$ (Pre-treatment) level $j$, factor $B$ (time) level $k$, and factor $C$ (temperature) level $l$. $j=1$ to $J$ levels for factor $A(j=1,2)$; $k=1$ to $K$ levels for factor $B (k=1,2,3)$; $l=1$ to $l$ levels for factor $C (l=1,2,3)$ $\mu = \text{the grand or overall mean regardless of treatment}$, $\tau_{Aj} = \text{the treatment effect for factor A (Pre-treatment), level } j$, $\tau_{Bk} = \text{the treatment effect for factor B (Time), level } k$, $\tau_{ABjk} = \text{the interaction for factor A (Species), level } j \text{ and factor B (water level), level } k$, $\varepsilon_{ijk} = \text{the difference between a particular measure for an experimental unit } i$, and the mean for a treatment: $\varepsilon_{ijk} = y_{ijk} - (\mu + \tau_{Aj} + \tau_{Bk} + \tau_{ABij})$.

To consider the control samples with treated samples simultaneously, Genstat (Nineteenth Edition) was used to analyze data. The method is based on a three factorial ANOVA with a control and Convstrt (control versus treatment) code, as an extra factor, separating the control from treated factors. In addition, the Fishers Least Significant Difference (LSD) at 5% probability level was used to estimate whether differences between individual means were statistically significant (Stern et al. 2001, Lotter 2014, Zhu 2018).
Chapter 4: Results and Discussion

4.1 Overview

As mentioned in section 3.3.6, the Genstat was used to analyze of results, by considering interactions among all three factors (pre-treatment, time, and temperature) in both treated and controls samples. In the following sections, the results of analyze are presented. It should be noted that only significant results are plotted.

4.2 Density Profile

The Figure 4.1 Illustrates the density profiles for treated and untreated samples based on distance from surface. The density of all treated western hemlock samples were significantly higher than density of control samples.

Figure 4.1. Density profiles for treated and untreated samples based on distance from surface.
Table 4.1 shows that while the mean value of density for control samples was approximately same in different layers, for treated wood, the surface layers were denser than the core. Especially the densest zones were located in the first few layers, which were 6 mm of both surfaces. Therefore, surface densification target regarding the density, which was gaining denser layers near the surface rather than the core layers, was achieved. The average density of control samples was smaller than those of all treated samples. The maximum density means (more than 800 kg/m$^3$) were found in samples that were treated for 10 and 15 minutes at 160°C. The densification process increased the density of control samples 1.5 to 2 times approximately. Particularly for surface layers of some treated wood, the density was increased about 2.5 times compared to control samples.

Table 4.1. Density profile data for control and densified samples.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>First 6mm</th>
<th>Second 6mm</th>
<th>Core</th>
<th>Second 6mm</th>
<th>First 6mm</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>445.7</td>
<td>441.3</td>
<td>461.4</td>
<td>457.4</td>
<td>441.0</td>
<td>449.3</td>
</tr>
<tr>
<td>N_5_120</td>
<td>715.7</td>
<td>652.4</td>
<td>650.7</td>
<td>649.6</td>
<td>705.6</td>
<td>674.8</td>
</tr>
<tr>
<td>N_5_160</td>
<td>760.1</td>
<td>683.0</td>
<td>612.1</td>
<td>616.6</td>
<td>714.4</td>
<td>677.2</td>
</tr>
<tr>
<td>N_5_200</td>
<td>735.7</td>
<td>652.4</td>
<td>649.7</td>
<td>667.0</td>
<td>705.4</td>
<td>682.0</td>
</tr>
<tr>
<td>N_10_120</td>
<td>745.6</td>
<td>672.5</td>
<td>658.4</td>
<td>664.8</td>
<td>705.4</td>
<td>689.3</td>
</tr>
<tr>
<td>N_10_160</td>
<td>780.2</td>
<td>775.9</td>
<td>705.6</td>
<td>698.5</td>
<td>735.7</td>
<td>739.2</td>
</tr>
<tr>
<td>N_10_200</td>
<td>778.0</td>
<td>704.9</td>
<td>658.0</td>
<td>674.5</td>
<td>746.0</td>
<td>712.3</td>
</tr>
<tr>
<td>N_15_120</td>
<td>733.6</td>
<td>667.9</td>
<td>614.7</td>
<td>660.2</td>
<td>717.2</td>
<td>678.7</td>
</tr>
<tr>
<td>N_15_160</td>
<td>805.4</td>
<td>749.4</td>
<td>618.0</td>
<td>714.1</td>
<td>786.5</td>
<td>734.6</td>
</tr>
<tr>
<td>N_15_200</td>
<td>979.3</td>
<td>717.0</td>
<td>586.8</td>
<td>764.0</td>
<td>983.8</td>
<td>806.2</td>
</tr>
<tr>
<td>WS_5_120</td>
<td>986.0</td>
<td>802.7</td>
<td>576.0</td>
<td>906.9</td>
<td>991.4</td>
<td>852.6</td>
</tr>
<tr>
<td>WS_5_160</td>
<td>1010.9</td>
<td>909.6</td>
<td>503.0</td>
<td>869.4</td>
<td>996.9</td>
<td>858.0</td>
</tr>
<tr>
<td>WS_5_200</td>
<td>1106.4</td>
<td>905.4</td>
<td>506.0</td>
<td>889.4</td>
<td>1034.7</td>
<td>888.4</td>
</tr>
<tr>
<td>WS_10_120</td>
<td>799.3</td>
<td>657.0</td>
<td>589.0</td>
<td>636.8</td>
<td>765.4</td>
<td>689.5</td>
</tr>
<tr>
<td>WS_10_160</td>
<td>832.2</td>
<td>668.0</td>
<td>566.2</td>
<td>631.1</td>
<td>857.7</td>
<td>711.0</td>
</tr>
<tr>
<td>WS_10_200</td>
<td>998.3</td>
<td>715.5</td>
<td>564.0</td>
<td>722.5</td>
<td>913.8</td>
<td>782.8</td>
</tr>
<tr>
<td>WS_15_120</td>
<td>966.8</td>
<td>697.4</td>
<td>531.1</td>
<td>708.7</td>
<td>957.9</td>
<td>772.4</td>
</tr>
<tr>
<td>WS_15_160</td>
<td>922.6</td>
<td>605.9</td>
<td>551.4</td>
<td>718.8</td>
<td>886.0</td>
<td>736.9</td>
</tr>
<tr>
<td>WS_15_200</td>
<td>966.4</td>
<td>673.3</td>
<td>507.2</td>
<td>706.4</td>
<td>919.4</td>
<td>754.5</td>
</tr>
</tbody>
</table>

