Schedule and Post-Drying Storage Effects on Western Hemlock Squares Quality

by

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Abstract

This study intends to explore the effects of two drying schedules with options of conditioning and post-drying storage on the drying speed and quality of western hemlock timbers.

Western hemlock (*Tsuga heterophylla*), the species of interest in this study, is one of British Columbia's most abundant tree species that accounts for 75 to 80% of British Columbia's exports to Japan. It is usually combined with amabilis fir (*Abies amabilis*) for processing and economical purposes. Hemlock is difficult to dry due to its compression wood, wetpockets and large spread of initial moisture content and basic density. Consequently, it seems practical to dry hemlock by itself.

In this study, hemlock was dried using two different schedules with optional conditioning and optional seven day post-drying storage in a covered and climatized space. These eight experimental runs were compared to a control run, which utilized an established drying schedule. To assess the kiln dried timber quality, twist, diamonding, and checks were evaluated using pre-drying and post-drying and/or post-storage measurements. Drying times and casehardening were also considered.

Data analysis and evaluation illustrated that conditioning and the harsher schedule reduced casehardening, while the milder schedule developed less twist and diamonding. Even though it appears that the control run developed less shape distortions than the treatment runs, the control run required longer drying times. When using the harsher schedule the kiln was immediately available for the next run, and the dried timber could be stored in a covered area in order to level out the moisture gradients and alleviate casehardening. As a subsequent step, the timber could be planed to reduce twist, diamonding and superficial checks.

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DBH	diameter at breast height [mm]
KD	kiln dry
M	moisture content [%]
PR	degree of casehardening [1/mm]
W	prong tip distance before cutting [mm]
W'	released prong tip distance [mm]
L	prong length [mm]
W_{actual}	actual weight [g]
$W_{oven\text{-}dry}$	ovendry weight [g]
W_{green}	green weight [g]
EMC	equilibrium moisture content [%]
T	temperature [°C]
WB	wet-bulb temperature [°C]
DB	dry-bulb temperature [°C]
RH	relative humidity [%]
"Control"	control run
"C"	control run
"I c ns"	schedule I, with conditioning, no storage
"I nc ns"	schedule I, no conditioning, no storage
"II nc ns"	schedule II, no conditioning, no storage
"II c ns"	schedule II, with conditioning, no storage
"I c s"	schedule I, with conditioning, with storage
"I nc s"	schedule I, no conditioning, with storage
"II c s"	schedule II, with conditioning, with storage
"II c ns"	schedule II, with conditioning, no storage
F_o	calculated F-value
F_{crit}	critical F-value
t_{calc}	calculated t-value
t_{crit}	critical t-value
n	number of replications
k	number of treatments
DF	degrees of freedom
SS	sum of squares
MS	mean squares
A	factor A (schedule)
B	factor B (conditioning)
C	factor C (storage)
H_o	null hypothesis
H_a	alternative hypothesis
st. dev.	standard deviation
Min	minimum value
Max	maximum value
M_i	initial moisture content

M_{final}	final moisture content
M_{KD}	kiln dry moisture content
ANOVA	analysis of variance
ANCOVA	analysis of covariance
Pr	probability
calc	calculated
sig. diff.	significant difference
M_{core}	moisture content of core
M_{shell}	moisture content of shell
FSP	Fiber saturation point
SOG	slope of grain

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Dedication

For my Family:
Ulrike and Jörg,
Kirsten and Toby
and
Zoran

1. Literature Review

1.1 Introduction

When timber is cut from trees it contains large quantities of water and if used in its wet condition, it will dry out while in service. When wood dries below a moisture content of about 30%, it will start to shrink. Uncontrolled shrinkage might result in defects that could affect performance; therefore, in order to avoid this unwanted shrinkage during service, timber is dried before it is used in construction or further manufacturing. Drying is costly and has to be carried out carefully according to timber species, dimensions, potential value and various applications.

For hardwoods and softwoods the conventional heat-and-vent kiln drying is the most common drying method. In general, a conventional kiln is a large insulated structure, where lumber is placed inside in specific packs made of lumber rows separated by stickers. Warm air is circulated by large fans mounted on the overhead fan deck of the kiln. Heating coils are positioned at the top or side of the kiln to regulate air temperature and roof or side wall vents open and close in order to control the relative humidity of the kiln interior. Specific sets of air temperature, relative humidity and air velocity, as a function of time called drying schedule, are commonly used.

In British Columbia, western hemlock (*Tsuga heterophylla*) is one of the most abundant species. It is usually harvested, processed, dried and manufactured together with amabilis fir (*Abies amabilis*). However, western hemlock is more difficult to dry than fir because it can contain wetpockets, which are areas of very high moisture content. The mix of hemlock and fir can show a large spread of initial moisture content and basic density which make a uniform final moisture content hard to achieve. Therefore, attempts have been made to dry those two species separately.

In this study, hemlock was dried alone using different drying strategies as well as, a seven day post-drying storage option, to investigate if its quality improved compared to standard industrial practice.

1.2 Hemlock

1.2.1 Anatomical and physical properties

Western hemlock (*Tsuga heterophylla*) is a large tree (30 to 50m tall) with a diameter at breast height (DBH) of up to 2m or more. The tree has a rather narrow crown and shows feathery foliage on down-sweeping branches, while new growth on top of the tree hangs down and gives the hemlock its distinct shape, as shown in Figure 1.1 (WWPA, 1997; B.C. Ministry of Forests, 2001; Earle, 2002). Due to the competition for sunlight, the lower branches die and fall off which produces a clear trunk up to ¾ of the tree's height (WWPA, 1997).

Figure 1.1 has been removed due to copyright restriction.
The information removed is a picture of a hemlock tree and
can be found at: B.C. Ministry of Forests. 2001.
Tree book. Learning to recognize trees in British Columbia 154p.

Figure 1.1: The Western hemlock tree (B.C. Ministry of Forests, 2001)

Hemlock grows along the Pacific coast, extending north from central California to the Kenai Peninsula in Alaska (Burns and Honkala, 1990; WWPA, 1997; Earle, 2002). Also, hemlock grows along the east and west side of the Coast Mountain Ranges (B.C. Ministry of Forests, 1999; Earle, 2002) and the interior wet belt west of the Rocky Mountains (Burns and Honkala, 1990; B.C. Ministry of Forests, 1999) as seen in Figure 1.2. Hemlock is the dominant tree species in British Columbia (Burns and Honkala, 1990) and prefers mild and humid areas (Burns and Honkala, 1990; WWPA, 1997) from sea level to mid elevations (B.C. Ministry of Forests, 1999).

Figure 1.2 has been removed due to copyright restriction.
The information removed is a map of North America showing the geographic distribution of western hemlock and can be found at: Little, E.L., Jr. 1971. Atlas of United States Trees, Volume 1, Conifers and important Hardwoods: U.S. Department of Agriculture Miscellaneous Publication 1146, 9 p., 200 maps. The second map showed the geographical distribution of western hemlock in British Columbia and can be found at: B.C. Ministry of Forests. 2001. Tree book. Learning to recognize trees in British Columbia 154p.

Figure 1.2: Western hemlock distribution in Western North America (Little, 1971), and in B.C. (B.C. Ministry of Forestry, 2001)

Hemlock is strong and at the same time, a beautiful wood, which makes it popular in the building industry (WWPA, 1997). The appearance of hemlock varies from a creamy white colour to a light, straw like colour with only a slight variation between sapwood and heartwood. Sometimes the colour is slightly purplish (WWPA, 1997; Earle, 2002) and even after exposure to sunlight, the colour will not darken like most other woods do (WWPA, 1997; Earle, 2002). In addition, hemlock wood shows smooth grain (B.C. Ministry of Forests, 2001).

Hemlock has a basic density ranging from 470 to 490kg/m^3 (macroHOLZdata, 2002; Coast Forest Products Association, 2003; Mullins, et al., 1981) and shows an average volumetric shrinkage of 13.0% (Mullins and McKnight, 1981). The literature cites an average Modulus of Elasticity (MOE) varying from 10,000MPa to 12,300MPa (macroHOLZdata, 2002; Coast Forest Products Association, 2003; Mullins and McKnight, 1981). For physical properties of hemlock please see Table 1.1.

