INTERNAL MOISTURE MOVEMENT IN HEM-FIR TIMBERS EXPOSED TO AMBIENT CONDITIONS FOLLOWING KILN DRYING

by

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ABSTRACT

This study aimed to investigate the changes of internal moisture content distributions of high-value hem-fir timbers after kiln drying while exposed to two different local outdoors seasonal conditions for a period of time of few weeks.

Hem-fir is the most abundant species in coastal British Columbia, Canada, and high-quality thick hem-fir timbers used as construction material are one of the most important, and profitable products due to international market demand especially in Japan. Presently more-and-more of those houses are pre-fabricated and dimensional stability is paramount. Internal moisture profiles after kiln drying and their behaviour as a function of weather exposure in storage can result in dimensionally unstable products and consequently compromise quality.

Conventional kiln drying of thick timbers is relatively difficult and requires long drying time to reduce final moisture content variation. Fast drying will result in steep moisture content gradients which may result in undesirable dimensional changes when products are used in normal service conditions. Thus, it is important to understand moisture behavior after drying and how that is affected by the environment.

In this study, 90 x 90 mm in cross-section hem-fir timbers were dried to three different target moisture contents. Thereafter, stickered packages were stored under two diverse seasonal coastal environments thus emulating outdoor timber storage in a local
sawmill. Moisture contents at 25 mm and 45 mm depths were continuously monitored for a period of three weeks.

The results showed that moisture movement was observed between at 25 mm and at 45 mm depths regardless seasonal conditions while no significant net moisture content reduction took place during the cold-wet season after kiln drying. Also, regardless seasonal condition or target moisture content, moisture movement between at 25 mm and at 45 mm depths slowed down when differential moisture content between them was below 2.5%. In particular, at high target moisture content of 22%, moisture content values both at 25 mm and at 45 mm depths remained constant at moisture content difference value of 2.5% after two weeks regardless seasonal conditions, and no further drying or no further moisture content equalization were observed after that point.
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1. INTRODUCTION

Hem-fir, also marketed as Pacific Coast Hemlock (PCH) in British Columbia (BC), is a wood species mix comprised of western hemlock (*Tsuga heterophylla*) and amabilis fir (*Abies amabilis*). Hem-fir is one of the best fiber quality, and the most plentiful softwood species along the BC coast. It has multiple uses such as in roof decking, in plywood manufacturing, in laminating stock to produce glued laminated timber, or pulp and newsprint, however, it is especially one of the best materials to be used as solid beams of high quality in construction due to its strength, tight grain, light color and beauty.

In addition to its multiple domestic uses, hem-fir is also widely sold to overseas markets. Thick solid hem-fir products with cross-sectional area of 90 x 90 mm, 105 x 105 mm, and 115 x 115 mm are common in the market, and known as “baby-squares”. They are also the most notable and profitable products overseas since these products are widely accepted and also preferred as high-quality construction material especially in Japan, which is one of BC’s largest overseas markets.

Hem-fir is a difficult wood to dry due to its high green moisture content, wetwood, compression wood and high variability in green moisture content and basic density. These difficulties are very pronounced especially in the case of thick timber products. Due to these difficulties, even after a long drying process, uneven moisture content distributions affect dimensional stability and therefore, quality of the final product. The purpose of this study was to investigate moisture distribution behavior during equalization periods after
kiln drying for timbers exposed to two typical seasonal environments for BC. Experimental runs were carried out for three different drying target moisture contents. After drying, specimens were exposed to summer and winter conditions in BC to simulate typical storage conditions observed in coastal mills.

The results obtained in this study are related to the potential improvement of moisture profiles between and within timbers during an ambient equalization period while still on stickers, and are expected to lead to a better understanding of moisture content adjustments during a post-drying period of outdoor storage. They can also provide useful information to mill personnel regarding optimum drying/storage conditions before planning or rough surface shipment to construction sites of prefabrication. Furthermore, the moisture behavior and trends observed in this study might be utilized to improve the drying strategy of baby-squares by reducing kiln residence time while improving stability, thus optimizing kiln usage and reducing drying costs.
2. BACKGROUND

2.1. Hem-fir

Hem-fir, specifically Pacific Coast Hemlock (PCH), is a commercial group of mixed species that is comprised of about 80% western hemlock (*Tsuga heterophylla*) and about 20% of amabilis fir (*Abies amabilis*) (Salamon and McBride 2007; Oliveira and Zhang 1994). The trees grow in mixed stands throughout the coastal and interior wet belt forests in BC extending from Alaska southward. BC’s topography and climate divides the province into two distinct forest regions: coast and interior. Coastal forests contain more hemlock than any other species. BC has 4.3 million cubic meters of hemlock forest, and it is 8.9% of all forest by volume (BC Stats 2010).

![Western hemlock](image)

*Figure 2-1: Western hemlock (B.C. Ministry of Forests 1999)*
Western hemlock also known as “west coast hemlock” or “Pacific hemlock” was discovered by botanist Stephen L. Endlicher in 1847. He named hemlock “tsuga,” which is named after Japanese name of the species (Western Wood Products Association 1997). Regarding the etymology of the word “tsuga”, Western Wood Products Association explains that “in Japanese, tsuga means ‘yew-leaved,’ referring to its short, flat – and contrary to legend – non-poisonous needles” and this explanation is widely accepted and well cited; however, it is not very accurate. In modern Japanese, at least in related industries, tsuga only means conifer species. When a single word “tsuga” is used as a name of species, it refers southern Japanese hemlock (*Tsuga sieboldii*), which is a conifer native to Japan. In particular, hem-fir is known as bei-tsuga (American tsuga). Though the word “bei” means “American”, the word “bei-tsuga” is commonly used to refer to all hem-fir related species or products including PCH, which is produced in Canada, not in the U. S. Nowadays, due to recent marketing effort of BC sawmilling industry for Japanese timber market, the word “kanada-tsuga” (Canadian Tsuga) is also used to call PCH specifically (Peter 2007). The name of “kanada-tsuga” was also historically used to refer to eastern hemlock (*Tsuga canadensis*) due to its botanical name, but generally in the industry today, it strictly refers to PCH, and differentiates it from other types of hemlock related species or products.

Hemlock is a uniform, medium- to fine-textured wood. It is mostly fairly straight and even grained. Both the heartwood and the sapwood are almost white light color in color, and sometimes have a tinge of pinkish, purplish or pale reddish-brown. The sapwood sometimes has little lighter color than the heartwood, and the annual rings are distinct
(Mullins and McKnight 1981). The wood is mostly free of resin and has no odor except the case the heartwood contains wetwood with some extractives (Kozlik 1970; Ward and Pong 1980).

Amabilis fir is also known as Pacific silver fir, white fir, red fir, lovely fir, Cascades fir or silver fir. Amabilis means “lovely” in Latin (B.C. Ministry of Forests 1999).

### 2.2. Market conditions of Pacific Coast Hemlock

For the BC sawmilling industry, Japan was the largest overseas softwood lumber market for a long time; however, recently, China rapidly increased its needs (Figure 2-2): after 2009 by quantity, and after 2010 by value. Presently, China is the largest overseas market for BC wood products (BC Stats 2011).

![Figure 2-2: Exports of softwood lumber](image-url)
For softwoods in general, China’s quantity of imports is about twice as many as Japan’s these days; however, its dollar value total is still almost the same to Japan. This is due to the difference of market preferences between those two countries, specifically, the unit volume value of softwood products that Japan imports is about twice as much as for China. Therefore, for PCH, as high-value softwood products, Japanese market is still important and dominant for BC’s sawmilling economy.