44
Figures 4.2, 4.3, and 4.4 show the density of samples pressed at 120, 160, and 200°C, respectively. For all three figures, the corresponding lines for control samples are approximately parallel to the horizontal line, which shows that there was little variation density of layers. There is an upward trend from core to surface for all treated wood samples, which shows denser layers were in surface area. At 160, and 200°C, the trends are more U-shaped compared to 120°C, which U-shaped profile is representative of surface densification.

![Figure 4.2. Density profiles for treated samples pressed 120°C.](image)
Figure 4.3. Density profiles for treated samples under 160°C.

Figure 4.4. Density profiles for treated samples pressed 200°C.
Statistical tests were carried out to examine the effect of treatment parameters on density. As shown in Table 4.2, for first surface layer (6 mm), all three factors (pre-treatment, time, and temperature) had significant effects on density. However, densification time and temperature were the most significant factors. In addition, there was a significant interaction between time and temperature as shown in Figure 4.6.

Table 4.2. The result of statistical test (ANOVA) for density.

<table>
<thead>
<tr>
<th>Response variable</th>
<th>Experimental factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-treatment (PT)</td>
</tr>
<tr>
<td>Density</td>
<td>*</td>
</tr>
</tbody>
</table>

* = p < 0.05; ** = p < 0.01; *** = p < 0.001; NS = not significant (p > 0.05).

As shown in Figure 4.5, regardless of pre-treatment, densification increased density. The difference between control mean (443.3 kg/m³) and both treated values, (838.1 and 870 kg/m³) is greater than the LSD (1), which is 59.1. Moreover, LSD (2) indicates that there was a significant change on density when the water spray was used.

Figure 4.5. Density means of untreated (control), none water sprayed (N) and water sprayed pre-treatment (W). Differences larger than the least significant difference (LSD) are statistically significant at a 5% level.
All densified samples were significantly \((p < 0.05)\) different from control controls (Figure 4.6). Treated samples with a mean difference in density greater than LSD (2) \((56 \, \text{kg/m}^3)\) were significantly different from each other. For instance, densification time had no \((p < 0.05)\) significant effect on density at 120°C. However, longer densification time increased density at 160 and 180°C. The significant interaction \((\text{time} \times \text{temperature})\) occurred at 200°C because increasing the densification time to 10 minutes increased density from 813 to 923 kg/m³, then; there was no significant change at the longer densification time (15 minutes).

![Figure 4.6. Interaction between time and temperature on density. Differences larger than the least significant difference (LSD) are statistically significant at a 5% level.](image)

In accord with the literature, the density of treated hemlock in this study was subject to an interaction between densification time and temperature (Rautkari et al. 2011, Laine 2014, Wu et al. 2019). It has been reported that as temperature increases, the density increases as well (Madhoushi et al. 2010, Belt et al. 2013, Laskowska 2017). Because wood just can be softened in higher temperatures \((>140°C)\). A higher temperature heats up the wood and removes the moisture faster than a lower one, leading to form harder area in a determined densification time (Zhou et al. 2019).
In this study, density decreased as temperature increased from 160 to 200°C in 10 and 15 minutes densification time (Figure 4.6). As this similar changing trend occurred for hardness, the reason could be a possible degradation in anatomy of wood at higher temperature, which is depends on type (anatomy) of species. This unprecedented behavior is explained in a study (Zhou et al. 2019) that at higher temperatures (>140°C), irregular shrinking or bubbling on the wood surface can occur due to the rapidly rising steam pressure.

Moreover, it is expected that increasing the densification time increase density (Zhou et al. 2019). It occurred in our study as well (Figure 4.6). Longer densification time led to increase in density. Because sufficient time is needed for heat transfer, and thus softening the wood layers. However, at 120°C, there was no significant change in density as densification time increased. As mentioned above, this temperature was too low for softening the wood.

4.3 Hardness

The hardness measurements are presented in Table 4.3. All treated samples had a higher mean compared to controls (2.22 kN). Thermal densification increased the hardness of western hemlock. Regardless of pre-treatment effect, the maximum increase occurred after 15 minutes densification at 160°C.