Table 1.1: Physical and chemical properties of Western hemlock (from: [1]macroHOLZdata, 2002; [2]Coast Forest Products Association, 2003; [3]Mullins, et al., 1981; [4]Earle, 2002)

Wood Property:	**Value:**
Density	470 to 490kg/m^3 (1,2,3)
Tangential Shrinkage	5.5%(1), 7.8%(2), 8.5%(3)
Radial Shrinkage	3.2%(1), 4.2%(2), 5.4%(3)
Volumetric Shrinkage	13.0%(3)
Modulus of Elasticity (Stiffness, MOE)	10,000MPa(1), 12,300MPa(2, 3)
Modulus of Rupture (Bending Strength, MOR)	75MPa(1), 81.1MPa(2, 3)
Tensile Strength	68MPa(1)
Compression Strength	45MPa(1)
Parallel to the grain	46.7MPa(2, 3)
Perpendicular to the grain	4.5MPa(2), 4.53MPa(3)
Tension Perpendicular to the grain	2.93MPa(3)
Shear Strength	7.8MPa(1), 6.5MPa(2), 6.48MPa(3)
Impact Bending Strength	45Kj/m^2 (1)
Hardness	2740N(2)
Tannin Content	High in the bark(1)
Ash Content	0.3%(3)
Lignin Content	27.8%(3)
Pentosans	9.2%(3)

1.2.2 Uses and economic importance

Hemlock wood shows a smooth grain and resists scraping which makes it easy to machine (WWPA, 1997; B.C. Ministry of Forests, 1999; Coast Forest Products Association, 2003). Furthermore, its strength and nailing characteristics make it a popular construction material in North America and overseas (Burns and Honkala, 1990; WWPA, 1997; Coast Forest Products Association, 2003). For instance, hemlock is used as a framing material for multi-story buildings. As a result of its strength properties, the lumber is able to cover long open spans in buildings or bridges. When dried, hemlock shrinks very little and is ideal for all kinds of climates (WWPA, 1997). The wood is also widely used for doors, windows, parts of staircases, ladders, pilings, poles and railway ties (Burns and Honkala 1990; B.C. Ministry of Forests, 1999). In general, western hemlock is a very important commercial tree species that works as an all purpose raw material (Burns and Honkala, 1990). In addition, pressure treatment makes it adaptable for outdoor uses like decks (Burns and Honkala, 1990; WWPA, 1997; Coast Forest Products Association, 2003). Finally, hemlock even has excellent pulping characteristics for Kraft and sulfite pulps (Burns and Honkala, 1990).

In the early 1960's, British Columbia experienced an increase in the export of lumber which was mostly 105 x 105mm (4x4inch) hemlock as J-Grade CLS in 2x4 housing to Japan (Barclay, 1997). This made Japan the second largest export lumber market for hemlock after the United States. Japan is also British Columbia's largest overseas export market with 75 to 80% (Barclay, 1997). Canadian hemlock maintains a steadier quality than American hemlock (Anonymous, 1999).

1.2.3 Housing in Japan

The Japanese housing market is very important to British Columbia's economy, since it strongly influences the export volume of hemlock lumber to Japan. In 1996, Japan's building market was worth US$676 billion, larger than the United States' value of US$406 billion (Barclay, 1997). Japan's housing starts have been between 1.4 and 1.7 million a year since 1987, which is even higher than United States' housing starts even though Japan has only about one third of the United States' population (Barclay, 1997). Moreover, Japan has the highest number of housing starts in the world at 12.8 per 1000 people, compared to the United States with only 5.7 per 1000 in 1997. Since 2000, the housing starts in Japan were around 1.2 million per year (Ministry of Infrastructure, Land and Transportation, 2003; American Forest & Paper Association, 2004; USDA Foreign Agricultural Service, 2005; Yahoo! Asia News, 2006). Cohen and Gaston (2003) forecasted a decrease in housing starts of 0.85 to 1 million new houses per year from 2006 to 2010 and an even further decrease of 0.75 to 0.9 million housing starts yearly from 2011 to 2015. The proportion of wood framed houses increased to 45.5% of the total housing starts of 1,189,049 units in 2004, which is a total increase of 2.5% for wooden housing starts (SEC, 2005). Figure 1.3 shows 83% of housing starts in 1980 were wooden, but this number decreased over 10 years to about 41% (Matsumura and Murata, 2005). During the last four years the wooden housing starts have been levelling off to about 45% of all housing starts (Matsumura and Murata, 2005; Ministry of Infrastructure, Land and Transportation, 2003; American Forest & Paper Association, 2004; USDA Foreign Agricultural Service, 2005). The wooden housing market in Japan has had a major influence on the demand for lumber due to the fact that 80% of all lumber is being used in construction (Matsumura and Murata, 2005).

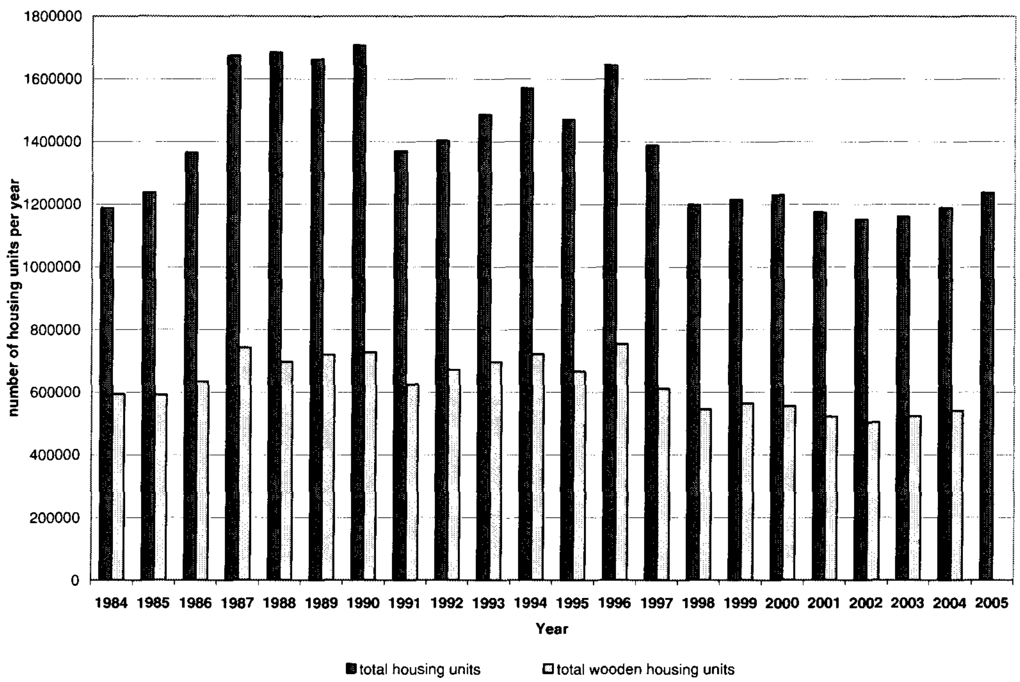


Figure 1.3: Number of housing starts and the wooden house rate in Japan (Numbers are taken from Table 1.2).

The 2x4 platform frame system is currently used for wooden houses in increasing numbers (Barclay, 1997). In 2004, the 2x4 style increased by 11% to 90,706 units, while the post and beam style increased by 2% to 427,726 units, compared to the previous year (SEC, 2005). The use of kiln dried lumber has increased from 2001 to 2003 by 59.2%; with an increase of 54.0% for sill and 44.8% for posts (Roos and Eastin, 2003). For more detailed numbers for the Japanese housing starts please see Table 1.2.

After the 1997 recession in Japan, the volume for hemlock timber exported to Japan started to decrease drastically, from 1.1 billion fbm (foot board measure) hemlock products in 1995 to 404 million fbm in 2002 (Zeek, 2003). Reasons included increased prices and the preference for dried lumber over green lumber. However, supplying kiln dried lumber has been economically difficult because of the complexity of drying hemlock due to wet pockets, compression wood, high cell density, and its tendency to twist (Zeek, 2003).

The trend for hemlock in construction has been moving away from green lumber and moving towards the kiln dried material to supply higher quality housing (Anonymous, 1999; Zeek, 2003). The export of American hemlock from the United States has decreased from 1,144,337m^3 in 1989 to 482,611m^3 in 1998.

Traditionally, the Japanese prefer wood as a building material compared to steel and concrete (Barclay, 1997; Lam et al., 2001). Wood has been used in most of Japan's construction for over 3,000 years. Moreover, trees and lumber, as building materials, were and are treated with great respect (Cohen and Gaston, 1996). In post and beam construction, as shown in Figure 1.4, which is commonly used for single family housing, the posts (Hashira) and sills (Dodai) have a cross section of 105mm by 105mm (Lam et al., 2001). Wood species commonly used in these applications are sugi (*Cryptomeria japonica*), which is grown locally and hemlock, which gets imported from North America (Lam et al., 2001). Figure 1.3 shows the number of wooden housing starts compared to the total housing starts in Japan from 1984 to 2005.

Japan's housing starts are not based on population growth, since its population only grows by 0.5% per year and growth is predicted to continue to decrease. However, housing starts are based on replacing existing housing (Barclay, 1997). Most houses were built after World War II and were never meant to last (Barclay, 1997; Cohen and Gaston, 1996). The new houses are more comfortable and have a much higher quality; they are meant to last (Barclay, 1997; Cohen and Gaston, 1996). Most new homes also have 15% more floor space than 10 years ago (Barclay, 1997; Cohen and Gaston, 1996).

In order to cut down on high building costs and shorten construction times, it is more popular to use factory pre-cut building components (post and beam construction) which are being assembled on site instead of the traditional craftsman built houses (Barclay, 1997; Matsumura and Murata, 2005). In 1996, more than 800 pre-cut factories existed in Japan which are machining an estimated 3.7 million m^3/year of lumber; they have become a major part of the Japanese wood industry (Matsumura and Murata, 2005). Table 1.2 shows the exact numbers of pre-cut houses compared to total housing starts from 1984 to 2005.