Japan is a mature market and the health of the BC coast forest sector and of coastal communities is directly tied to the Japanese wood products demand. Around 2005, eighty percent of homes in Japan were built by pre-cutters, and their preference was clearly for laminated and engineered wood products (Edgington 2004). European whitewoods dominated the market by running on pulp economics, dumping product into the marketplace at breakeven or below cost, and making the competition for coastal green or kiln dried hemlock fierce (Jeffery 2005). Today, the BC sawmilling industry faces significant challenges to maintain its share of market in Japan. United States suppliers offering Douglas-fir products have increased their shipments to Japan three-fold over the last three years. In 2010 these shipments totaled more than 775000 m³, which is equivalent to the output of three coastal sawmills (Demens 2011). The demand for the quality of timber is growing, and for PCH, high quality is essential to compete in the global market. Clearly, China that is one of the largest and the most growing market will soon also have similar needs for high quality wood products for construction. To maintain or gain market share, development and adoption of new technologies and strategies to further improve the quality of wood products is essential and necessary (Peter 2007).
2.3. Pacific Coast Hemlock market in Japan

Aside from North America, Japan is the only country where people traditionally build and live in wooden-frame detached homes (Edgington 2004). Traditionally, those housings are designed and built as “post-and-beam” structure (Figure 2-3), which is also known as “zairai” (“在来”, literal meaning is “conventional”). Though they use different methods and require distinctively different dimensions for structural components, since the mid 1920s, thanks to its fine, smooth appearance and high physical properties observed in shear strength, bending strength, and stiffness, hem-fir timbers were accepted in Japanese market, and BC coastal forest industry started producing distinct thick hem-fir products to satisfy that need. Those products were not sold in significant quantities for 30-40 years. However, in early 1960s, BC industry started shipping them on a regular basis. Soon after they started regular shipments, the amount gradually increased and it was quickly realized that these thick timber products, specifically called “baby-squares”, could be very profitable. So, in the early 1980s, many coastal BC sawmills switched from the classic “two-by-four” timber products and retooled to produce the structural components in metric dimensions demanded by the Japanese construction market (Edgington 2004). In early 1990s, BC coastal hem-fir products were solely preferred in Japanese construction market over all other competitors both international and domestic in Japan, thus the industry established a firm position as the “price setter” for the first time in the history rather than a “price taker” which is common situation in the industry.
Figure 2-3: Typical PCH usage in Japanese traditional housing (Eastin 2004)

 Until the early 1990s, much volume of those hem-fir products was typically shipped in a green condition without kiln-drying. Those timbers often warped or shrank as they lose moisture during transit, however, experienced Japanese carpenters hand chiseled and re-shaped them right before they were used in construction (Hayter and Edgington 1997; Edgington and Hayter 1997; Edgington 2004). However, after 1995, those green products became non-competitive in the market anymore.

 In January 17, 1995, the Great Hanshin earthquake occurred in the southern part of Hyogo Prefecture in Japan. It damaged over 200,000 houses were completely or partially destroyed. Many of those collapsed post-and-beam buildings were old buildings and their weaknesses were mainly from their untreated wooden beams that had been subjected to
decades of rot due to humidity; however, regarding hem-fir products, relatively new buildings were also completely or partially destroyed due to damage from termites (Doi et al. 1995; Miyano et al. 1995).

Due to those changes, green and untreated hem-fir products soon fell into disrepute and were considered as “weak” products. Consequently, due to the preference shift from green products to kiln-dried products, other international competitors such as Finland, Sweden, Germany and Austria increased their presence in Japanese construction market. Their engineered and laminated timber products were often preferred by Japanese importers, since they were kiln- more dimensionally stable.

In 2000, very strict new building standards were formally introduced in Japan. The new standards are performance based and all timber products are ranked according to factors such as shear strength and bending strength strictly. Therefore, timber products shipped to Japan have to be sufficiently kiln-dried and carefully treated to be produced as consistent and high quality material (Edgington 2004).

![Figure 2-4: PCH baby-square pre-cut “dodai” (ground sill) (source: INTERFOR website)](source: INTERFOR website)
At the same time, due to lack of experienced carpenters who used to hand chiseled deformed timber products, and efforts to reduce time and cost in construction, most of structural components used in post-and-beam constructions are “pre-cut” timbers nowadays (Figure 2-4). Those pre-cut products are incised at the mill, and at the construction site, they are easy to be assembled even with inexperienced workers. Needless to say, due to its mechanism, the preciseness in dimension of those products is paramount. Any shrinkage or other types of deformations cannot be overlooked after its final cut.

2.4. Water in wood

Living trees take water up and store water in them. Even after they are cut, there are large amounts of water left inside; therefore those timbers called “wet”. The amount of water in the wood is usually measured by the moisture content. Wood moisture content ($M$ [%]) is calculated from the weight of wet timber ($W_{wet}$) and the weight of it when it is completely dry ($W_{od}$) by using the following formula:

$$M = \frac{W_{wet} - W_{od}}{W_{od}} \times 100$$  \hspace{1cm} (Eq 2-1)

Water is stored inside wood in two forms, namely, “bound” and “free”. Bound water, also known as hygroscopic water is attached to wood via hydrogen bonds. Hydroxyl groups which allow hydrogen bonding exist in the cell walls as a part of cellulose,
hemicelluloses and lignin (Bowyer et al. 2007); thus bound water is chemically bonded in the cell walls. On the other hand, free water is located in the cell lumens, and is simply held by capillary forces. Hydrogen bonds are much stronger than capillary forces; thus, free water is the first to be removed from wood in drying (Siau 1971; Skaar 1988; Stamm 1964).

The moisture content point where all free water is removed from the cell lumens, but bound water still remains in the cell walls is defined as the fiber saturation point (FSP). For temperate zone wood species, FSP averages around 30%. (Siau 1984; Skaar 1972)

There are two major factors which drive moisture movement during drying, namely, capillary action and diffusion. The former is much faster, but much weaker driving force. Thus capillary action determines the movement of free water; however, once it is below FSP, diffusion becomes the major driving force and capillary action becomes negligible.

Capillary action is a phenomenon in which liquid flows in narrow spaces without any external forces. As wood dries, water evaporates from the drying surface, and creates a pressure difference which pulls free water beneath the surface.

Diffusion is a transport phenomenon occurred as a result of the random walk of particles, in this case, water molecules. Due to the effect of diffusion, water in wood cells is transported from a region of high concentration of water to a region of low concentration. When wood is dried below FSP, bound water is removed from the cell walls which are close to the drying surface, and water diffuses from the center of the wood to the drying surface.
As bound water is removed from cell walls, vacated bounding sites of hydroxyl bond are left. These bounding sites make new bonds with adjacent bounding sites in cell micro structure, and cell walls start shrinking. Due to their multilayered complex structure, cell walls do not shrink evenly, and this uneven shrinkage induces internal stress in the cell and consequential dimensional changes (Bowyer et al. 2007; Siau 1971, 1984; Simpson 1991).

2.5. Conventional kiln drying

The purpose of drying wood is to produce wood of lower moisture content to take advantage of superior attributes and physical properties of dry timbers. In the case of industrial drying, to save drying times and minimizing quality losses related to drying is also quite important (Simpson 1991; Skaar 1988; Walker 2006).

The most common type of industrial drying in BC is the conventional (heat-and-vent) kiln drying. A typical conventional kiln is a compartmental structure which is generally constructed of aluminum or stainless steel for drying wood. It is thermally insulated and specifically designed to control drying parameters affecting drying speed or condition such as temperature, humidity and air flow inside (Figure 2-5).
Figure 2-5: Schematic model of a small-medium size conventional kiln (Simpson 1991)

The idea of a conventional kiln is based on natural drying process, but it also increases the speed of drying and tries to minimize drying degrade by taking the advantage of well-controlled conditions in the kiln. Heat is generally supplied by one or a combination of methods following, namely, electricity, steam, thermal oil or direct fire. Thanks to controllable temperature and humidity, there is wide range of drying schedule available depending on various species and thickness. The temperature inside the kiln is controlled by heat supply and ventilation, and humidity is also kept at certain level by introducing steam in some cases. Lumbers are stacked in layers separated by stickers to keep air circulation spaces between each layer. Stickers are mostly made of wood or aluminum, and vary in width and thickness depending on situations such as species or the dimensions of the lumber dried. Air flow is controlled by large fans and pushed through openings in the
packages created by stickers between adjacent layers to ensure uniform distribution of heat and air humidity as the air moves through lumber packages. Kiln conditions such as temperature and humidity are monitored by dry-bulb and wet-bulb sensors according to the drying schedule.