Table 4.3. The descriptive statistics for hardness test.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Mean (kN)</th>
<th>StDev (kN)</th>
<th>Cov (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>2.22</td>
<td>0.56</td>
<td>25.23</td>
</tr>
<tr>
<td>N_5_120</td>
<td>3.35</td>
<td>0.29</td>
<td>8.66</td>
</tr>
<tr>
<td>N_5_160</td>
<td>5.28</td>
<td>0.67</td>
<td>12.69</td>
</tr>
<tr>
<td>N_5_200</td>
<td>5.50</td>
<td>0.45</td>
<td>8.18</td>
</tr>
<tr>
<td>N_10_120</td>
<td>3.68</td>
<td>0.27</td>
<td>7.34</td>
</tr>
<tr>
<td>N_10_160</td>
<td>7.82</td>
<td>0.62</td>
<td>7.93</td>
</tr>
<tr>
<td>N_10_200</td>
<td>7.38</td>
<td>0.47</td>
<td>6.37</td>
</tr>
<tr>
<td>N_15_120</td>
<td>4.38</td>
<td>0.45</td>
<td>10.27</td>
</tr>
<tr>
<td>N_15_160</td>
<td>8.25</td>
<td>0.52</td>
<td>6.30</td>
</tr>
<tr>
<td>N_15_200</td>
<td>7.42</td>
<td>0.43</td>
<td>5.80</td>
</tr>
<tr>
<td>WS_5_120</td>
<td>3.90</td>
<td>0.33</td>
<td>8.46</td>
</tr>
<tr>
<td>WS_5_160</td>
<td>5.90</td>
<td>0.48</td>
<td>8.14</td>
</tr>
<tr>
<td>WS_5_200</td>
<td>6.05</td>
<td>0.77</td>
<td>12.73</td>
</tr>
<tr>
<td>WS_10_120</td>
<td>4.57</td>
<td>0.52</td>
<td>11.38</td>
</tr>
<tr>
<td>WS_10_160</td>
<td>7.98</td>
<td>0.98</td>
<td>12.28</td>
</tr>
</tbody>
</table>
Based on statistical test (Table 4.4), while all three factors had a significant ($p < 0.05$) effect on hardness, the interaction among three parameters was not significant. There was no significant ($p < 0.05$) interaction between pre-treatment with other factors. However, the interaction between temperature and time was significant ($p < 0.05$).

Table 4.4. The result of statistical test (ANOVA) hardness.

<table>
<thead>
<tr>
<th>Experimental factors</th>
<th>Pre-treatment (PT)</th>
<th>Time (T)</th>
<th>Temperature (TEM)</th>
<th>PT×T</th>
<th>PT×TEM</th>
<th>T×TEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; NS = not significant ($p > 0.05$).

Hardness of all treated samples were significantly ($p < 0.05$) different compared to controls since the difference between both mean values of none-water–sprayed (5.90 kN), and water-sprayed densified wood (6.47 kN) with that of controls (2.22 kN) was greater than LSD (1) (Figure 4.7).

Moreover, the difference between means of both pre-treatments was greater than the value of LSD (2), (6.47-5.90=0.57> 0.28), which shows water spray was an effective pre-treatment to improve hardness of western hemlock. With regard to effect of water spray on hardness, there is no peer research for comparison with our results. However, the reason of positive effect of water spray might be related to density. According to section 4.2, the density mean for water sprayed wood was significantly ($p < 0.05$) higher than none-water-sprayed one. As there is a positive correlation between density and hardness (Bao et al 2016), the reason of effectiveness of water spray could be explained by results of density.
Figure 4.7. Hardness means of untreated (control), none water sprayed (N) and water sprayed pre-treatment (W). Differences larger than the least significant difference (LSD) are statistically significant at a 5% level.

According to Table 4.4, both densification time and temperature were significant factors on hardness since there was a significant ($p < 0.05$) interaction between these two factors. As shown in Figure 4.8, and based on LSD (1), all treated means were significantly different compared to the controls.

At 120°C (Figure 4.8), increasing the densification time to more than 10 minutes led to significant increase on hardness. Regardless of densification time, increasing the temperature from 120 to 160°C, caused to significant improvement on hardness, which is in accordance with the literature (Zhou et al. 2019). At 160°C, longer densification improved the hardness from 5 to 10 minutes. Nonetheless, longer densification (15 minutes) had no significant effect on hardness. From 160 to 200°C, although the downward trend was seen for 10 and 15 minutes densification time, the means were not significantly different based on LSD (2). For 5-minute densification, there was an insignificant increase from 160 to 200°C. However, the hardness in the 5-minute densification at
200°C was significantly different compared to the values for 10- and 15-minute densification at the same temperature.

![Figure 4.8](image)

Figure 4.8. Interactions between time and temperature on hardness. Differences larger than the least significant difference (LSD) are statistically significant at a 5% level.

The results of this section are compatible with several researches on hardness that as temperature increases, hardness increases (Li et al. 2013, Fu et al. 2016, Hiziroglu 2017). Since density of wood correlates with its mechanical properties, denser layers is expected to have greater hardness. Especially, thickness of densified zone plays a key role in the hardness since the penetration of ball is 5.65 mm in Janka test. As the denser layers were at the first 6 mm of each surface, significant increase of hardness on those layers is reasonable.

Although there is no research to show that effect of water spray on hardness of densified wood, based on result of this study, pre-treatment by water spray was able to improve hardness of wood significantly. Furthermore, at each temperature longer densification time led to produce a harder wood. Based on the mentioned results from Figure 4.8 in related section, 10 and 15 minutes
densification led to gain a better results compared to the 5 minutes. The reason could be the lack of time for plasticization stage in 5 minutes densification compared to the longer time.

According to results of Section 4.2, trend of hardness plot (Figure 4.8) is compatible with density one (Figure 4.6). Similar to density plot, exceeding heating after the certain degree of temperature (160°C) reduces hardness as well. Degradations of lignin and hemicellulose would be the main reason of this variation about hardness of densified wood at a higher temperature (Fu et al. 2016, Zhou et al. 2019).

In literature, range of increase on hardness was between 1.5 to 3 times in different densification researches (Zhou et al. 2019, Chen et al. 2020). In this study, while the average hardness of control samples was 2.22 kN, the highest hardness was 7.90 kN (about 3.5 times increase), which was achieved after 10 minutes densification at 160°C.

### 4.4 Spring-back

Spring-back was observed until 240 hours after densification (Table 4.5). The data were recorded in four different periods. As a general trend, the amount of spring-back decreased with time.

The maximum and minimum spring-back were recorded at 1 hour and 240 hours after densification, respectively. After 200 hours, the treated samples reached a stable condition that the variation was less than 1%.