Table 1.2: Japanese Housing Starts from 1984 to 2005 (from: [1] Ministry of Land, Infrastructure and Transportation, 2003; [2] Yahoo! Asia News, 2006; [3] USDA Foreign Agricultural Service, 2005; [4] Cohen, et al. 2003; [5] American Forest & Paper Association 2004; [6] calculated from existing numbers)

Japanese Housing Units from 1984 to 2005								
						pre-fabricated housing		
Year	total housing units	% previous year	total wooden housing units	wooden as % of total units	post & beam	Wooden	Total	2x4 housing
1984	1187282 [1]	104.4 [1]	594144 [1]	50.0 [1]	535442 [1]	37661 [1]	162833 [1]	21041 [1]
1985	1236072 [1]	104.1 [1]	591911 [1]	47.9 [1]	522569 [1]	43344 [1]	177842 [1]	25998 [1]
1986	1364609 [1]	110.4 [1]	633858 [1]	46.4 [1]	549033 [1]	52642 [1]	203365 [1]	32183 [1]
1987	1674300 [1]	122.7 [1]	741552 [1]	44.3 [1]	631543 [1]	67824 [1]	247455 [1]	42185 [1]
1988	1684644 [1]	100.6 [1]	697267 [1]	41.4 [1]	593756 [1]	71647 [1]	218716 [1]	31864 [1]
1989	1662612 [1]	98.7 [1]	719870 [1]	43.3 [1]	640348 [1]	31950 [1]	211210 [1]	47572 [1]
1990	1707109 [1]	102.7 [1]	727765 [1]	42.6 [1]	642102 [1]	34570 [1]	219186 [1]	51093 [1]
1991	1370126 [1]	80.3 [1]	624003 [1]	45.5 [1]	545366 [1]	33200 [1]	219774 [1]	45437 [1]
1992	1402590 [1]	102.4 [1]	671130 [1]	47.8 [1]	580799 [1]	37398 [1]	252398 [1]	52933 [1]
1993	1485684 [1]	105.9 [1]	697496 [1]	46.9 [1]	603666 [1]	37531 [1]	246108 [1]	56299 [1]
1994	1570252 [1]	105.7 [1]	721431 [1]	45.9 [1]	619103 [1]	38291 [1]	2273311 [1]	64037 [1]
1995	1470330 [1]	93.6 [1]	666124 [1]	45.3 [1]	554690 [1]	37445 [1]	224758 [1]	73989 [1]
1996	1643266 [1]	111.8 [1]	754296 [1]	45.9 [1]	619027 [1]	41575 [1]	251296 [1]	93694 [1]
1997	1387014 [1]	84.4 [1]	611496 [1]	44.1 [1]	498023 [1]	34015 [1]	206532 [1]	79458 [1]
1998	1198295 [1]	86.4 [1]	545133 [1]	45.5 [1]	447287 [1]	29923 [1]	182399 [1]	67923 [1]
1999	1214601 [1]	101.4 [1]	564524 [1]	46.5 [1]	457126 [1]	31534 [1]	185724 [1]	75864 [1]
2000	1229833 [1]	101.3 [1]	555814 [1]	45.2 [1]	446359 [1]	30341	175069 [1]	79114 [1]
2001	1173858 [1]	95.4 [1]	522823 [1]	44.5 [1]	418402 [1]	27186 [1]	165257 [1]	77235 [1]
2002	1151016 [1]	98.1 [1]	503761 [1]	43.8 [1]	401029 [1]	23744	160871 [1]	78988 [1]
2003	1160083 [5]	100.8 [6]	523192 [5]	45.1 [5]		23264 [5]		81502 [5]
2004	1189049 [3]	102.5 [6]	541017 [6]	45.5 [3]		22304 [3]	159930 [3]	90706 [3]
2005	1236122 [2]	104.0 [6]						
expected housing starts in Japan:								
2006 - 2010		0.85 to 1 million per year [4]						
2011 - 2015		0.75 to 0.9 million per year [4]						

1.3 Wood drying

1.3.1 Water in wood

Wood moisture content (M) is a measure of the amount of water in the wood. It is usually expressed as a percentage of dry weight using the following equation (Kollmann, 1951; Kollmann and Côté, 1968; Panshin, 1964; Skaar, 1972, Siau, 1984):

$$M[\%] = \frac{Weight_{actual} - Weight_{oven-dry}}{Weight_{oven-dry}} * 100 \qquad (1)$$

Every living tree contains water that is stored in the wood in two phases, namely "bound" and "free". The bound water is attached to the hemicellulose and to the cellulose's amorphous regions in the cell walls by hydrogen bonds, while the free water is located in the cell lumens, see Figure 1.4. After a tree is cut down, the wood soon begins to dry; the free water is the first to leave the cells during the drying process as it evaporates.

Figure 1.4 has been removed due to copyright restrictions. The information removed is a picture of wood cells indicating the free water located in the lumen and bound water in the cell walls. This picture can be found at: Anonymous b. Http://cfquesnel.com, accessed August 07, 2007

Figure 1.4: Section of a wood cell showing water in liquid and chemically bound stages (Anonymous b, cfquesnel.com, 2007)

The point when all the free water is removed from the lumens, but the cell walls are still saturated is defined as the fiber saturation point (FSP) which for temperate zone wood species is at approximately 30% moisture content. Drying wood below fiber saturation point, removes the water molecules that were attached to the cell walls. By removing those chemically bound molecules, the cell walls begin to shrink. Cell walls do not shrink evenly due to its multi layered composition and different slopes of the cellulose bundles in its layers. This uneven shrinkage induces stress in the wood. The moisture content of the final product not only depends on the targeted dry moisture content but also on the temperature and relative humidity of the environment it is going to be used in. The wood loses or gains moisture according to changes of the external temperature and relative humidity until it reaches an equilibrium , the so called equilibrium moisture content (EMC) (Culpepper, 1990; Hartley and Marchant, 1988; Haygreen and Bowyer, 1996; Kuroda, 1996; Reeb, 1995; Reeb, 1997; Siau, 1984; Skaar, 1972).

Considering all the steps involved with wood products processing, the drying of lumber is often the most expensive step, as well as, the most time and energy consuming one. The time spent on drying depends on the anatomical structure of the species dried along with the timber dimensions and the drying schedule used. Each schedule consists of a sequence of temperature and humidity combinations which can be customized for each kiln load. Usually, the faster lumber is dried, the more likely it is to develop drying defects. The art of drying is to develop a schedule that will remove the free and some of the bound water fast, but still result in superior product qualities. Too many drying defects would decrease timber quality and value (Simpson, 1991; Reeb, 1997).

1.3.2 Reasons for drying wood

Traditionally, timber has been dried to ensure dimensional stability and predictable physical properties, dry timber is also lighter and thus easier to handle and transport than wet timber and specifically, decreased weight reduces land shipping costs. Coatings are easier to apply to dry lumber. Furthermore, dried lumber is easier on the cutting tools of the machines for remanufacturing. Dry wood does not decay as easily if it is properly treated and inhibited from gaining moisture again. As a result, the service life of lumber is increased substantially by drying, which also plays an important role in preserving the forests.

Each wood species has different drying properties and even within a species there are notable differences; for example, green moisture content distribution and basic density distribution. The goal of each company is to increase its throughput and revenue (Bachrich, 1980; Simpson, 1991; Reeb, 1997).

In addition, it is very important to dry the lumber for construction, furniture or flooring to the moisture content corresponding to the environment it is being used in order to avoid shrinkage or swelling which would cause cracks and stresses to develop (Hartley and Marchant, 1988; Haygreen and Bowyer, 1996; Kuroda and Choon, 1996; Reeb, 1997).

1.3.3 Difficulties in drying hemlock

Drying thick hemlock to uniform final moisture content is very difficult (Zhang et al. 1996). Furthermore, with wet pockets present in the timber, drying difficulty increases and costly defects could appear (Mackay and Oliveira 1989). Wet pockets are also referred to as "wet wood", "sinker stock", and "heavy wood" (Kozlik, 1970; Simpson, 1991; Chafe, 1996; Cooper and Jeremic, 1998) or less often as "sinker heartwood" (Kozlik, 1970; Warren, 1991) and add to drying difficulties. Some hardwoods like poplar, oak, elm, beech and maple, as well as some softwoods, like hemlock, redwood, some pines and true firs are prone to develop wet pockets (Simpson, 1991; Cooper and Jeremic, 1998). The reason why wet pockets are common in these species is probably due to their way of branch shedding (Schroeder and Kozlik, 1972) and their way of healing themselves when they get injured (Cooper and Jeremic, 1998).

Wet pockets are a type of heartwood that has a higher moisture content than the surrounding wood cells (Chafe, 1996; Cooper and Jeremic, 1998). The cell lumens are filled with water and contain hardly any air which sometimes can make the wood sink in water (Simpson, 1991). Wet pockets are also infested with bacteria that change its physical biological and chemical properties (Bauch et al., 1975; Schink and Zeikus, 1981; Ward and Pong, 1980). Wet wood appears in the longitudinal direction of the stem in conical form or as pockets (Kozlik, 1970) while in hemlock it may appear in form of stripes or streaks of up to 60mm wide. It usually has a darker colour and a wetter appearance than the neighbouring wood (Cooper and Jeremic, 1998; Kozlik, 1970).