Frequently cited advantages of these types of compartmental kilns are cheaper building cost, less land area requirement, and large capacity with low running cost due to cheap fossil fuels. In a commercial run, thousands of pieces are dried simultaneously (Elustondo and Avramidis 2003). On the other hand, there are also some disadvantages such as long down time for loading and unloading of stacks of lumbers, and generally less uniform drying if initial moisture content of lumbers is above 25%. Also, while conventional kiln is relatively easy and fast to raise and maintain temperature via heat supplied directly, due to loss of steam and warm air during ventilation process, it is not energy efficient (Keey and Nijdam 2002; Simpson 1991).

2.6. Drying stresses

When a very thin (such as less than 15 mm thick) board dries, it does fairly uniformly that is, different parts of the board dries at the same time and stresses due to uneven shrinkage are minimized or nor significant. However, when thicker lumber dries, drying proceeds more or less layer-by-layer, with the outer faces and edges drying first, and this dry zone gradually moving towards the center of the cross-section of a piece (Mackay and Oliveira 1989; Walker 2006).
Casehardening is a term used to describe a particular distribution of stresses which are found in lumber after drying. In the early stages of drying the shell is restricted from shrinking by the non-shrinking core that is still above FSP. The shell is in tension while the core is in compression. Later in drying the core begins to dry below FSP and it begins to shrink. If compression set had developed earlier, then the shrinkage of the core will tend to be greater than it would have been otherwise. When the core begins to shrink, it is at first aided by the shell which had been stretched while trying to shrink. The shrinkage of the core is said to relieve some of the tension stress in the surface layers. However, as the core continues to shrink as it dries, it is prevented by the shell which has a tension set; that is, the shell is fixed in a stretched condition (Mackay and Oliveira 1989; Bramhall and Wellwood 1976). The shell goes from a stretched condition to a tendency to be pulled by the core, and it becomes compressed or goes into compression, the stresses start to reverse. The core goes from a compressed condition to being pulled by the surface shell and it therefore goes into tension. Once the shell and the core is separated (in the process of manufacturing, this can happen), the shell would enlarge and the core would shrink.

Casehardening could be prevented through the maintenance of sufficiently high relative humidity to prevent the surface from drying too fast especially in the early drying stages (Mackay and Oliveira 1989; Bramhall and Wellwood 1976). However, in conventional kiln drying, this solution is time consuming especially if the timber is thick.

Drying stresses cause unequal shrinkage. If the stresses are so severe that the wood cannot withstand them, then the failure of the wood will occur in the form of a check or
split. Stresses are caused by unequal shrinkage, and unequal shrinkage has three principal causes (Mackay and Oliveira 1989): i) the difference in shrinkage between shell and core; ii) the difference in shrinkage in the radial and tangential directions of the wood; iii) the difference in the directions of shrinkage between normal wood and reaction wood.

2.7. Difficulties in drying hemlock

Hem-fir has difficulties in drying to the desired moisture content and quality. One of the most important factors affecting lumber quality/value is wide variation in final moisture content after drying (Elustondo et al. 2010). There are several factors that cause the problem; one of the largest factors is wetwood that are localized regions of high-moisture-content wood (Ward and Shedd 1981; Nicholls et al. 2003).

Wetwood is a condition in which a certain region of the wood has higher moisture content than the surrounding areas (Chafe 1996; Cooper and Jeremic 1998). The cell lumens are filled with water and contain hardly any air which sometimes could make the wood sink in water (Simpson 1991). Wetwood appears in the longitudinal direction of the stem in conical form or as pockets thus those pockets are referred to as “wet pockets” (Kozlik 1970). Wetwood has a distinctive odor and darker color or wetter appearance than normal heartwood. Wetwood is also referred to as “sinker stock” and “heavy wood” (Kozlik 1970; Kozlik et al. 1972; Cooper and Jeremic 1998; Simpson 1991; Chafe 1996) or less often as “sinker heartwood” (Kozlik 1970; Warren 1991). They are also known to be
infested with bacterial infested wood trunks that change their physical, chemical, and biological properties (Bauch et al. 1975; Schink and Zeikus 1981; Ward and Pong 1980).

In 1970, Kozlik compared the green moisture contents of normal heartwood and wetwood of some 54 wood samples. According to his result, while the average moisture content of normal heartwood of hemlock is 66%, the average moisture content of wetwood is 153%. Furthermore, even in the same category of wood, moisture content of normal heartwood varies in a wide range (Table 2-1).

<table>
<thead>
<tr>
<th></th>
<th>Average green moisture content [%]</th>
<th>Range of green moisture content [%-%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal heartwood</td>
<td>66</td>
<td>33-152</td>
</tr>
<tr>
<td>Wetwood</td>
<td>153</td>
<td>108-186</td>
</tr>
</tbody>
</table>

Wetwood dries very slowly due to its pit aspiration which reduces permeability and fluid flow (Chafe 1996), and is prone to collapse at the early stages of drying when liquid water is present in its lumens (Simpson 1991). Moreover, uneven drying conditions frequently occur when lumber of higher and lower moisture content is mixed together in a dry kiln. Since hem-fir is a species mix, there are some species other than hemlock (such as Amabilis fir), which result wide variability of moisture content. Even if there are only hemlock lumbers, wide range of moisture content exists. When an individual board has significant moisture content variation from end to end, it results warping, checking, and other degrade that can reduce lumber value. Especially for high-value thick hem-fir timbers, straight stable shape and high physical strength are required.
Technically, wet pockets can be visualized by using non-destructive evaluation methods such as near-infrared spectroscopy (NIRS) (Watanabe et al. 2010) and X-ray computed tomography, also known as computed tomography (CT scan) (Lazarescu et al. 2010; Watanabe et al. 2012). Because these methods are quick and non-destructive, they can be a quite convenient and essential tool under a specific situation such as sorting as a part of quality control, quality assurance, and process optimization. However, the high costs involved in these equipments are major limiting factors.

When a living tree is exposed to constant lateral pressure such as wind, snow buildup, and soil movement or it is growing on a steep slope, the longitudinal tracheids of the pressured part change their form their usual rectangular shape into a shorter and rounder form. It is termed reaction wood, or more specifically, in the coniferous species, compression wood. It also shows larger fibril angle and higher lignin content than normal wood, and more rigid and less vulnerable against forces (Bowyer et al. 2007; Kellogg and Warren 1979; Siripatanadilok and Leney 1985). Due to its low permeability and higher density, and different chemical composition of wood, it is known that it is harder to dry than normal wood.

Also, hemlock trees show considerable variation in the characteristics of the growth ring. While some show gradual transition between adjacent annual rings from earlywood to latewood, others may show abrupt transition between them. This uneven density distribution within timbers is also one of the causes of uneven drying during in a kiln (Keey et al. 2000; Kellogg and Warren 1979; Siripatanadilok and Leney 1985).
In recent years, because of increased degradation of the natural environment, the old-growth forested areas as a natural source of wood, are obtaining protected status. For that reason, wood manufacturers are trying to process small-diameter wood from second-growth and ecologically suitable plantation forests (LeVan-Green and Livingston 2001). This type of tree is harvested at a younger age, and because the growth is generally greatest during the formation of juvenile wood, its core may represent a larger proportion of a smaller diameter of modern log supplies compared with old-growth trees (Kretschmann et al. 1993). However, it is considered that juvenile wood typically has characteristics that negatively impact a number of wood properties. If the juvenile wood is in solid timber products, the quality of the products suffers due to its inconsistent density and higher longitudinal shrinkage as a result of greater fibril angle in the layer of cell wall (Bradic and Avramidis 2007; Cave 1976; Jozsa et al. 1998).