Statistical test was conducted for period of 200-240 hours as the steady stage of spring-back. Table 4.6 shows that pre-treatment and time were the only significant ($p < 0.05$) factors on spring-back, and there was no significant interaction among pre-treatment, time, and temperature.
### Table 4.5. The percentage of spring-back until 240 hours after densification

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Percentage (%) of spring-back based on time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1hr-24hr</td>
</tr>
<tr>
<td>N_5_120</td>
<td>12.39</td>
</tr>
<tr>
<td>N_5_160</td>
<td>11.83</td>
</tr>
<tr>
<td>N_5_200</td>
<td>12.42</td>
</tr>
<tr>
<td>N_10_120</td>
<td>7.76</td>
</tr>
<tr>
<td>N_10_160</td>
<td>6.29</td>
</tr>
<tr>
<td>N_10_200</td>
<td>20.43</td>
</tr>
<tr>
<td>N_15_120</td>
<td>10.38</td>
</tr>
<tr>
<td>N_15_160</td>
<td>7.51</td>
</tr>
<tr>
<td>N_15_200</td>
<td>5.04</td>
</tr>
<tr>
<td>WS_5_120</td>
<td>7.74</td>
</tr>
<tr>
<td>WS_5_160</td>
<td>6.61</td>
</tr>
<tr>
<td>WS_5_200</td>
<td>9.11</td>
</tr>
<tr>
<td>WS_10_120</td>
<td>6.13</td>
</tr>
<tr>
<td>WS_10_160</td>
<td>6.44</td>
</tr>
<tr>
<td>WS_10_200</td>
<td>15.82</td>
</tr>
<tr>
<td>WS_15_120</td>
<td>10.38</td>
</tr>
<tr>
<td>WS_15_160</td>
<td>7.51</td>
</tr>
<tr>
<td>WS_15_200</td>
<td>5.04</td>
</tr>
</tbody>
</table>

### Table 4.6. The result of statistical test (ANOVA) for spring-back (200hr-240 hr).

<table>
<thead>
<tr>
<th>Response variable</th>
<th>Experimental factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-treatment (PT)</td>
</tr>
<tr>
<td>Spring-back</td>
<td>*</td>
</tr>
</tbody>
</table>

* = p < 0.05; ** = p < 0.01; *** = p < 0.001; NS = not significant (p > 0.05)

Since pre-treatment and time were determined as two significant factors, their related mean values are shown in Figure 4.9, and 4.10. The value of LSD in Figure 4.9 shows that time is the most significant factor on spring-back.

While there was no significant difference for spring-back between 10 and 15 minutes of densification (Figure 4.10), both these two periods had significantly different effects on spring-back compared to 5 minutes densification.
Figure 4.9. The spring-back means of treated samples, none water sprayed (N) and water sprayed pre-treatment (W). Differences larger than the least significant difference (LSD) are statistically significant at a 5% level.

Figure 4.10. The spring-back means of treated samples, for three different densification time. Differences larger than the least significant difference (LSD) are statistically significant at a 5% level.
Same as our results, Xu and Tang (2012) reported that a sharp increase for spring-back during the first 24 hours after THM. Finding the stable condition after densification was the main purpose of measuring spring-back, which occurred 200 hours after THM in our study.

Laine et al. (2016) reported that temperature as a more important factor than densification time on spring-back, which is opposite to result of our study. However, in their study, unless of our study, spring-back was not measured in different times.

According to Figure 4.10, longer densification time decreased spring-back since internal stress can be released in sufficient densification time. Therefore, there was a significant different between 5 minutes and longer densification times (10 and 15 minutes).

4.5 Color

Visual inspection showed that by increasing the temperature wood became darker (Figure 4.11), which the darkest treated samples belonged to 200°C.

![Figure 4.11. Visual inspection between control and densified samples.](image)
Minimum color changes occurred for samples were treated at 120°C (Table 4.7). Color change were 2.3, 4.23, and 4.77 for N_5_120, N_10_120, and WS_5_120, respectively. On the other hand, the maximum color changes were 38.28, 30.87, and 26.47 for WS_15_200, WS_10_200, and N_15_200, respectively.

Table 4.7. Color changes in treated and control samples.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
<th>Color change (ΔE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>71.60</td>
<td>7.32</td>
<td>24.20</td>
<td>-</td>
</tr>
<tr>
<td>N_5_120</td>
<td>69.31</td>
<td>7.46</td>
<td>24.30</td>
<td>2.3</td>
</tr>
<tr>
<td>N_5_160</td>
<td>64.58</td>
<td>9.34</td>
<td>23.07</td>
<td>7.39</td>
</tr>
<tr>
<td>N_5_200</td>
<td>60.57</td>
<td>9.34</td>
<td>22.83</td>
<td>11.29</td>
</tr>
<tr>
<td>N_10_120</td>
<td>67.73</td>
<td>8.86</td>
<td>24.91</td>
<td>4.23</td>
</tr>
<tr>
<td>N_10_160</td>
<td>61.04</td>
<td>9.39</td>
<td>23.79</td>
<td>10.76</td>
</tr>
<tr>
<td>N_10_200</td>
<td>49.91</td>
<td>11.64</td>
<td>23.48</td>
<td>22.13</td>
</tr>
<tr>
<td>N_15_120</td>
<td>66.08</td>
<td>8.61</td>
<td>25.11</td>
<td>5.74</td>
</tr>
<tr>
<td>N_15_160</td>
<td>60.66</td>
<td>9.07</td>
<td>23.55</td>
<td>11.09</td>
</tr>
<tr>
<td>N_15_200</td>
<td>45.66</td>
<td>10.20</td>
<td>19.74</td>
<td>26.47</td>
</tr>
<tr>
<td>WS_5_120</td>
<td>66.94</td>
<td>8.33</td>
<td>24.10</td>
<td>4.77</td>
</tr>
<tr>
<td>WS_5_160</td>
<td>61.62</td>
<td>10.12</td>
<td>24.02</td>
<td>10.36</td>
</tr>
<tr>
<td>WS_5_200</td>
<td>53.57</td>
<td>9.20</td>
<td>22.94</td>
<td>18.17</td>
</tr>
<tr>
<td>WS_10_120</td>
<td>59.19</td>
<td>6.51</td>
<td>19.26</td>
<td>13.38</td>
</tr>
<tr>
<td>WS_10_160</td>
<td>59.69</td>
<td>8.34</td>
<td>22.48</td>
<td>12.07</td>
</tr>
<tr>
<td>WS_10_200</td>
<td>41.78</td>
<td>8.29</td>
<td>16.29</td>
<td>30.87</td>
</tr>
<tr>
<td>WS_15_120</td>
<td>59.82</td>
<td>6.25</td>
<td>19.14</td>
<td>12.86</td>
</tr>
<tr>
<td>WS_15_160</td>
<td>52.88</td>
<td>7.57</td>
<td>18.96</td>
<td>19.43</td>
</tr>
<tr>
<td>WS_15_200</td>
<td>35.55</td>
<td>6.67</td>
<td>11.32</td>
<td>38.28</td>
</tr>
</tbody>
</table>