Wetwood dries very slowly and is prone to collapse at the early stages of drying when liquid water is present in its lumens (Simpson, 1991). Moreover, wide variations in final moisture content are quite common. Some researches have found a range from 8% to 25% when drying hemlock to a target moisture content of 19% (Abner, 1964; Dedman and Vandusen, 1965; Kozlik 1963). Besides a wide range in final moisture content and drying defects like ring shake (Kozlik, 1970; Warren, 1991) and pit shake (Kozlik, 1981), hemlock with wet pockets also has a slower drying rate (Chafe, 1996) that might be due to increased pit aspiration which reduces permeability and fluid flow. Furthermore, there might be a reduction in the diffusion coefficient due to deposits of extractives and other incrustations on the pit membranes (Bramhall and Willson, 1971; Comstock, 1965; Kozlik, 1970; Krahmer and Cote, 1963).

With the logging of large volumes second growth hemlock in British Columbia comes an increase in the percentage of juvenile wood due to the smaller diameter of the trees. Increased juvenile wood in a timber can cause a predisposition for twist and surface checks due to uneven shrinkage. Juvenile wood shows inconsistent density and higher longitudinal shrinkage due to a greater fibril angle in the S_2 layer of the cell wall. Since juvenile wood is difficult to distinguish from mature wood, its only visual indicator is the presence of the pith on the cross section of the timber (Bradic and Avramidis, 2007).

According to Bradic and Avramidis (2006) the presence of compression wood does not have a significant influence on the quality of the dried hemlock.

1.3.4 The conventional kiln

Wood is termed “kiln dried” or “KD” when it is dried in an insulated chamber with air circulation of controlled temperature and relative humidity (Reeb, 1997). The most common dry kiln is the heat-and-vent kiln or conventional (sometimes also called “convective”) drying kiln, that has a very flexible design system. These kilns can be side loaded by using a forklift or front loaded by using carts on tracks. A conventional kiln can be very large in sawmills with a high throughput or rather small for small remanufacturing operations (Reeb, 1997; Anonymous, 2001).

Figure 1.5 shows a schematic of a heat-and-vent kiln. Large axial fans are used to circulate the heated air through stickered loads of lumber. The fans are usually reversible to dry the load uniformly. In order to force the air to flow through the timber load, baffles are used at the top, bottom and ends of the kiln (Simpson, 1991; Reeb, 1997; Anonymous, 2001).

Figure 1.5 has been removed due to copyright restriction. The information removed is a schematic of a heat-and-vent- kiln that is being loaded from the side. All necessary parts of the kiln are labelled. The schematic can be found at: Simpson, W. T. 1991. Dry Kiln Operator's Manual. Forest Products Society. 274 pp.

Figure 1.5: Schematic of a conventional heat-and-vent kiln being loaded from the side (Simpson, 1991)

The water evaporating from the wood surface during drying raises the humidity of the air. During the drying process, the air becomes more humid and when it exceeds the drying schedule specified, maximum humidity air vents in the roof open (low pressure side of fans) to release the warm, moist air. By opening another set of vents, cool drier air is brought in to continue the drying process. This cooler air has to be warmed up in order to keep the temperature in the kiln constant. Steam, gas, oil or electricity is used to heat the kiln's air (Kollmann, 1955; Simpson, 1991; Reeb, 1997; Anonymous, 2001).

Figure 1.6 has been removed due to copyright restriction. The information removed is a photograph of a front loaded aluminum drying kiln. It can be found at: Anonymous a. http://muehlboeckcanada.com/products_kilns_track_kilns.htm; accessed: October 5th, 2007

Figure 1.6: Front loaded drying kiln (Anonymous a, http://muehlboeckcanada.com/products_kilns_track_kilns.htm)

By changing the air velocity, the temperature or the relative humidity in the kiln during the different drying steps, the drying speed can be controlled. Temperature and relative humidity are monitored by electronic dry-bulb and wet-bulb thermometers; the higher the wet-bulb depression the faster and harsher is the drying (Simpson, 1991). Kang and Hart (1997) found that higher temperatures lead to increased drying rates only at low moisture contents, but not so much at high moisture contents. Harsh drying schedules usually lead to higher degradation of the lumber due to drying stresses. The effect of these drying stresses may be reversed by conditioning the lumber at the end of its drying cycle. Nogi et al. (2003) observed, that in order to relieve the residual stress in lumber, the temperature has to be above 80°C for at least 15 hours and this only works when moisture and heat both exist in the lumber. The stress relaxation in an experiment using Japanese cedar (*Cryptomeria japonica*) was associated with lignin softening as well as degradation of the matrix substance in the cell walls.

1.3.5 Moisture content gradient

The drying of timber is a continuous process which can be split into three distinct stages as shown in Figure 1.7. In the first stage (Figure 1.8 a) the timber is wet and filled with bound and liquid water, and is consequently above FSP.

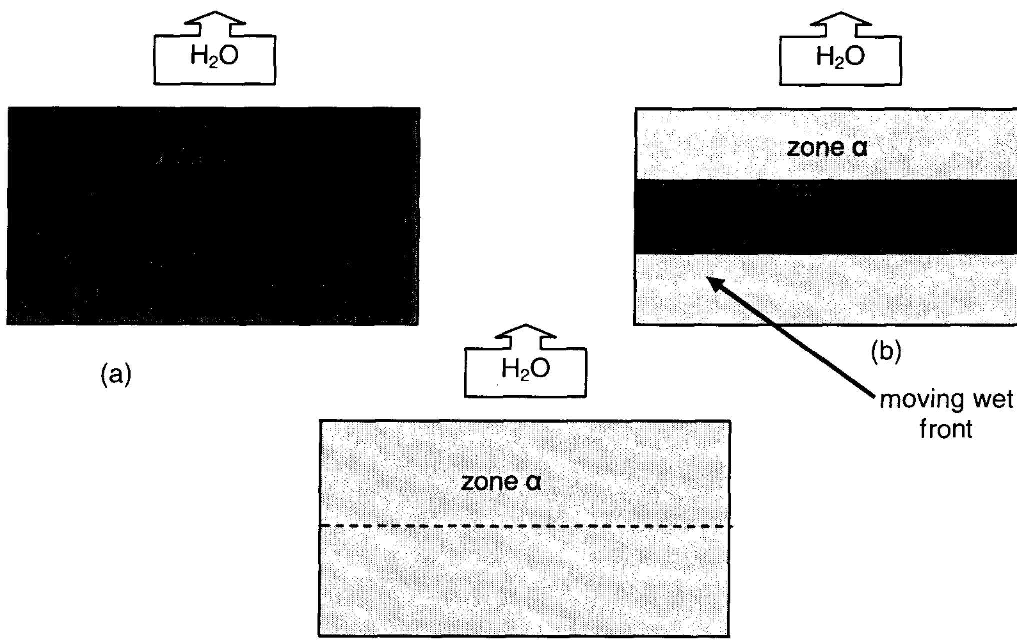


Figure 1.7: Moving wet front in timber cross-section during drying process

During this period, there is a flow of liquid water from the centre of the timber to its surface. The water evaporates very quickly on the timber's surface and high air velocities are needed to transport the evaporated water away from the timber. The limiting factor on the drying time during this stage is the permeability of the wood itself. Once the surface has dried out, the wet front moves further into the timber. The surface forms a dry layer (Zone A) and a still wet core (Zone B) which can be seen in Figure 1.8 b. When the moisture content moves from above FSP to FSP and then below, the drying process is slowied down. Zone A dries by diffusion and the timber begins to shrink on the outside, while Zone B still shows water flow. During the last stage of drying, only Zone A is present in the timber (Figure 1.8 c). The water is transferred only by diffusion at this point and the drying process slows down even more. Stresses are being generated in the timber due to more shrinkage. The three stages of drying can also be shown in terms of drying rate as seen in Figure 1.8 where the constant rate period represents the first stage The second stage corresponds to the 1st falling rate period and the 2nd falling rate period is the last stage of the process (Henderson, 1951; Pratt, 1974; Bachrich, 1980; Brunner-Hildebrand, 1987; Forest Products Laboratory, 1999; Traub, 2005).

Figure 1.8 has been removed due to copyright restriction. The information removed is a graph showing the constant rate period, 1st falling rate period and 2nd falling rate period as drying rate over moisture content. The graph is adapted from Jankowsky, I.P., dos Santos, G.R.V. 2005. Drying behaviour and permeability of Eucalyptus grandis lumber. Maderas. Ciencia y tecnologia, 7(1): 17 – 21.

Figure 1.8: Drying rate curve with drying periods (after Jankowsky and dos Santos, 2005)

The drying rate curve shows dM/dt, which is the drying rate of the lumber versus the average moisture content during a drying run. It illustrates the decrease of moisture content in the lumber during all three stages of drying. The drying rate curve plots the derivative of the drying curve over the moisture content. The stages of drying are easier to identify on this drying rate curve than on the drying curve. It is possible to manipulate the drying rate by changing the temperature, humidity and air velocity during the three periods of drying (Jankowsky and dos Santos, 2005).

The moisture content of the timber core is usually higher than that of the shell during drying and for some time afterwards. The cross sections of a piece of lumber during drying indicates a characteristic moisture gradient profile, as seen in Figure 1.9.

Figure 1.9 has been removed due to copyright restriction. The information removed shows a graph of a timbers cross section with moisture content levels across the timber at three different times. The graph can be found at: Forest Products Laboratory. 1999. Wood Handbook – Wood as an engineering material, Gen. Tech. Rep. FPL-GTR-113, Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 463 p.