2.8. Environmental effect on moisture content

Even after kiln drying, especially in the case of thick timber products, it is likely that moisture profile will change, and it will affect dimensional stability to a certain degree. There are mainly two possible factors that may contribute to changes in moisture profile of timbers: uneven moisture content distribution at the end of drying and environmental conditions (temperature and relative humidity) where timbers are going to be used.

Depending on external conditions of temperature and relative humidity, even after kiln drying, lumber will lose or gain moisture and moisture content tends to be a certain
value and the wood reaches a dynamic equilibrium. Dynamic equilibrium means the condition where water moves between timbers and surrounding air at an equal rate and there is no net change of water. The moisture content value at this point is termed equilibrium moisture content (EMC).

There are many factors that affect EMC values such as species, basic density, microstructure of wood, wood extractives and sorption hysteresis since they affect chemical or structural property of wood (Ahmet et al. 1999; Obataya et al. 2000; Obataya and Tomita 2002; Skaar 1988). EMC values can be approximately predicted as a function of temperature and relative humidity (Hailwood and Horrobin 1946; Siau 1984; Simpson 1973; Skaar 1972).

Although temperature has very small effect on EMC value itself, it affects the speed of internal moisture movement since thermal energy accelerates the diffusion process. Therefore, moisture content changes are more prominent at higher temperature (Siau 1984; Keey et al. 2000; Walker 2006).

**2.9. Moisture control strategy after drying**

Immediately after drying, moisture content of kiln packages can be easily affected by external conditions since they still have large amounts of thermal energy. Therefore, commonly in the industry, as soon as packages are unloaded from the kiln, they are cooled down and stickers are removed. They are also wrapped in various types of coated paper or
tarpaulins to avoid possible moisture gaining from surrounding air before shipping (Simpson 1991).

Also as described, thick timbers can be difficult to dry evenly; the shell dries first, and the core dries much slower, layer-by-layer. As a result, uneven moisture content distribution within a timber is formed during drying, and if the drying is over before minimizing moisture content variation and stresses, casehardening will result which will invariably affect quality of the product during subsequent manufacturing. (Sackey et al. 2004; Bradic and Avramidis 2006, 2007; Rohrbach 2008; Lazarescu et al. 2010).

Moisture diffusion occurs between regions of high and low concentration of water. Ideally, uneven moisture content distribution is leveled out over time. However, as moisture content distribution changes, internal stress distribution also changes. Consequently, further dimensional changes are induced due to internal stress changes. Indeed, Rohrbach (2008) reported one week of storing after harsh drying schedule, which was relatively short and resulted in steep moisture content distribution, had significant influence on reducing casehardening. It suggests a possibility that by counting on this type of post-drying storing period before shipping timbers to a sawmill, better quality of timbers can be expected and furthermore, drying strategy can be optimized for saving both time and energy usage of the kiln. Therefore better understanding about moisture content distribution changes during post-drying period is essential.
2.10. Electrical resistance moisture meters

Since moisture content is one of the most essential and convenient indicators to understand the drying (or wet) condition of timbers, there are several different types of moisture content meters that can measure or estimate moisture content of timbers.

One of the types of moisture content meter available in the market is an electrical resistance moisture meter, which utilize the relation between electrical conductivity and moisture content of wood.

Below FSP, when free water is no longer present in the wood, the moisture content can be linearly related to the logarithm of the specific electrical resistance value. Thus, electrical resistance moisture meters can estimate moisture content value of wood from its conductivity measurement fairly well from moisture content values between 6 and 30%. On the other hand, above FSP, the relation is rather complex and moisture content measurements using electrical resistance devices are not really accurate (Stamm 1930).

Due to its anisotropic properties, the ratio of longitudinal to radial conductivity is 1.9 to 3.2 while the one of longitudinal to tangential conductivity is 2.1 to 3.9. The average ratio of longitudinal to transverse conductivity is 2.0 to 3.7 (Stamm 1959, 1960). Since conductivity measurement in radial or tangential direction is also affected by various factors such as earlywood and latewood, electrical resistance meters are normally designed to measure in longitudinal direction to get stable moisture content value.
A pin-type moisture content meter is frequently used in the lumber industry. Number of electrodes used in a pin-type moisture meter is depending on the design of the machine, but mostly a pair of electrodes is equipped. On measurement, pins are driven into wood, and conductance of wood is measured. Conductance is translated into moisture content value by using equations based on relation between them (James 1988). Pin-type electrodes are often electrically insulated with an insulator such as fluoropolymer (Teflon), and only the ends are un-insulated. By using those types of insulated pins and altering the length of pins, pin-type moisture meters can measure moisture content at different depths.

Conveniently, in the case of pin-type moisture content meter, the width, height and length of the measured timber have no effect on the relation between the conductivity and the moisture content described before. Therefore pin-type moisture content meters can be used against any sizes of timbers. Basic density and temperature are the two factors that are considered to have some effect on results, though it is only a slight amount (Stamm 1930).

Electrical resistance meters have a function to specify a basic density value either by selecting species or inputting a value directly. Most electrical resistance meters also have an interface to input current specimen temperature, or some high-end moisture meters such as a remote controllable type for in-kiln use are sometimes coupled with a thermometer which automatically updates current temperature correlated with the determination of the moisture content value.
3. MATERIALS AND METHODS

3.1. Materials

A total of one hundred seventy-nine green, hem-fir timbers were used for this study. They were all purchased from International Forest Products Limited (Interfor) - Acorn Division mill in Delta, BC. Due to the limitation of the space for storage, the acquisition of the total population was done in two installments. The green timbers had an average cross sectional area of 90 x 90 mm$^2$, and the first 96 pieces of them were 2.1 m long (Group I), whereas the other 83 pieces were 4 m long (Group II). Group I was delivered on June 20$^{th}$, 2011, and Group II was delivered on September 26$^{th}$, 2011.

*Figure 3-1: Four meter long timbers (Group II) before cutting*
3.2. Pre-drying specimen preparation

Each timber was then cut into two or three 910 mm long kiln specimens (A and B) and 25 mm thick cookies in between and on the left-and-right (a, b, c), the latter used to determine green moisture content and basic density of each kiln specimen. To avoid very dry timber end-areas, rejects of 100 mm in thickness were cut from each end (x, x). The cutting pattern for two specimens is shown in Figure 3-2.

![Figure 3-2: Cutting pattern for green specimens and cookies; where A and B are kiln specimens; a, b, and c are cookies; x are discards.]

Each kiln specimen was numbered, and each cookie and kiln specimen were labeled such as 1-A, 1-B (specimens) and 1-a, 1-b (cookies). During cutting, an effort was made not to include any knots in the cookies to avoid any inaccuracies in green moisture content determination.

<table>
<thead>
<tr>
<th>Group</th>
<th>Timber</th>
<th>Cookie</th>
<th>Specimen</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group I</td>
<td>90 x 90 x 2440</td>
<td>90 x 90 x 25</td>
<td>90 x 90 x 910</td>
<td>96</td>
</tr>
<tr>
<td>Group II</td>
<td>90 x 90 x 3960</td>
<td>90 x 90 x 25</td>
<td>90 x 90 x 910</td>
<td>83</td>
</tr>
</tbody>
</table>

Table 3-1: Specimen dimensions and quantities
The green weights of all cookies and kiln specimens were obtained with electronic balances and thereafter, the cookies were oven-dried at 103±2°C for twenty-four hours and their oven-dry weights were measured. From these values, the green moisture content of each cookie was determined (Figure 3-3). Dimensions of specimens were measured with a tape and a pair of calipers to determine their volume. Thereafter basic density of specimens was calculated along with corresponding oven-dry weight.