Statistical test (Table 4.8) showed that all three factors had significant ($p < 0.05$) effects on color change. All three possible interactions among factors were significant; especially the interaction between time and temperature ($T\times TEM$) was the most significant one.

Table 4.8. The result of statistical test (ANOVA) for color change (ΔE).

<table>
<thead>
<tr>
<th>Response variable</th>
<th>Experimental factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color change (ΔE)</td>
<td>Pre-treatment (PT)</td>
</tr>
<tr>
<td></td>
<td>***</td>
</tr>
</tbody>
</table>

* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; NS = not significant ($p > 0.05$)
Regarding the interaction between pre-treatment and time (Figure 4.12), color change for water-sprayed samples was significantly greater than that of non-water-sprayed one (LSD=2.77). For both pre-treatments, by increasing the densification time, the color change increased significantly.

![Figure 4.12](image)

**Figure 4.12.** Interaction between pre-treatment (none- water- sprayed) and time on color change (ΔE). Differences larger than the least significant difference (LSD) are statistically significant at a 5% level.

As shown in Figure 4.13, interaction of water-sprayed pre-treatment and temperature resulted in significantly greater color change compared to another pre-treatment interaction. Furthermore, for both pre-treatments, as temperature increased, the color change increased significantly (LSD=2.77).

In terms of interaction between densification time and temperature (Figure 4.14), in each densification time, increasing the temperature led to increasing the color change. However, the change from 160 to 200°C was more important. Regarding the temperature, color change from 5 to 10 minutes of densification time was more evident compared to that of from 10 to 15 minutes (LSD=2.77).

These results are in accordance with the literature where temperature increase, especially above 150°C, color change increases (Huang et al. 2012, Bekhta et al. 2014, Cruz et al. 2018).
Figure 4.13. Interaction between pre-treatment (none- water- sprayed) and temperature on color change (ΔE). Differences larger than the least significant difference (LSD) are statistically significant at a 5% level.

Figure 4.14. Interaction between time and temperature on color change (ΔE). Differences larger than the least significant difference (LSD) are statistically significant at a 5% level.
In terms of lightness (L*), based on Table 4.9, the lightest woods were control samples (71.6), and the darkest ones (35.55) belonged to WS_15_200, which were water sprayed samples under 200°C for 15 minutes. THM was able to increase the darkness of western hemlock up to 50% compared to control samples. The mean value of lightness for water sprayed samples was 54.56 compared to 60.62 for none-water sprayed treated samples. Increasing the densification time and temperature resulted in darker wood. Regarding densification time, L* were 62.76, 56.56, and 53.44 for 5 (minutes), 10 (minutes), and 15 (minutes), respectively. In terms of temperature, lightness index was 64.84, 60.08, and 47.84 at 120, 160, and 200°C respectively.

Statistical descriptions for lightness (L) shows that all three factors (pre-treatment, time, and temperature) were significant ($p < 0.05$) factors. However, significant interaction just occurred between time and temperature as shown in Table 4.9.

<table>
<thead>
<tr>
<th>Response variable</th>
<th>Pre-treatment (PT)</th>
<th>Time (T)</th>
<th>Temperature (TEM)</th>
<th>PT×T</th>
<th>PT×TEM</th>
<th>T×TEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightness (L)</td>
<td>***</td>
<td>***</td>
<td>***</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; NS = not significant ($p > 0.05$)

According to Figure 4.15, aside from type of pre-treatment, the treated wood was significantly darker than control one (LSD (1)). Beside, water spray was able to provide a significantly darker densified western hemlock compared to treated wood that did not pre-treated by water spray.

Figure 4.16 illustrates that all kind of interactions between time and temperature led to have a significantly darker wood compared to untreated samples (LSD (1)). Besides, LSD (2) shows that the interaction trends for 10 and 15 minutes densification had similarity. However, 15 minutes densification produced a significantly darker wood at 160°C and 200°C.
Figure 4.15. Lightness (L) means of untreated (control), none water sprayed (N) and water sprayed pre-treatment (W). Differences larger than the least significant difference (LSD) are statistically significant at a 5% level.