Figure 1.9: Moisture content gradient as seen from timber cross section (Forest Products Laboratory, 1999)

The gradient develops because the shell dries much faster than the core. During the constant rate period, the gradient is the steepest since the free water from the shell is removed much faster than the free water from the core. The gradient loses its steepness during the first and second falling rate period. At the end of a typical drying schedule the core has a higher moisture content than the shell, which is of no significance if large pieces of lumber are being used in construction. However, if the dried wood is being cut in smaller sizes for remanufacturing, the moisture content of the wood (core) might be too high or the stresses too large. It is possible to reduce this difference between core and shell by conditioning the lumber at the end of the drying cycle (Brunner-Hildebrand, 1987; Simpson, 1991; Reeb, 1997).

1.3.6 Relative humidity and temperature effects on drying

Temperature and relative humidity are carefully controlled during the drying process by a computer. The dry-bulb temperature indicates the air temperature inside the kiln; this information is fed into the computer and compared to the dry-bulb set point temperature of the chosen drying schedule. The computer then opens or closes the heat valve connected to the heating pipes, accordingly. To control the humidity, the dry-bulb temperature is used in combination with the difference of dry-bulb and wet-bulb, the so called wet-bulb depression. The wet-bulb temperature is measured by an electronic thermometer that has a constantly wet wick, which is a piece of cloth that is wrapped around the thermometer's tip. The wet-bulb thermometer is cooled as the water evaporates from the wick. The lower the measured wet-bulb temperature (a large wet-bulb depression), the higher the evaporation rate and the drier the kiln environment. A computer program monitors the temperatures and compares it to the temperatures stipulated by the drying schedule. The opening and closing of the vents or the steam/water spray are coordinated by the software according to the requirements of the drying schedule. High temperatures in the kiln increase the speed of drying, while lower temperatures dry the timber slower and are used in mild drying schedules. When the kiln has a low relative humidity it causes the moisture in the timber to move faster in order to decrease the difference of inside/outside moisture. In contrast, higher relative humidity dries the timber more carefully (Simpson, 1991; Reeb, 1997; Anonymous, 2001).

Figure 1.10 has been removed due to copyright restriction. The information removed is a picture of stickered stacks of lumber. It can be found at: Anonymous c. (http://www.timber.org.au/NTEP/menu.asp?id=86), accessed October 5th, 2007

Figure 1.10: Timber piled ready to go into the kiln (Anonymous c, http://www.timber.org.au/NTEP/menu.asp?id=86)

The air velocity in a conventional kiln is controlled by the speed of the fans fixed to the kiln's upper deck. The air flow in a kiln is influenced by the shape of the kiln chamber and the shape of the timber pile. Properly stacked and positioned timber guarantees a constant and even airflow throughout the timber pile (Figure 1.10). Kollmann and Schneider (1960) found that the effect of air velocity changes to be most significant when the lumber still had a high moisture content, usually labelled as the constant rate period of drying. Higher air velocities induced faster drying since the evaporated water molecules escaped from the lumber surface a lot quicker, making room for more evaporating water. At the same time, the positive effect of a higher air velocity decreases continuously during the falling rate period and finally becomes insignificant. The critical point at which the air velocity becomes insignificant with the drying rate varies with the species, board thickness and initial moisture content. However, changes in the air velocity did not affect total energy consumption of the kiln or the strength properties of the lumber dried.

1.3.7 Stresses and degrade

There are two primary causes of drying degrade: hydrostatic tension and differential shrinkage. Capillary water and its flow is the main reason for hydrostatic tension forces. By water evaporating from cell lumens near the surface of the wood, a force is applied on the water in the cell lumens which are deeper in the wood. This tension might cause the caving in of the water filled cell lumens by applying a suction on the cell walls. This phenomenon mainly occurs during the early drying stages when many cell lumens are still filled with water and is more likely to occur if early drying temperatures are high (Simpson, 1991).

Drying defects are caused by the differential shrinkage between the shell and the core of lumber. The fibres in the shell dry early in the drying process and consequently begin to shrink; however, the drying and shrinking of the core has not yet started and thus prevents the shell from shrinking. As a result, the shell develops tension stresses while the core experiences compression stresses as can be seen in Figure 1.11.

Figure 1.11 has been removed due to copyright restriction. The information removed shows the moisture – stress relationship at six stages of drying shown in cross section. The graph can be found at Simpson, W. T. 1991. Dry Kiln Operator's Manual. Forest Products Society. 274 pp.

Figure 1.11: Moisture – stress relationship during six stages of kiln drying for 2 inch red oak (Simpson, 1991)

If the shell is stressed beyond its elastic limit due to a high drying rate, it dries in a permanently stretched condition without completing the shrinkage. As the drying proceeds, the core dries and shrinks. Since the shell is set in its condition, it prevents the shrinkage of the core which reverses the stresses of the core and the shell and causes the core to go into tension and the shell into compression. Internal cracks like honeycombing occur due to this phenomenon. In addition, warp is caused by the differential shrinkage of the three different directions of the wood. Finally, the presence of juvenile wood or reaction wood on one side of the lumber will cause uneven shrinkage and warp (Pratt, 1974; Simpson, 1991; Reeb, 1997; Forest Products Laboratory, 1999).

Figure 1.12 has been removed due to copyright restriction. The information removed is a drawing of two cross sections, showing the development of drying stresses over time. It can be seen at: Forest Products Laboratory. 1999. Wood Handbook – Wood as an engineering material, Gen. Tech. Rep. FPL-GTR-113, Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 463 p.

Figure 1.12: End view of a board showing development of drying stresses (a) earlier and (b) later in drying (Forest Products Laboratory, 1999)

At the end of the drying process, the lumber surface is stressed by compression while the centre is stressed by tension (Figure 1.12). This phenomenon is called casehardening and presents a major concern for dried lumber. If the lumber is processed (resawn or surfaced) in this state, the stresses will cause the lumber to distort. To avoid this, the load of lumber is usually conditioned at the end of the drying schedule. The test used to check the degree of casehardening in lumber is called the prong test. It is widely used by the industry even though there is no consistent standard of performing this test for prong geometry and prong response. The prong test shows if there is a stress gradient in the lumber that causes it to deform. This test does not, however, show the stresses of the whole timber. The prong test easily provides misleading results since prong length and thickness influence the movement of the prongs. It is advisable to keep constant prong dimensions from one kiln charge to the next to achieve consistent and comparable results (Fuller, 1995 a, b; Fuller, 1999; Fuller, 2000 a, b). He also found that prong thickness influences the prong test results; thinner prongs respond more easily than thicker prongs. A cutting guide (template) was used to insure equal prong sizes. Figure 1.13 shows the prongs geometry. Another one of Fuller's studies (2000 b) indicates that the prong test can only be used to show that stress exists; however, it does not indicate the quality of the drying performed since storage and transportation might be influencing the prong results to a great extent.

Figure 1.13 has been removed due to copyright restriction. The information removed is a drawing of prongs in their green and dry stage with the appropriate measurements. The drawing can be found at: Fuller, J., 1995 a. Conditioning stress development and factors that influence the prong test. Res. Pap. FPL-RP-537. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 6 pages.

Figure 1.13: Prong test geometry and recorded measurements: W = pre-cut prong tip distance; W' = released prong tip distance; L = prong length; t = prong thickness (Fuller, 1995 a)

In a series of studies related to casehardening, Fuller (1995 a) developed an equation to calculate the degree of casehardening by taking the size of the prongs into account. He found that the prongs bow along their entire length and that the curve of the circle followed by bowing can be described as a second degree polynomial, which makes the prong movement a function of the squared prong length. Shown below is Fuller's equation:

$$PR = \frac{W - W'}{L^2} \qquad (2)$$

where:

PR: degree of casehardening [mm^{-1}]
W: pre-cut prong tip distance [mm]
W': released prong tip distance [mm]
L: prong length [mm]

In a positive result, casehardening is present in the lumber and the prongs will move inward. If the prongs move outward, reverse casehardening is apparent and the result will be negative.

Shape deformations caused by wood properties due to uneven dimensional changes during the drying process are bow, crook, twist and cup. Cracks are caused directly by the drying process; when the drying stresses are greater than the strength of the wood, the wood may be damaged. With a decreasing moisture content, the wood becomes stronger and can tolerate higher drying temperatures and lower relative humidities without sustaining significant damage (Simpson, 1991). One of the wood properties proven to cause shape distortion during the drying process is the slope of grain (SOG). The slope of grain is defined as the angle between the main axis of the piece of timber and the direction of the wood grain. It can be caused by either natural occurrence in the trees as spiral grain or it is due to the sawing process (Hao and Avramidis, 2004). The presence of juvenile wood can also cause shape distortions (Hao and Avramidis, 2006).

Figure 1.14 has been removed due to copyright restriction. The information removed is a drawing of bow, crook, twist, diamond and cup. The drawing can be found at: Forest Products Laboratory. 1999. Wood Handbook – Wood as an engineering material, Gen. Tech. Rep. FPL-GTR-113, Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 463 p.

Figure 1.14: Various types of degrade that can develop during drying (Forest Products Laboratory, 1999)

Figure 1.14 shows different kinds of deformations that timbers might develop during drying.

Bow is a deviation along the fibre due to juvenile or reaction wood shrinkage differences. The timber is arching longitudinal, flatwise, from a straight line drawn end to end of the piece. Pressure on top of the stack will control bow. It mostly occurs on flat sawn wood (Brunner-Hildebrand, 1987; Ward and Simpson, 1991; Reeb, 1995; Reeb, 1997).