![Figure 3-3: Labeled cookie being weighed](image)

Using the green moisture content values of the cookies located at the both ends of each specimen (e.g. cookies a and b for the specimen A in Figure 3-2), the green moisture content of that specimen was determined as the average, and thereafter, the basic densities were calculated based on their dimensions.

In each group, specimens were sorted by their green moisture content, and numbered accordingly in an ascending order (for example, the one which had the highest
green moisture content was numbered 1, and so on). Subsequently, they were divided into several sub-groups to get more even average green moisture content among sub-groups. In Group I, specimens were divided into three sub-groups, while there were four sub-groups in Group II. Each sub-group and the patterns of contained specimens were listed in Table 3-2.

<table>
<thead>
<tr>
<th><strong>Table 3-2: Specimens sort and sub-groups</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sub-group</strong></td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Group I</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Group II</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

\(A) \) “contained specimens” represents specimen numbers picked for the package.

In order to minimize any unintended moisture loss of kiln specimen before kiln drying, they were tightly wrapped in thick plastic bags individually (Figure 3-4), covered by tarpaulins, and stored in a cold room which was kept at constant temperature of 5°C until kiln drying.

Each sub-group was named after its corresponding seasonal condition and target moisture content as listed in Table 3-3, such as W12 and C22, where the first letter represents seasonal condition, W for warm-dry season and C for cold-wet season, and the following numerical value shows its target moisture content.
Table 3-3: Sub-groups and corresponding conditions matrix

<table>
<thead>
<tr>
<th>Target moisture content</th>
<th>12%</th>
<th>17%</th>
<th>22%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm-dry season</td>
<td>W12</td>
<td>W17</td>
<td>W22</td>
</tr>
<tr>
<td>Cold-wet season</td>
<td>C12</td>
<td>C17</td>
<td>C22</td>
</tr>
</tbody>
</table>

All specimens were stored in the cold room at least two weeks before drying to eliminate any possible biases that might be occurred due to refrigeration process such as temperature difference among kiln specimens.

Figure 3-4: Wrapped specimens after sorting
3.3. Kiln drying runs

A laboratory dry-kiln, which is capable to hold roughly 0.7 m$^3$ (stickered package of 0.9 x 0.9 x 0.9 m$^3$) was used for specimen drying in this study. It was an all-aluminum conventional kiln that was heated electrically and had two fans to control air circulation (Figure 3-5). Due to lack of fan reversibility, air circulation inside the kiln was unidirectional throughout the experiments, which is not of any consequence to the drying homogeneity due to the small width of the package. The kiln was fully computerized thus, all monitoring and operation was done through a software interface automatically. Also, the mass change of the load was continuously monitored by using an electronic scale installed beneath the floor of the kiln for accurate drying schedule implementation.

*Figure 3-5: The conventional kiln with a stickered kiln package loaded*
For each drying run, a total of forty-two kiln specimens out of sixty-two to sixty-four specimens per sub-group were randomly selected by using pseudorandom generator to make up a kiln package. Each specimen was weighed before placing in the kiln.

Both ends of each kiln specimen were coated by polyvinyl acetate (PVA) glue to prevent excessive moisture loss during drying (Figure 3-6), that can result in significant drying degrade such as end-cracks and can also skew drying results due to the shortness of the specimens. After coating, all kiln specimens were stacked in a 6-high and 7-wide pile (Figure 3-5) with aluminum stickers whose cross-sectional area were 19 x 19 mm$^2$. A pair of stickers were placed about 100 mm from the end of specimens for each layer respectively and perpendicular to the longitudinal direction of specimens.

![Figure 3-6: A kiln package ends coated by PVA glue](image)

The relative humidity inside the kiln was controlled by a steam boiler and the venting system and monitored based on dry-bulb and wet-bulb temperatures measured by resistance temperature detectors (RTDs) installed inside the kiln. The electrical heating
device was located on right top of the kiln, and a baffle was placed between kiln ceiling and the top of the kiln load to prevent air flow over the timber pile. Both intake and outtake vents were on the right side of the kiln, facing a wall and the air velocity through the kiln load was set to range between 3.0 and 3.5 m/s throughout the experiments.

The drying schedule used for this study is shown in Table 3-4 and was based on the one used by Bradic and Avramidis (2007) for hem-fir baby square timbers. To compare the effect of different drying levels, three different target moisture contents were used, namely, 12, 17 and 22%. Moisture content of the kiln package was automatically calculated and monitored according to its weight weighed by the scale installed inside the kiln, and used to determine if it reached its target moisture content given.

<table>
<thead>
<tr>
<th>Step</th>
<th>Length [hour]</th>
<th>$T_{db}^{A)}$ [°C]</th>
<th>$T_{wb}^{A)}$ [°C]</th>
<th>$RH^{B)}$ [%]</th>
<th>$M_{emc}^{C)}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>49</td>
<td>49</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>52</td>
<td>51</td>
<td>95.2</td>
<td>21.5</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
<td>55</td>
<td>53</td>
<td>90.8</td>
<td>17.5</td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>58</td>
<td>55</td>
<td>86.7</td>
<td>15.6</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>62</td>
<td>57</td>
<td>79.3</td>
<td>12.6</td>
</tr>
<tr>
<td>6</td>
<td>24</td>
<td>66</td>
<td>59</td>
<td>72.7</td>
<td>10.6</td>
</tr>
<tr>
<td>7</td>
<td>24</td>
<td>70</td>
<td>61</td>
<td>66.9</td>
<td>8.6</td>
</tr>
<tr>
<td>8</td>
<td>24</td>
<td>74</td>
<td>63</td>
<td>61.8</td>
<td>7.8</td>
</tr>
<tr>
<td>9</td>
<td>last until $M^{D)} = target moisture content</td>
<td>78</td>
<td>65</td>
<td>57.2</td>
<td>7</td>
</tr>
</tbody>
</table>

$A)^{T_{db}}$: dry-bulb temperature; $T_{wb}$: wet-bulb temperature  
$B)^{RH}$: relative humidity  
$C)^{M_{emc}}$: estimated equilibrium moisture content  
$D)^{M}$: moisture content, 12, 17 or 22%
Except for the last step, each step was time-based and constant among all the drying runs. On the other hand, length of the last step depended on target moisture content; thus it was different in each drying run. No conditioning steps were used.

3.4. Post-drying evaluation and measurement preparation

As soon as the timber package in the kiln reached the target moisture content, the kiln stopped automatically. To avoid unintentional further drying in the kiln, drying runs were carefully timed not to finish during a weekend or in the evening; thus immediately after the kiln stopped, all specimens were unloaded from the kiln, each specimen was weighed and moisture content values of each right after drying were determined.

Due to monetary limitation, sufficient amount of electrodes and wires for moisture content measurement (described at a later part of this section) for all the specimens could not be obtained. Thus, among the forty-two specimens comprising a kiln package, one third of them (fourteen specimens) were selected by picking one in every three specimens following the pattern shown in Figure 3-7. These fourteen specimens created a sub-set of each drying package to be measured during ambient equalization period.
To measure moisture content of these representative specimens continuously, two pairs of electrodes (contact pins) were inserted at two depths, namely, quarter-point (QP, located roughly located at about 25 mm depth from the surface) and the geometric center (GC, located at 45 mm depth from the surface) as showed in Figure 3-8. Two different lengths of electrodes, which are designed for use with a pin-type resistance moisture content meter, were used in this study (Table 3-5). They were made out of hardened steel, and tapered for ease of penetration. They were designed to use with a pin-type moisture meter, and their side-area was Teflon-insulated (Figure 3-9). Specimens were pre-drilled and two pairs of electrodes were inserted around the middle of the length, respectively. Electrodes were kept inside the specimens for three weeks during each ambient equalization periods as will be described later.
Some electrodes were retrieved from specimens used in completed runs and reused again. In the case a tapered tip of an electrode was covered with rust due to exposure to moisture inside specimens, rust was scraped out by using a sand paper.
Once electrodes were inserted into specimens, specimens were re-stacked and stickered on a pallet into the exact same layout and order as they were placed in the kiln. Electrical wires were connected to all inserted electrodes with alligator clips on each end.