Figure 4.16. Interaction between time and temperature on lightness (L). Differences larger than the least significant difference (LSD) are statistically significant at a 5% level.
Chromatic coordinates \( (a^*) \) indicates red/green mean values of samples. The red/green \( (a^*) \) mean value was 9.32 for treated samples that did not receive pre-treatment, while this value was 7.92 for treated samples, which received pre-treatment by water spray. By considering the time of densification, chromatic coordinates were 8.967, 8.84, and 8.06 for 5 (minutes), 10 (minutes), and 15 (minutes) of densification, respectively. However, when the temperature increased from 120°C to 160 °C, then 200 °C, the \( a^* \) were 7.67, 8.97, and 9.23 respectively. Although it seems that by increasing the temperature and decreasing the time of densification, the chromatic coordinates \( (a^*) \) increased, the statistical test did not show such a meaningful and significant difference among all treatments.

Regarding the blue/yellow \( (b^*) \) mean values, using the water spray as a pre-treatment caused to decrease this value compared to treated samples that did not receive any pre-treatment (19.84 vs 23.42). Increasing temperature and time of densification led to decreasing \( b^* \) value. The blue/yellow \( (b^*) \) mean values were 23.42, 21.70 and 19.64 for 5 (minutes), 10 (minutes), and 15 (minutes) of densification, respectively. In addition, this value was 22.80, 22.65, and 19.43 at 120 to 160 °C, then 200 °C respectively.

In comparison with literature, our results for lightness \( (L^*) \) was compatible, which generally heat treatment, and especially thermal densification method decreases the lightness of wood (Fang et al. 2012, Cruz et al. 2018, Shi et al. 2020). However, there are contradictions among researches regarding \( (a^*) \) and \( (b^*) \) of densified wood. For instance, while Fang et al. (2012) reported that in densification of Sugar maple, \( (a^*) \) increased significantly, and \( (b^*) \) increased slightly, Shi et al. (2020) saw a significant decrease in value of \( (b^*) \), and just a slight increase for \( (a^*) \).

Degradation in hemicellulose and lignin, especially producing phenolic substances such as the quinones derived from change in lignin structure, are reported as main reasons of color change in a heat treatment process (Sikora et al. 2018, Sun et al. 2019). Heating the wood leads to releasing various organic acids that accelerate degradation of hemicellulose and lignin. In fact, formic and acetic acids are formed during heat treatment in high temperatures. Formation of acids creates acidic condition that causes hydrolysis and degradation in wood. This degradation produces chromophore groups that are main responsible of color change. Higher treatment temperatures and
longer densification times bring about high concentrations of acetic and formic acids leading to more degradation and color change in wood (Sundqvist et al. 2006).

4.6 Abrasion

Table 4.10 shows that four different measured abrasion rates. The total rate (last column) represents the overall rate of abrasion after 1500 cycles compared to initial weight before abrasion test. Abrasion rate in control samples was greater compared to value of all treated samples. Generally, the abrasion rate decreased by increasing the number of cycles. At 300 cycles, the highest abrasion rate happened in control samples (2.20%), following by samples were treated at 120°C (1.11% and 0.99%). The minimum abrasion achieved for samples were treated at 160°C (0.41% and 0.42%). According to table 4.10, THM decreased the percentage of abrasion from 6.33% to 1.45%.

Table 4.10. The abrasion rate for control and densified western hemlock in different cycles.

<table>
<thead>
<tr>
<th>Abrasion rate (%)</th>
<th>300 cycles</th>
<th>600 cycles</th>
<th>1000 cycles</th>
<th>1500 cycles</th>
<th>Total rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>2.20</td>
<td>1.57</td>
<td>1.39</td>
<td>1.33</td>
<td>6.33</td>
</tr>
<tr>
<td>N-5-120</td>
<td>1.11</td>
<td>0.96</td>
<td>0.77</td>
<td>0.90</td>
<td>3.69</td>
</tr>
<tr>
<td>N-120-10</td>
<td>0.99</td>
<td>0.88</td>
<td>0.68</td>
<td>0.93</td>
<td>3.43</td>
</tr>
<tr>
<td>WS-10-120</td>
<td>0.89</td>
<td>0.81</td>
<td>0.77</td>
<td>0.66</td>
<td>3.10</td>
</tr>
<tr>
<td>N-5-160</td>
<td>0.88</td>
<td>0.81</td>
<td>0.72</td>
<td>0.70</td>
<td>3.08</td>
</tr>
<tr>
<td>WS-5-120</td>
<td>0.86</td>
<td>0.89</td>
<td>0.60</td>
<td>0.84</td>
<td>3.15</td>
</tr>
<tr>
<td>WS-15-120</td>
<td>0.77</td>
<td>0.79</td>
<td>0.71</td>
<td>0.68</td>
<td>2.93</td>
</tr>
<tr>
<td>N-15-120</td>
<td>0.72</td>
<td>0.69</td>
<td>0.65</td>
<td>0.69</td>
<td>2.72</td>
</tr>
<tr>
<td>N-5-200</td>
<td>0.70</td>
<td>0.67</td>
<td>0.70</td>
<td>0.68</td>
<td>2.72</td>
</tr>
<tr>
<td>WS-5-160</td>
<td>0.69</td>
<td>0.66</td>
<td>0.75</td>
<td>0.60</td>
<td>2.66</td>
</tr>
<tr>
<td>WS-5-200</td>
<td>0.65</td>
<td>0.60</td>
<td>0.45</td>
<td>0.80</td>
<td>2.48</td>
</tr>
<tr>
<td>N-15-200</td>
<td>0.60</td>
<td>0.58</td>
<td>0.55</td>
<td>0.59</td>
<td>2.30</td>
</tr>
<tr>
<td>WS-15-200</td>
<td>0.59</td>
<td>0.41</td>
<td>0.46</td>
<td>0.43</td>
<td>1.88</td>
</tr>
<tr>
<td>N-10-200</td>
<td>0.54</td>
<td>0.91</td>
<td>0.63</td>
<td>0.44</td>
<td>2.50</td>
</tr>
<tr>
<td>WS-10-200</td>
<td>0.51</td>
<td>0.58</td>
<td>0.60</td>
<td>0.53</td>
<td>2.20</td>
</tr>
<tr>
<td>N-10-160</td>
<td>0.49</td>
<td>0.58</td>
<td>0.61</td>
<td>0.37</td>
<td>2.03</td>
</tr>
<tr>
<td>WS-10-160</td>
<td>0.42</td>
<td>0.41</td>
<td>0.38</td>
<td>0.37</td>
<td>1.58</td>
</tr>
<tr>
<td>N-15-160</td>
<td>0.41</td>
<td>0.39</td>
<td>0.31</td>
<td>0.36</td>
<td>1.46</td>
</tr>
<tr>
<td>WS-15-160</td>
<td>0.39</td>
<td>0.38</td>
<td>0.41</td>
<td>0.28</td>
<td>1.45</td>
</tr>
</tbody>
</table>
Wear index values after each cycle number are shown in Table 4.11. The minimum amount was for WS-160-15, while control samples had the maximum values. For instance, at 300 cycles, while wear index was 2.03 gr, related value for WS-160-15 was 0.39 gr, which was about five times lower than non-treated samples.