Crook is the deviation along the fibre due to juvenile or reaction wood shrinkage differences. The deviation occurs edgewise. This is almost impossible to control and mostly occurs on quarter sawn wood. There is no difference between bow and crook on boards with a square cross section (Ward and Simpson, 1991; Reeb, 1995; Reeb, 1997).

Twist is the turning of any face of a board so that the four corners are no longer at the same plane. That is due to spiral, wavy or diagonal slope of the grain in combination with anisotropic shrinkage. A high juvenile wood content in a timber can also make it prone to twisting. It is possible to control twist by applying pressure on the lumber pile (Ward and Simpson, 1991; Reeb, 1995; Reeb, 1997; Hao and Avramidis, 2004, Bradic and Avramidis, 2007).

Cup is a deviation flatwise because of tangential and radial shrinkage differences which develop only on rectangular boards, but not on square timber (Ward and Simpson, 1991; Reeb, 1995; Reeb, 1997).

Diamonding is due to radial and tangential shrinkage differences and it occurs mainly in square timbers. It might be controlled by sawing patterns and/or air drying or pre-drying (Ward and Simpson, 1991).

Surface checks are cracks on the flat surface of the lumber and usually occur along the grain. They develop when the drying stresses exceed the tensile strength perpendicular to the grain. Also, surface checks are caused by the slope of grain and a fast drying of the surface which is caused by unusually low relative humidity early in the drying process. The highest danger of surface checks forming is during the early stages of drying; however, with some softwoods, the drying checks can develop throughout the whole drying process (Ward and Simpson, 1991; Reeb, 1997). Mild surface checks in wall studs should not be a cause for concern.

End checks are cracks formed on the end grain surface of the timber due to quick evaporation of moisture. These can be prevented by covering or coating the freshly cut ends. Furthermore, end checks usually occur in the early drying stages and can be minimized by using a high relative humidity. Specifically, end checks are caused by faster moisture movement in the longitudinal direction compared to the transverse direction of the timber. This makes ends of a board dry faster than the middle and develops stresses at the end of the boards. The risk of end checks increases with increasing thickness and width of the lumber (Ward and Simpson, 1991).

End splits often result from the expansion of end checks further into the timber. To reduce these extensions, stickers are often placed at the very ends of the timber. Sometimes end splits are caused by growth stresses and thereby, not always attributed to a drying defect (Ward and Simpson, 1991).

Honeycomb is internal checking due to a high internal pressure (tensile failure across the grain). It usually evolves parallel to the grain; a delamination of fibres along the cell walls in the radial direction, the longitudinal plane. The causes are internal tension stresses that are induced in the core of the timbers during drying. For instance, the core still has a relatively high moisture content and the drying temperatures are too high for too long during this specific period of the drying schedule. If the high temperatures are only induced after the free water has been evaporated, honeycombing might be minimized. Generally, moisture content of the core should be below FSP before the temperature increases. Usually, the moisture content of the core and thus the moisture gradient is unknown during the drying process; consequently, a board can have a high moisture content in the core even though the average moisture content is fairly low. When using moisture content based schedules, the dry-bulb temperature might be increased while the core is still wet causing honeycombing. Honeycomb can cause value losses and is mostly not detectable on the surface, unless machining of the lumber takes place (Ward and Simpson, 1991; Reeb, 1997).

Collapse is a distortion of the cells like flattening and/or crushing. In severe cases, it becomes visible as grooves or corrugations, such as a washboard effect or as excessive shrinkage. Slight amounts of collapse are very hard to detect, but are not a significant problem. Collapse is usually due to either compressive drying stresses in the inner parts of boards that are larger than the compressive strength of the wood or to liquid tension in cell lumens which are entirely filled with water. These conditions happen early in the drying process when the lumber is still above the fibre saturation point; however, the collapse of the cells only becomes visible in later stages of drying. Low dry-bulb temperatures should be used for drying species that are prone to collapse or contain wetwood. Collapse might be reduced if the boards are air dried before being kiln dried. Excessive shrinkage and/or the washboard effect can be removed by reconditioning or steaming the lumber after drying (Keey et al., 2000; Ward and Simpson, 1991).

1.4 Drying schedules

Every wood species requires a different drying schedule considering temperature, relative humidity, air velocity and drying time. Softwoods, for example, dry much faster than hardwoods and can tolerate higher temperatures with less degrade (Simpson, 1991). One way to improve the quality of the dried lumber and shorten the drying time is to use more unconventional types of drying kilns, such as a radio frequency vacuum or a superheated steam vacuum. On the other hand, modifying the species specific drying schedules for the conventional heat-and-vent kiln might improve lumber quality and also reduce drying times.

1.4.1 Types of drying schedules

There are two general types of drying schedules: the moisture content-based and the time-based drying schedules. In moisture content based schedules, the wet-bulb and dry-bulb temperatures are changed when the average moisture content of the load reaches a pre-determined target value. Time based schedules change the wet-bulb and dry-bulb temperatures at certain time periods without taking in account the actual moisture content. These schedules are usually used for softwoods and also when the properties of the load are well known. Generally, moisture content-based schedules allow a more controlled drying process than time-based schedules, since they adapt automatically to each new kiln load (Simpson, 1991).

1.4.2 Drying schedule steps

A conventional drying schedule is comprised of several steps:

1. The heat-up step is used to warm up the kiln and the stacks of wood before the actual drying is started; low temperatures and high relative humidities are usually employed in this stage (Brunner-Hildebrand, 1987).
2. The first drying step increases the temperature and decreases the humidity to dry the lumber down to the fibre saturation point while removing the free water (Brunner-Hildebrand, 1987).
3. In the second drying step, the temperature and humidity are either increased further or held constant. The purpose of this step is to remove as much bound water as necessary to reach the desired target moisture content (Brunner-Hildebrand, 1987).
4. The equalizing step is traditionally used for drying hardwoods. It is used to reduce the moisture content variation between the boards (Boone et al., 1988; Culpepper, 1990).

5. The conditioning step uses high temperatures and humidity for internal stress relief by reducing the moisture content gradient between the core and the shell of each board.
6. The last step in the drying schedule is usually the cooling period where the heat is turned off, the vents are closed but the fans are working. The purpose is to cool down the lumber temperature in order to avoid surface checks. Very often, this step is omitted to free the kiln space for the next load (Kollmann, 1955; Brunner-Hildebrand, 1987).

1.4.2.1 Heat-up step and pre-steaming

Several studies were conducted on the effect of pre-steaming lumber before kiln drying. Pre-steaming is usually introduced to relax growth stresses and accelerate the heat-up step; as well as, a softening treatment for the manufacturing of bent furniture and for sterilization purposes against fungi, moulds and insects. Kubinsky (1971) reported an increase in shrinkage due to sustained steaming that caused collapse in red oak. For lumber with a higher moisture content, the transverse compressive strength was reduced significantly with longer steam treatments for softwoods and hardwoods. Both phenomena are reported to be caused by an increased internal swelling of the wood.

Avramidis et al. (1993) reported that the pre-steaming of 105 x 105mm hemlock and fir lumber has no obvious effect on the drying rate; however, the study showed a significant reduction of the core-shell moisture content gradient with increasing pre-steaming time. Moreover, longer pre-steaming decreased the shrinkage variability even though it did increase the absolute shrinkage; most importantly, lumber quality was not negatively affected. Pre-steaming of hem-fir from 8 to 12 hours also reduced the appearance of brown stain formation on the lumber during drying.

Pre-steaming also causes the initial moisture content to drop by approximately 10% and the moisture gradient from shell to the core was altered as well. Harris et al.

(1989) assumed that an increase in permeability or the changed moisture profile or even a combination might prove to be the reason for the increased drying rate. Kubinsky and Ifju (1973, 1974) performed a study on pre-steaming red oak (*Quercus rubra*) and found that steaming up to 48 hours decreased the lumen size and led to increased shrinkage while steaming of up to 96 hours caused collapse. The shrinkage was explained by chemical and structural changes in the cell walls. Pre-steamed boards also showed a smaller moisture gradient from the core to the shell after drying which might account for the decrease of checks, twist and casehardening during drying. Pre-steaming of tiaong boards for more than 2 hours did not increase the effects. Finally, the shrinkage of steamed boards increased with increasing steaming times.

To decrease the drying time, reduce the variability of the drying rate, and collapse of red beech (*Nothofagus fusca*), a pre-steaming step was recommended by Haslett and Kininmonth (1986). The increased drying rate seems to be due to a partial relocation of polyphenols. The pre-steaming step is only effective though, if the lumber is pre-dried or air dried to a moisture content of below 40%, especially if steamed at 100°C, otherwise, the degrade would be too severe for the commercial use of the lumber.

In contrast to the last study, Chafe (1990) found the total volumetric shrinkage to be higher in pre-steamed samples. This might be due to the fact that Chafe used *Eucalyptus regnans* instead of *Eucalyptus pilularis* or that he used core samples instead of planks like Alexiou et al. (1990a) and steamed them for only 30 minutes compared to 3 hours. He also found a decrease in initial moisture content after steaming and justified his findings with changes in permeability.