<table>
<thead>
<tr>
<th>Table 3-5: Types of pins and measuring depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring depth [mm]</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>Short</td>
</tr>
<tr>
<td>Long</td>
</tr>
</tbody>
</table>

*Calculation methods for target moisture content and average moisture content*

To calculate moisture content values, each specimen was oven-dried, and the weight of water ($w_{wet}$) and the weight of oven-dried specimen ($w_{od}$) were determined respectively.

The moisture content value of the package ($M_t$) which was used to determined if it reached the target moisture content or not was calculated by using eq A-1.

$$
M_t = \frac{\sum (w_{wet} - w_{od})}{\sum w_{od}} \quad \text{(Eq A-1)}
$$

On the other hand, the average moisture content of each specimen (\(\bar{M}\)) was determined following the way described in eq A-2.

$$
\bar{M} = \sum \frac{w_{wet} - w_{od}}{w_{od}} \quad \text{(Eq A-2)}
$$
As showed above, $M_t$ indicates the moisture content of the entire drying package while $\bar{M}$ shows the average value of each moisture content value of each specimen which comprise of the package. Thus, $M_t$ and $\bar{M}$ are different by definition.

### 3.5. Ambient equalization

When all kiln specimens were re-stickered the packages were moved outdoors to a dry shed (Figure 3-11) that faces east and can protect the wood specimens from direct rain and sunlight. All packages were exposed to outdoor conditions for three weeks and during that time period, moisture content was measured by connecting a pin-type moisture meter to each pair of electrodes inserted in selected specimens as explained in the previous subsection (Figure 3-10). Moisture content readings at QP and GC were taken every Monday, Wednesday and Friday around noon time.

*Figure 3-10: Moisture content measurement for a package during equalization*
For comparison purposes, two different seasonal conditions, warm-dry summertime and cold-wet wintertime that correspond to the months of August-October and December-March, respectively, were used as seasonal conditions for ambient equalization (Table 3-6). These seasonal conditions are common in Vancouver, British Columbia.

Table 3-6: Seasonal conditions

<table>
<thead>
<tr>
<th>Period</th>
<th>Temperature[°C]</th>
<th>Relative humidity (Mean) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max</td>
<td>Mean</td>
</tr>
<tr>
<td>Warm-dry</td>
<td>26.1</td>
<td>14.7</td>
</tr>
<tr>
<td>Cold-wet</td>
<td>13.9</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Figure 3-11: Packages placed in the dry shed
4. RESULTS AND DISCUSSION

4.1. Green moisture content and basic density

4.1.1. Green moisture content

Equally split in a total of six drying runs, altogether, 252 hem-fir specimens were used in this study. Measured green moisture contents and basic densities are listed in Table 4-1. Green moisture content ranged from 30 to 175%, with an average value of 84% and standard deviation of 32%. These numbers are comparable to data reported by other researchers. For pure western hemlock, Nielson et al. (1985) reported mean green moisture content as about 55% in heartwood and 143% in sapwood, with an average of 85%. For pure amabilis fir, they also reported about 55% in sapwood to 164% in heartwood, with an average of 65%. For hem-fir some researchers investigated the same size timbers from the same sawmill, and reported their range as from 33.9 to 186.5%, with an average of 61.6% (Sackey et al. 2004), or from 16.8 to 166.8% (Bradic and Avramidis 2006, 2007), which are very close to the values obtained in this study.
**Table 4-1. Green moisture content and basic density of each drying run**

<table>
<thead>
<tr>
<th></th>
<th>Green moisture content [%]</th>
<th>Basic density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD&lt;sup&gt;A&lt;/sup&gt;</td>
</tr>
<tr>
<td>W12</td>
<td>82</td>
<td>33</td>
</tr>
<tr>
<td>W17</td>
<td>86</td>
<td>30</td>
</tr>
<tr>
<td>W22</td>
<td>82</td>
<td>33</td>
</tr>
<tr>
<td>C12</td>
<td>78</td>
<td>31</td>
</tr>
<tr>
<td>C17</td>
<td>81</td>
<td>33</td>
</tr>
<tr>
<td>C22</td>
<td>79</td>
<td>30</td>
</tr>
</tbody>
</table>

<sup>A</sup>) SD: standard deviation  
<sup>B</sup>) CV: coefficient of variation (in %)

The moisture content distributions within each kiln-package are shown in Figure 4-1. The peak is about at 60%, however, there is also a second peak observed around 90% in W22, C17 and C22. It is speculated that this is due to their composition of species ratios. Hem-fir is comprised of hemlock and fir with different moisture content distributions. As cited before, Nielson et al. (1985) reported average green moisture content of hemlock and fir are about 85% and 65%, respectively, and they roughly match the distribution peaks observed in this study.

In the case of W17, the distribution shape seems like a positively skewed normal distribution with the peak of but such is probably a coincidence mainly due to the small sample size. Still, it is worth mentioning that W17 had very few low green moisture content specimens.

Coefficient of variation for green moisture content was ranged from 35 to 41%.
Figure 4-1: Distribution of green moisture contents
4.1.2. Basic density

Basic density ranged from 316 to 564 kg/m$^3$, with an average of 404 kg/m$^3$. The specimen that had the highest density of 564 kg/m$^3$ was observed in W17, but it was omitted from Figure 4-1 because the value was out of range. These values are also comparable to findings of former researchers. Sackey et al. (2004) reported a range from 302 to 511 kg/m$^3$ with an average of 380 kg/m$^3$, Li et al. (1997) reported a range from 362 to 451 kg/m$^3$, and Zhang et al. (1996) reported it from 316 to 563 kg/m$^3$.

Though these distributions are widely scattered a vast majority (more than 70%) of the specimens were between 350 and 450 kg/m$^3$ in all runs, which resulted in relatively low coefficient of variation value range from 9 to 13%.
Figure 4-2: Distribution of basic density
4.2. Moisture content right after drying

Moisture content measured right after drying is listed in Table 4-2, along with green moisture contents and drying length for comparison purpose. Due to size and green moisture content differences among specimens, a mean value of a package did not match its target moisture content.

Table 4-2: Moisture content of each drying run after drying

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Mean</th>
<th>SD</th>
<th>CV</th>
<th>Min</th>
<th>Max</th>
<th>M_g</th>
<th>Drying length</th>
</tr>
</thead>
<tbody>
<tr>
<td>W12</td>
<td>12</td>
<td>5.0</td>
<td>42</td>
<td>3.0</td>
<td>29</td>
<td>82</td>
<td>364 (15)</td>
</tr>
<tr>
<td>W17</td>
<td>16</td>
<td>4.4</td>
<td>28</td>
<td>8.1</td>
<td>27</td>
<td>86</td>
<td>317 (13)</td>
</tr>
<tr>
<td>W22</td>
<td>21</td>
<td>4.0</td>
<td>19</td>
<td>8.4</td>
<td>29</td>
<td>82</td>
<td>220 (9)</td>
</tr>
<tr>
<td>C12</td>
<td>11</td>
<td>3.9</td>
<td>34</td>
<td>3.1</td>
<td>25</td>
<td>78</td>
<td>478 (20)</td>
</tr>
<tr>
<td>C17</td>
<td>15</td>
<td>7.1</td>
<td>46</td>
<td>5.4</td>
<td>39</td>
<td>81</td>
<td>384 (16)</td>
</tr>
<tr>
<td>C22</td>
<td>22</td>
<td>9.7</td>
<td>45</td>
<td>7.4</td>
<td>54</td>
<td>79</td>
<td>263 (11)</td>
</tr>
</tbody>
</table>

A) M_g: green moisture content  
B) SD: standard deviation  
C) CV: coefficient of variation (in %)

The distribution of moisture content right after drying is shown in Figure 4-3. The specimen that had the highest moisture content of 54% was observed in C22, but it was omitted from Figure 4-2 because the value was out of the range.
Figure 4-3: Distribution of moisture content right after drying
Regarding relation between those moisture content values and drying runs, there were two things worth mentioning.