Table 4.11. The wear index for control and densified western hemlock in different cycles.

<table>
<thead>
<tr>
<th>Wear index(gr):</th>
<th>300 cycles</th>
<th>600 cycles</th>
<th>1000 cycles</th>
<th>1500 cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>2.03</td>
<td>1.70</td>
<td>1.38</td>
<td>1.15</td>
</tr>
<tr>
<td>N_120_5</td>
<td>0.83</td>
<td>0.77</td>
<td>0.64</td>
<td>0.56</td>
</tr>
<tr>
<td>N-120_10</td>
<td>0.95</td>
<td>0.90</td>
<td>0.73</td>
<td>0.67</td>
</tr>
<tr>
<td>WS-120_10</td>
<td>1.02</td>
<td>0.96</td>
<td>0.84</td>
<td>0.70</td>
</tr>
<tr>
<td>N-160-5</td>
<td>0.98</td>
<td>0.94</td>
<td>0.80</td>
<td>0.69</td>
</tr>
<tr>
<td>WS-120_5</td>
<td>0.80</td>
<td>0.80</td>
<td>0.65</td>
<td>0.58</td>
</tr>
<tr>
<td>WS-120-15</td>
<td>0.75</td>
<td>0.76</td>
<td>0.66</td>
<td>0.57</td>
</tr>
<tr>
<td>N-120-15</td>
<td>0.59</td>
<td>0.57</td>
<td>0.50</td>
<td>0.45</td>
</tr>
<tr>
<td>N-200-5</td>
<td>0.82</td>
<td>0.80</td>
<td>0.73</td>
<td>0.64</td>
</tr>
<tr>
<td>WS-160-5</td>
<td>0.80</td>
<td>0.79</td>
<td>0.73</td>
<td>0.62</td>
</tr>
<tr>
<td>WS-200-5</td>
<td>0.83</td>
<td>0.78</td>
<td>0.63</td>
<td>0.62</td>
</tr>
<tr>
<td>N-200-15</td>
<td>0.71</td>
<td>0.70</td>
<td>0.61</td>
<td>0.54</td>
</tr>
<tr>
<td>WS-200-15</td>
<td>0.75</td>
<td>0.64</td>
<td>0.56</td>
<td>0.48</td>
</tr>
<tr>
<td>N-200-10</td>
<td>0.51</td>
<td>0.68</td>
<td>0.59</td>
<td>0.47</td>
</tr>
<tr>
<td>WS-200-10</td>
<td>0.58</td>
<td>0.62</td>
<td>0.57</td>
<td>0.50</td>
</tr>
<tr>
<td>N-160-10</td>
<td>0.64</td>
<td>0.70</td>
<td>0.66</td>
<td>0.54</td>
</tr>
<tr>
<td>WS-160-10</td>
<td>0.57</td>
<td>0.56</td>
<td>0.49</td>
<td>0.43</td>
</tr>
<tr>
<td>N-160-15</td>
<td>0.51</td>
<td>0.50</td>
<td>0.42</td>
<td>0.37</td>
</tr>
<tr>
<td>WS-160-15</td>
<td>0.39</td>
<td>0.38</td>
<td>0.41</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Statistical descriptions of three factors (pre-treatment, time, and temperature) in four different cycles are shown in Table 4.12. The abrasion rate in treated samples was significantly ($p < 0.05$) better (smaller) than the control one. However, just in 300 cycles there was a significant ($p < 0.05$) interaction. The statistical results of 300 and 1500 cycles are shown in the following figures as the most important cycles.
Table 4.12. The result of statistical test (ANOVA) for abrasion rates in different cycles.

<table>
<thead>
<tr>
<th>Abrasion</th>
<th>Experimental factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-treatment (PT)</td>
</tr>
<tr>
<td>300 cycles</td>
<td>NS</td>
</tr>
<tr>
<td>600 cycles</td>
<td>NS</td>
</tr>
<tr>
<td>1000 cycles</td>
<td>NS</td>
</tr>
<tr>
<td>1500 cycles</td>
<td>NS</td>
</tr>
</tbody>
</table>

* = p < 0.05; ** = p < 0.01; *** = p < 0.001; NS = not significant (p > 0.05)

For abrasion rate after 300 cycles (Figure 4.17), the effect of interaction between time and temperature on improvement of abrasion rate for all treated samples was significantly different compared to control samples (LSD 1). At 5 minutes densification, as temperature increased the abrasion rate decreased. However, the lowest rate took place at 160°C for 10 and 15 minutes densification time.

![Figure 4.17. Interaction between time and temperature on Abrasion rate (%) after 300 cycles. Differences larger than the least significant difference (LSD) are statistically significant at a 5% level.](image)

Figure 4.17. Interaction between time and temperature on Abrasion rate (%) after 300 cycles. Differences larger than the least significant difference (LSD) are statistically significant at a 5% level.