Pre-steaming of Southern pine from 1 to 5 hours at 100°C was found to increase the moisture diffusion coefficient in both sapwood and heartwood below and above fibre saturation point which was in part caused by a changed extractive distribution profile. The outer extractives were found to be removed during pre-steaming which affected the internal wood structure by opening more passageways for the water molecules (Choong et al., 1999).

1.4.2.2 Equalizing and conditioning steps

The purpose of the equalization step in hardwoods is to minimize the variation of moisture content within and between the boards in a load of lumber. This equalization step is also a preparation for the conditioning step. The equalizing is supposed to begin when the driest board reaches the target moisture content minus two percentage points and is continued until the wettest board reaches the target moisture content. An equilibrium moisture content equal to the moisture content of the driest board is established by using a dry-bulb temperature as high as the highest temperature of the drying schedule used. With the equalization step completed, the load should have a moisture content range between target moisture content and target minus three percentage points (Simpson, 1991).

After the equalizing is executed properly, the conditioning of the lumber can begin. The purpose of the conditioning is to relieve the transverse drying stresses and simultaneously, correct the casehardening it also creates a more uniform moisture content throughout the boards. For the conditioning, the equilibrium moisture content is set to the target moisture content plus three. This step is continued until all stresses are removed. It has to be stopped in time because over-conditioning may result in reverse case hardening which is a permanent condition. It is also emphasized that both steps have to be executed very carefully and precisely in order to have a major impact on the drying quality and time.

Moreover, the dry-bulb temperature during equalizing should be lower than during conditioning to increase efficiency; furthermore, the dry-bulb temperature during conditioning should be the highest temperature possible for the species dried and the wet-bulb temperature should be reached as quickly as possible. If not done properly, this period will be unnecessarily long and the stress removal will prove to be more difficult (Simpson, 1991). The equalization is only used for hardwoods while the conditioning step is used for hardwoods, as well as, softwoods. Practically, it might be advisable to use an equalization step when drying valuable softwoods.

1.4.2.3 Cooling down

Haslett and Simpson (1992) investigated the influence of lumber temperature, moisture content and cooling time on the effectiveness of steam conditioning with high temperature dried radiata pine (*Pinus radiata*) in New Zealand. The lumber was dried at a dry-bulb temperature of 120°C and a wet-bulb temperature of 70°C; the cooling times varied with the thickness of the lumber. Cooling the lumber to a core temperature of 75 - 90°C was found to be ideal before steaming, while an average temperature below 100°C already improved the desired effect of the steaming. In addition, the moisture content was found to have a major effect on steaming; the efficiency of the steaming process was found to increase with a decreasing moisture content. Steaming took only 1 hour per 25mm board thickness if the moisture content was below 7% compared to 2 hours per 25mm thickness at a 8 – 16% moisture content.

Pang et al. (2001) came to the same general conclusions for high temperature dried radiata pine (*Pinus radiata*). Additionally, they mentioned that it is important to let the lumber remain in the kiln after steaming to cool down gradually under controlled conditions. This is done to prevent a quick surface moisture loss which could result in surface micro-cracks due to the shrinkage of the outer layers and thermal shock if the environment happens to be cold and dry. Haslett and Dakin (2001) steamed radiate pine at 100°C under atmospheric pressure and at 150°C under atmospheric pressure. It was found that the twist in the pressure steamed run was permanently reduced by up to 25%; alternately, an increase in steaming time from 0.25 to 0.7 hours did not increase the reduction in twist.

1.4.3 Storage

Morén (1994) reported that when conditioning scots pine after drying, the reversal of the drying stress is achieved within one or two hours, depending on the dimensions of the lumber and the amount of initial stress. It was recommended storing the lumber after drying in an airy place, so that the lumber is able to lose the moisture it gained during conditioning.

In Japan, some companies opt to store the lumber after drying for a period of seven to ten days. The lumber is stacked outside, using stickers to promote airflow. During this time, the moisture content gradient within each piece equalizes and thus reduces the stress in the timber that was induced during drying (Oliveira, 2005). Hemlock baby squares stored in a climate chamber set to Tokyo winter conditions for 14 weeks after being dried to 19% moisture content in the core showed changes in moisture content and distortions that would be considered acceptable when considering the natural variability of wood. Neither bow nor crook changed significantly after conditioning. Also, twist did not show a significant increase during storage. The shell moisture content acclimatized to the new EMC very quickly, while the core moisture content needed more time to reach the new equilibrium (Wallace, 2001; Wallace et al., 2003).

2. Objectives and Hypothesis

2.1 Objective

To investigate the effect of schedule conditions and post-drying treatments on the drying rate and the quality of western hemlock baby-squares dried in a laboratory conventional kiln. Specifically to investigate the effect of different drying schedules on the drying rate and the effect of application or absence of conditioning and storage on the timber quality.

2.2 Hypothesis

At least one of the chosen drying schedules with the application or absence of conditioning for conventional kiln-drying of western hemlock baby-squares including an option of 7-day post-drying storage in a conditioned space will increase timber quality without considerably extending total drying time.

2.3 Rationale

Traditionally, western hemlock has been dried jointly with amabilis fir. However, a separation of the species might become necessary due to their different physical properties which greatly influence the quality of the kiln dried timber. But there is little information about drying western hemlock individually, thus making it an interesting topic to investigate the use of different drying schedules.

In Japan, the largest importer of West Coast hemlock, the timber is being acclimatized for at least 7 days in a storage facility after drying. The suggestion of including this permanently into the drying process appears to be worthwhile and beneficial to exploring its benefits.

3. Materials and Methods

3.1 Pre-drying protocol

3.1.1 Lumber

The wood used for this study comprised ninety-six timbers of second growth western hemlock (*Tsuga heterophylla*) baby-squares, 116mm x 116mm in green condition, with a grade of standard or better (Figure 3.1). The lumber came from Saltair Timber Products, located in Chemainus on Vancouver Island, British Columbia, Canada.

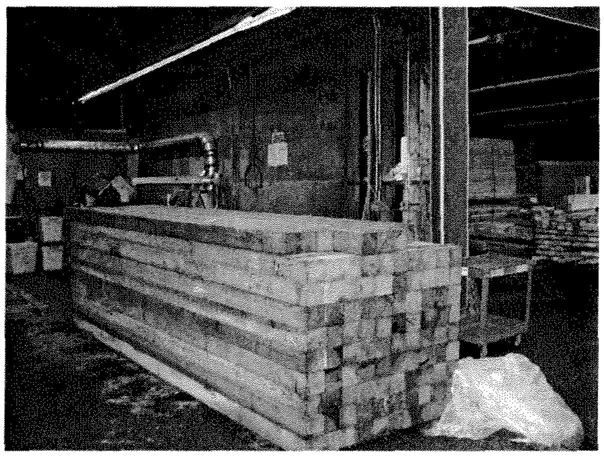


Figure 3.1: Green timber piled up by the saw, waiting to be cut

3.1.2 Specimen preparation

Each of the ninety six green timbers was 3.96m long. Each piece was cut into four kiln specimens and five sections (cookies), according to the cutting pattern in Figure 3.2.

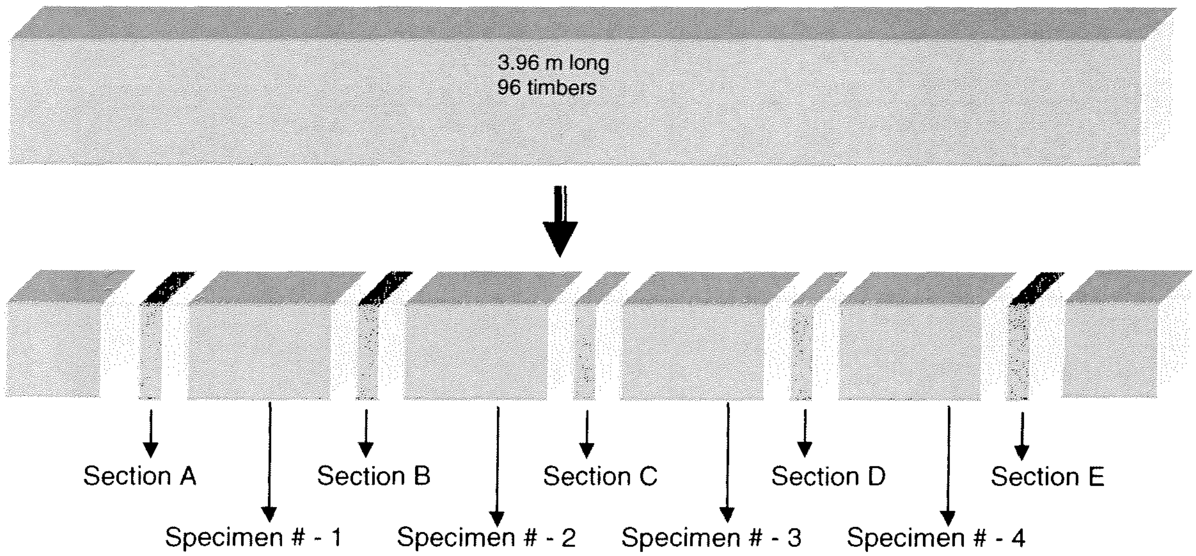


Figure 3.2: Cutting pattern for green specimens and sections

The cutting was done using a circular arm saw as can be seen in Figure 3.3.