First, though average green moisture content values of C-group (C12, C17 and C22) were lower than W-group (W12, W17 and W22), they took generally longer time to reach target moisture content. Moreover, in spite of the fact that C-group was dried for as longer period of time, C17 and C22 had several under-dried specimens that still had high moisture content larger than 30% and consequently standard deviation values for those runs were clearly higher than the other runs.

As those under-dried specimens had high basic density, those differences were considered to be from those specimens. As described before, it is known that high basic density lumber takes longer drying time than low basic density lumber (Avramidis and Oliveira 1993; Zhang et al. 1996). Though average basic densities of each package were nearly the same (ranged between 389 and 409), C17 and C22 had several high density specimens which were under-dried. Also, since those long drying length and high standard deviations were caused by just a small number of specimens that had extreme basic density values, the apparent differences between seasonal conditions may not be representative.

Second, it can be observed that in W-group, standard deviation increased as target moisture content lowered while in C-group standard deviation decreased as target moisture content lowered. Theoretically, a standard deviation value of moisture content is supposed to reduce as target moisture content lowered since overall moisture content range is narrowed through drying. However, in the W-group, regardless the numerically similar
mean values and standard deviations of green moisture content, they showed an opposite
trend; the range was wider as its corresponding target moisture content value reduced.

This is caused by corresponding green moisture content range of each kiln package. Though standard deviation values and coefficient of variation values of each package in green moisture content were quite similar, their max values and ranges were different (Table 4-3).

<table>
<thead>
<tr>
<th></th>
<th>Min [%]</th>
<th>Max [%]</th>
<th>Range [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>W12</td>
<td>36</td>
<td>175</td>
<td>139</td>
</tr>
<tr>
<td>W17</td>
<td>31</td>
<td>167</td>
<td>136</td>
</tr>
<tr>
<td>W22</td>
<td>30</td>
<td>148</td>
<td>118</td>
</tr>
</tbody>
</table>

As Table 4-3 shows, the range was larger as its corresponding target moisture content value lowered. Thus, those differences were reflected to the range of moisture content after drying, consequently, standard deviation of moisture content and corresponding coefficient of variation.
4.3. Ambient equalization

Time periods and properties of each ambient equalization run are listed in Table 4-4. The moisture content values measured by the pin-type resistance moisture meter during ambient equalization are plotted in Figure 4-4 (GC), 4-5 (QP), 4-6 (mean value between GC and QP), and 4-7 (difference between GC and QP), respectively.

<table>
<thead>
<tr>
<th>Seasonal conditions</th>
<th>Target $M^A)$</th>
<th>Equalization period $[YYYY-MM-DD, &lt;start&gt;/&lt;end&gt;]$</th>
<th>$M_d^B)$ [% (SD)]</th>
<th>$M_f^B)$ [% (SD)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>W12 Warm C)</td>
<td>12</td>
<td>2011-10-26/2011-11-14</td>
<td>12 (5.3)</td>
<td>10 (3.5)</td>
</tr>
<tr>
<td>W17 Warm</td>
<td>17</td>
<td>2011-09-26/2011-10-14</td>
<td>18 (3.6)</td>
<td>16 (3.8)</td>
</tr>
<tr>
<td>W22 Warm</td>
<td>22</td>
<td>2011-08-19/2011-09-07</td>
<td>22 (4.0)</td>
<td>20 (4.3)</td>
</tr>
<tr>
<td>C12 Cold</td>
<td>12</td>
<td>2012-01-30/2012-02-17</td>
<td>11 (3.9)</td>
<td>11 (3.2)</td>
</tr>
<tr>
<td>C17 Cold</td>
<td>17</td>
<td>2012-02-17/2012-03-07</td>
<td>15 (7.1)</td>
<td>15 (3.9)</td>
</tr>
<tr>
<td>C22 Cold</td>
<td>22</td>
<td>2012-12-09/2011-12-28</td>
<td>22 (9.1)</td>
<td>21 (3.3)</td>
</tr>
</tbody>
</table>

A) Target $M$: target moisture content  
B) $M_d$, $M_f$: moisture content right after drying, and at the end of equalization period;  
SD: standard deviation  
C) Warm-dry condition for W12 was simulated in the lab

For the W12 run, due to time restriction of the season, the package was in the laboratory and exposed to temperature and relative humidity similar to those observed during a warm-dry seasonal conditions defined in this study. $M_d$ and $M_f$ values listed in this table do not match the start or the end values plotted in Figure 4-6 because the former were determined by weight while the latter were average values measured by the moisture resistance pins.
Figure 4-4: Moisture content changes at GC

Figure 4-5: Moisture content changes at QP
Figure 4-6: Average moisture content between QP and GC

Figure 4-7: Moisture content difference between QP and GC
Environmental changes of a typical day in each seasonal condition were showed in Figure 4-8 and Figure 4-9.

**Figure 4-8: Clear warm-dry day**

**Figure 4-9: Cloudy with drizzle day in cold-wet season**
As shown in Figure 4-8 and 4-9, the difference in temperature was clear between seasonal conditions. On the other hand, especially during night time, the differences in relative humidity and EMC value were similar – at least from 11 p.m. to 6 a.m. About one third of a day, the EMC was around 20% regardless seasonal condition or weather condition. In a sunny warm-dry day time, with the temperature of 20°C or higher, EMC can be as low as 10%. In a cloudy cold-wet day, EMC did not turn below 15%, and it kept about 20% level more than half the day.

Based on the trends shown in the Figures from 4-4 to 4-7, it is apparent that regardless target moisture content or seasonal conditions, moisture content values continuously decreased during the ambient equalization period. The reduction in moisture content and rate of change is illustrated in Table 4-5 (assuming their moisture content before equalization was $M_d$, and it decreased $x\%$ during ambient equalization, $x$ is listed as “Size of decrease” and $x/M_d$ is listed as “ratio of decrease”).

<table>
<thead>
<tr>
<th></th>
<th>Size of decrease</th>
<th>Ratio of decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>W12</td>
<td>2.0</td>
<td>17</td>
</tr>
<tr>
<td>W17</td>
<td>1.4</td>
<td>8.0</td>
</tr>
<tr>
<td>W22</td>
<td>1.0</td>
<td>4.8</td>
</tr>
<tr>
<td>C12</td>
<td>0.4</td>
<td>3.5</td>
</tr>
<tr>
<td>C17</td>
<td>0.8</td>
<td>5.2</td>
</tr>
<tr>
<td>C22</td>
<td>0.9</td>
<td>4.1</td>
</tr>
</tbody>
</table>
In W-group, the size of moisture reduction is greater than C-group, which is due to higher temperature, lower relative humidity and lower EMC value in warm-dry season. Moisture content decreases are observed in all runs even in a cold-wet season. As it was showed in Figure 4-9, due to high relative humidity, EMC value of timbers could be higher than 12%, which is the lowest target moisture content in this study, and it might result in some moisture gain. However, it is also known that moisture content change at a low temperature is very slow process, which might take months (Mazzanti and Uzielli 2009). Therefore, those decreasing trends in the cold-wet season are considered mainly due to the fact that packages included some high moisture content (under-dried) specimens as showed before. Moisture gains observed during ambient equalization were rather small amount while high moisture content timbers showed significant moisture losses after drying run. Therefore, the impact of moisture losses had larger impact on the mean value of moisture content changes.