Regarding temperature (Figure 4.18), while the lowest abrasion rate was for 160°C, the maximum rate was recorded for control samples. At 1500 cycles (Figure 4.19), abrasion rate in longer densification times (10 and 15 minutes) was significantly lower compared to 5 minutes.
Figure 4.18. Abrasion rate (%) after 1500 cycles for untreated (control), and treated samples at different temperatures. Differences larger than the least significant difference (LSD) are statistically significant at a 5% level.

Figure 4.19. Abrasion rate (%) after 1500 cycles for untreated (control), and treated samples at different densification time. Differences larger than the least significant difference (LSD) are statistically significant at a 5% level.
In comparison with literature, the only similar research with our study was reported by Coelho et al. (2017). They showed that after 600 cycles, there was no significant difference between abrasion rate of 160 and 190°C. However, the highest abrasion resistance was achieved at 190°C, which was 1.66 times better than that of controls.

4.7 Summary

- THM had a significant effect on all variables of interest in this study, which were density, hardness, spring-back, color, and abrasion resistance.
- Aside from abrasion resistance, pre-treatment with water spray was an effective method to improve properties of western hemlock.
- The most important interaction occurred between densification time and temperature, which were significant parameters on all variables of interest.
- The denser layers were achieved in surface (first 6 mm), which was an indicator of a surface densification treatment.
- While hardness mean for control samples was 2.2 kN, THM increased it to 8.57 kN, which it occurred in 15 minutes densification time at 160°C.
- Spring back reached to a steady state condition 200 hours after densification with the less than 1% variation.
- THM darkened color significantly. However, at the highest temperature (200°C), undesirable change occurred due to possible carbonization of wood.
- THM increased abrasion resistance significantly. Combination of 15 minutes densification time and heating at 160°C schedule resulted in the lowest abrasion rate (1.45%).
Chapter 5: General Discussion and Conclusion

5.1 General Discussion

In this thesis, some significant knowledge gaps on thermal densification of western hemlock were addressed. Western hemlock was chosen for two main reasons: 1- It is an important source of lumber in British Columbia; 2- Western hemlock has rarely been the subject of research on thermal modification and densification. In particular, there have been no studies on thermal modification of hemlock to improve its mechanical properties.

To address my hypothesis, first examined the THM of western hemlock. Results showed that THM of western hemlock is a promising technology to improve properties of wood that are important to the flooring industry. The results that support this conclusion were derived from an experimental study that investigated three factors and their interactions on properties of THM western hemlock. Water spray proved to be an effective pre-treatment to thermally soften the wood, and the interaction of pressing time and temperature had significant effects on wood properties.

As mentioned above, there have been no studies on densification of western hemlock. Hence, information on interactions of pre-treatment, densification time, and temperature on THM western hemlock is not available. However, the results of this thesis broadly accrued with literature finding for other species that THM can successfully improve the density, hardness, and abrasion rate of wood. Spring-back reached to a steady state after 200 hours, and this information is a useful finding from this study. In addition, my prediction that THM would make western hemlock wood darker, was validated.

In terms of relevance the results to industrial expectations, hardness was comparable to that of wood species that are used by international flooring companies. In this study, hardness of western hemlock increased from 2.22 to 8.5 kN. In comparison to hardness of commercial Brazilian Cherry, hand-scraped aspen, and phoenix birch are 8.1, 4.1, 3.5 kN, respectively. Water spray, as a pre-treatment, was able to improve hardness, density, spring-back, and darkness of wood. It should be noted that water spray is a cheap and simple softening method, compared to other pre-treatments. Therefore, it could be easily employed on an industrial scale. Although most thermal modification methods cause decrease in mechanical properties, THM was able to improve
mechanical properties significantly, and also improve other wood properties. Introducing a new domestic species, such as western hemlock, could be of benefit to Canadian flooring companies. This thesis was limited to using an open hot press, which provided limitations in terms of THM process, for example steam injection was not possible. In addition, this study was limited to the use of determined sample dimension due to press safety, and the need to conduct standard tests for hardness.

5.2 Conclusion

As a result of THM, hardness, density, spring-back, color, and abrasion resistance of western hemlock were improved significantly. Therefore, my results suggest that THM western hemlock could be a new material for flooring, leading to new opportunities for this valuable domestic species and possibly reducing need to import expensive hardwood species from overseas.

In summary, thermally densified western hemlock should be considered as a viable domestic and environmentally friendly enhanced product for many applications particularly flooring. However, further research is required to translate my findings to an industrial scale.
Chapter 6: Proposed Further Research

- Aside from western hemlock, running experiments on other Canadian species, such as white spruce and trembling aspen, could be beneficial for finding other species for use in flooring industries.

- Although the results of this study show that surface densification can add more value to a domestic wood, experiments at an industrial scale are required to demonstrate the commercial viability of this method for the flooring industry.

- The focus of this study was on flooring applications of surface densified wood. However, densification is able to increase strength properties of wood for use in structural applications.

- This thesis mostly focused on parameters that are important during the densification such as time and temperature. However, focusing on important parameters for pre-treatment (before densification) and post-treatments (after densification) could be examined in future. For instance, more researches are needed in terms of anatomical behavior of wood during process, and finding the best way to decrease spring-back.

- This thesis is the only study that examined interaction among three important factors (pre-treatment (water-spray), time and temperature) on THM. However, more chemical and anatomical tests are needed to interpret results.

- As this study was limited to use of an open system, using a press machine with a closed system that could allow more options such as steaming during densification, without a risk of exploding wood.
References


Kultikova, E. V. (1999). Structure and properties relationships of densified wood (Thesis), Virginia Polytechnic Institute and State University, USA.


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Siau JF. (1995). Wood: influence of moisture on physical properties. Virginia Polytechnic Institute and State University, USA.