4.4. Spatial trends in moisture content changes

Analysis of variance (ANOVA) was carried out in order to identify significance among moisture content changes during equalization periods. The results of the analysis indicated that regardless of target moisture content and seasonal conditions, it failed to find large enough impacts which show statistical significance. Since there were no significant difference found even between moisture content value of different target moisture content packages, this is considered a Type II, false negative error due to the small sample size and
high variance. However, aside from the pure statistical analysis, some trends can still be observed in the recorded moisture content changes.

4.4.1. Moisture content at GC

At GC (Figure 4-4), several different trends of moisture content changes were observed.

Firstly, there was no clear difference observed between W22 and C22. Their moisture stabilized around 22% after fourteen days, and did not go below that point. This indicates that ambient condition has small impact on moisture content changes at GC with target moisture content of 22%, and regardless ambient conditions, further quick, significant internal moisture redistribution or moisture content decrease at GC cannot be expected after this point. Also, it is worth mentioning that the moisture content value of 22% is higher than 19%, which is considered “dry” in several construction export standards or certifications (Western Wood Products Association, 2001). In other words, in fourteen days after the 22% drying run, moisture content of timbers at GC are stabilized but still generally considered under-dried and not appropriate for shipment.

Secondly, W12 and W17 showed the same trend in moisture content changes. Their moisture content decreased faster than the other runs with an overall decrease rate of about 0.27% moisture content per day. Rate changes were observed after around nine days. The rate was initially at 0.46% moisture loss per day; after nine days, it changed to about 0.14% moisture loss per day. This suggests that in a warm-dry season with target moisture content
lower than 17%, the surrounding area of GC remained at low enough moisture content level to allow constant moisture flow from GC during three weeks of ambient equalization period.

On the other hand, C12 and C17 showed very low but still decreasing trend in moisture content changes of about 0.07% moisture losses per day. There are two possible explanations for that trend: i) unlike the warm-dry season, moisture content distribution inside the specimen reached near equilibrium early, thus there was no major moisture movement occurred; ii) due to low temperature, the speed of moisture transportation itself, which is driven by diffusion, was slowed down.

4.4.2. Moisture content at QP

At QP (Figure 4-5), moisture content changed at half or lower rate compared to the ones at GC.

Firstly, the moisture content of C12 and C17 were almost constant or even increased during ambient equalization period. As a middle point between GC and surface, there are two factors which affect moisture content changes, namely, moisture flow from GC, and the one to the surface. In other words, the rate of moisture change at QP is determined by the speed of moisture movement between GC and QP and the one between QP and the surface. Also, moisture flow from GC to QP is considered to be a reason why moisture content reduction at QP is slower than at GC (as showed before, at GC, moisture
content losses were observed in the all cases. In other words, some moisture moved from GC to QP throughout ambient equalization).

Thus, the fact that the moisture content of C12 and C17 at QP increased is explained as moisture that moved from GC to QP was greater than the one moved from QP to the surface. Also, it is considered that the speed of moisture movement from QP to the surface is consequently determined by the one from the timber surface to the air (if the surrounding air is warm and dry, the surface area is also getting dry and has more capacity to allow some moisture moving from QP, and vice versa). Therefore, this moisture content increasing behavior observed in C12 and C17 is considered as a consequential result of the external wet air during ambient equalization period.

Secondly, in the case of W12 and W17, although the starting moisture content of W12 (16.7%) was lower than that of W17 (18%), W12 decreased at the rate of 0.13% moisture content per day which is faster than W17 whose drying rate was 0.06% moisture content per day. This suggests that the extremely over-dried surface which induces moisture redistribution from QP to the surface has larger impact than the effect of the ambient condition. In other words, because the target moisture content of W12 was very low, the timber thickness that is less than 25 mm was considered to be very dry right after exiting the kiln due to the convective drying mechanism. Thus, there was greater moisture content difference between QP and the surface which speeded up moisture redistribution between them.
Lastly, the trends of W22 and C22 were almost identical at QP, as they were at GC too. Also their moisture content stabilized at around 19.5% in twelve days after drying run, which is two days earlier than at GC. However, this does not mean there was no more moisture flow at QP after twelve days, but a dynamic equilibrium was attained after that.

At GC, moisture movement is unidirectional – GC to the outer area. On the contrary, at QP, some moisture flows in from at GC, and some moisture moves out from QP to the surface. Therefore, though moisture content value turned stable at QP in twelve days after drying, since there was still moisture content decreasing observed at GC, there was some moisture flow coming from GC to QP until moisture content at GC also reached equilibrium in fourteen days after drying. Thus, it can be concluded that during the extra two days from twelve to fourteen days after drying, moisture moved from QP to the surface as much as it moved from GC to QP. After all, this suggests that the moisture content distribution reaches equilibrium at about two weeks time, and deeper areas require more time to stabilize (to reach dynamic equilibrium) since stability of outer areas is required first.

4.4.3. Moisture content difference between QP and GC

In comparison to the accuracy of measurement method of their original values (0.1% resolution at best), since those difference values shown in Figure 4-7 are very small numbers that is, less than 4% at most, and mostly focusing 0.1% order changes, the values are considered to be strongly affected by errors of original moisture content values originated from their measurement procedure and statistical processing such as averaging;
therefore plots are a little skewed and spiking. However, as supplemental data, they show several interesting trends. In particular, it is worth mentioning that the level of 2.5% moisture content difference can be considered as an indicator of moisture content distribution stability because of the following trends.

Firstly, for W17, W22 and C17, the speed of moisture content reduction is slowed down below this point, and in the case of W22, this trend is particularly clear. The timing where W22 dropped below 2.5% was around two weeks, and it correlates with the one where its original moisture content both at QP and GC became constant. Also, in the cases of W12 and C12, these plots are mostly linear curves and they start from the point below 2.5%.

Secondly, in the case of C12 and C17, the moisture content relation between QP and GC were not so clear because their original moisture content plots waved and did not linearly decreased; however, plots of moisture content difference shows they moved to the way to reduce their moisture content difference at constant rate as other kiln packages did. It also clarifies the fact that regarding the speed of moisture content difference changes, there was no clear difference between seasonal conditions.

Lastly, in terms of moisture content difference itself, it reaches the 2.5% level earlier in the cold-wet season than in the warm-dry season. This is considered mainly due to moisture content stability (timber surface dries faster under high temperature) and moisture gain from outer area or wet surrounding air.
5. CONCLUSION

In this study, moisture content changes are examined with three different target moisture contents and two different seasonal conditions. The following conclusions are drawn in the light of this investigation for ambient conditioning.

1. With high target moisture content such as 22%, the moisture content values of packages were too high to be affected by seasonal conditions. Also, due to early equilibrium after two weeks with large amount of moisture, which is still considered under-dried, both further drying and internal moisture redistribution cannot be expected in a short term ambient conditioning such as less than a month; therefore it is not appropriate for the drying strategy with ambient conditioning.

2. In a cold-wet season, no major further drying is anticipated while some can be expected in a warm-dry season.

3. Seasonal condition has no major impact on internal moisture content difference between QP and GC and it does drop regardless outside ambient similarly.

4. It is considered that 2.5% is a threshold value to evaluate moisture content difference between QP and GC. Below that point, moisture content difference changes slowly, and linearly regardless seasonal condition or its current moisture content value.
Based on the observations of this preliminary study the following possible courses of action are recommended to the timber industry regarding the post-drying period:

1. Target moisture content of 22% or higher is not recommended, and regardless seasonal condition, timber core moisture content is higher than the level considered to be dry (19%) even after a month, and it would be too long to wait for further drying or further internal moisture redistribution which may happen more than a month after kiln drying.

2. Lower target moisture content clearly results both low moisture content and low moisture content difference but it results in longer drying times and higher energy consumption. To optimize drying strategy, further post-drying storage period can be relied on as a part of drying schedule. In the case of the same type of drying schedule which is used in this study, it is recommended to take six days in a cold-wet season, or about nine days in a warm-dry season, which are the length which the packages with target moisture content of 17% took to reach the moisture content difference level of 2.5% in this study, respectively.
REFERENCES


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