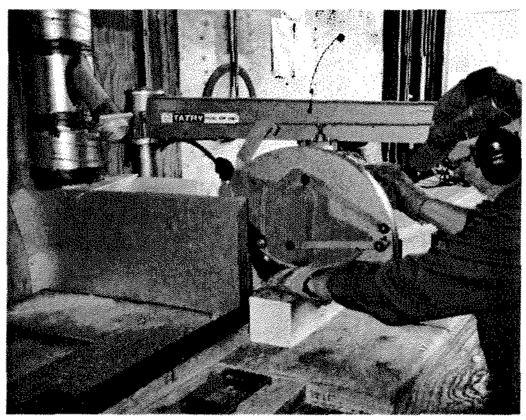


Figure 3.3: Cutting of green timber into specimens and sections

About 100mm was cut from the end of each piece of timber and then discarded. Thereafter, one 25mm thick section, called a "cookie" was cut at each end of the specimens. The sections were measured for basic density and initial moisture content. Each specimen and section was labeled carefully, using a permanent marker, so it could be traced back to the exact board and its location on the board (Table 3.1). Each specimen was labeled at the end that pointed to the right side.

This was determined as the "front" and the side surface that had the label written on was always "up".

Table 3.1: Labelling for green specimens and sections

Name	Label	Dimension [mm]	Quantity
timber	1 to 96	112.5 x 112.5 x 3900	96
section "cookie"	Board # and A, B, C, D, E (labeled from left to right)	112.5 x 112.5 x 25	5*96=480
specimen	Board # - sequential # 1 to 96 – 1 to 4	112.5 x 112.5 x 900	42*9=178

From each of the sections, the green weight was measured and rounded to the nearest 0.01g (Mettler PM 4600 Delta Range). The volume was determined using the water-replacement method (Figure 3.4).

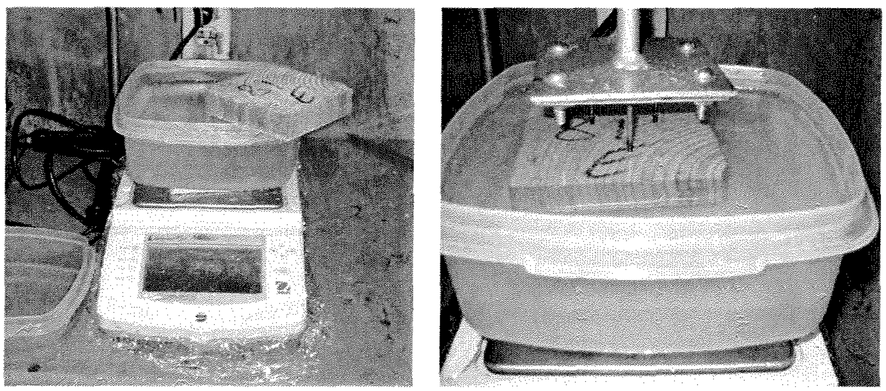


Figure 3.4: Measuring the weight of a green section and the volume using the water replacement method

Thereafter, the sections were dried in an oven at 103±2°C (Figure 3.5) until their weight was constant (Kollmann, 1955; Skaar, 1972; Forest Products Laboratory, 1999).

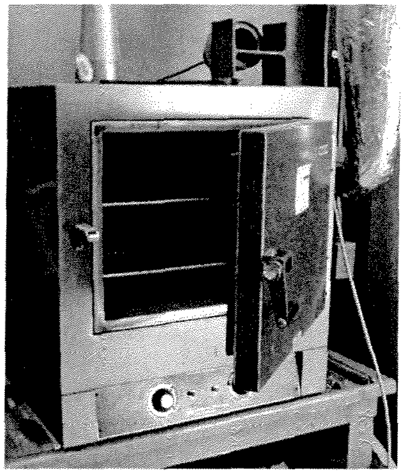


Figure 3.5: Drying oven used to dry sections down to 0% moisture content

From these values the green moisture content and the basic density of each section were determined using equation 1 and the following equation for density:

$$\text{Density} = \frac{\text{weight}_{\text{oven-dry}}}{\text{volume}} \ [\text{kg/m}^3] \qquad (3)$$

Using the value of the sections located at the ends of each specimen, the moisture content and basic density of that specimen was averaged.

3.1.3 Storage of green lumber

After cutting, the specimens were stored outside, tightly wrapped in plastic (Figure 3.6) for a few weeks since the temperature was approximately 10°C (December 2004). Ambient temperature and relative humidity measurements were taken for monitoring purposes.

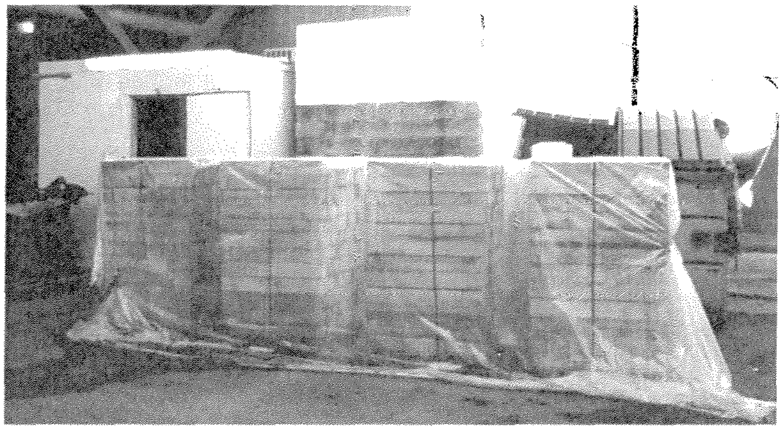


Figure 3.6: Storage of green specimens, wrapped in plastic to prevent drying

In January 2005, they were moved into a cold room as indicated in Figure 3.7 (T=10°C, EMC=18.5%). They were wrapped in plastic bags in threes and stacked without stickering and also tightly wrapped in a large plastic sheet.

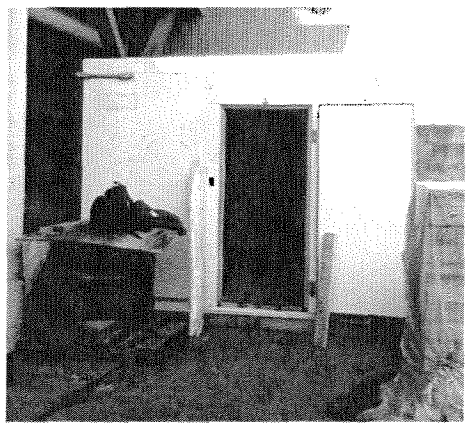


Figure 3.7: Cold room used for storage of green specimens

Although cold room storage was used to minimize moisture loss, a certain amount of moisture was expected to evaporate, since the cutting was done in December 2004 and the last load was dried at the end of August 2005.

3.1.4 Pre-drying sorting of specimens

Each of the nine kiln loads contained forty two specimens. The results of drying are influenced by moisture content and basic density of the lumber to be dried. Therefore, to compare one drying run to the other, it was necessary to neutralize the influence of these two wood properties. The specimens were sorted using a computer program written especially for the sorting process (Shen, 2005). The computer repeatedly produced nine groups of forty-two specimens each by randomly selecting specimens and comparing the resulting standard deviations for moisture content and density. The sorting resulting in the smallest standard deviations for both properties was selected for this study.

3.1.5 Pre-drying measurement and protocol

To determine the quality of the kiln specimens before drying, all checks were recorded by type and length. The length of each check was measured using a Starrett C1-8M8 measuring tape. Each check was marked with a colored crayon on the timber in order to distinguish between pre- and post-drying checks. Then twist and diamonding were measured at the front end of each specimen. A shop-built aluminum table, consisting of a "U" shaped aluminum base clamped upside down onto two support stands with leveling feet, was used for these measurements (Figure 3.8). The flatness of the base surface was ground to 0.25mm and an aluminum fence was lapped, shimmed, and mechanically clamped at 90° to the long edge of the base. The straightness of the table was adjusted to 0.25mm and the table was fixed to the same location in the lab where it was leveled with the ground.

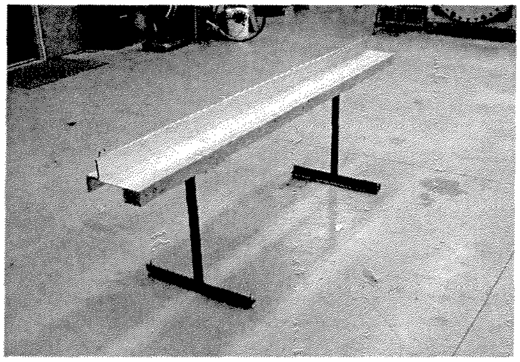


Figure 3.8: Measuring table

Two custom shop-built digital dial gauges were used to measure twist and diamonding as shown in Figure 3.9. Twist was measured using a Mitutoyo Model ID-C1012EB Digital Dial Gauge attached to a flat aluminum reference plate at a 90° angle. The resolution was 0.01 mm and the measurement accuracy was better than ±0.5 mm when used by an experienced operator. To measure diamonding another shop-built gadget was used, also consisting of a Mitutoyo Model ID-C1012EB Digital Dial Gauge attached to a precision machined steel square. The resolution was 0.01 mm and the measurement accuracy was better than 0.25 mm.

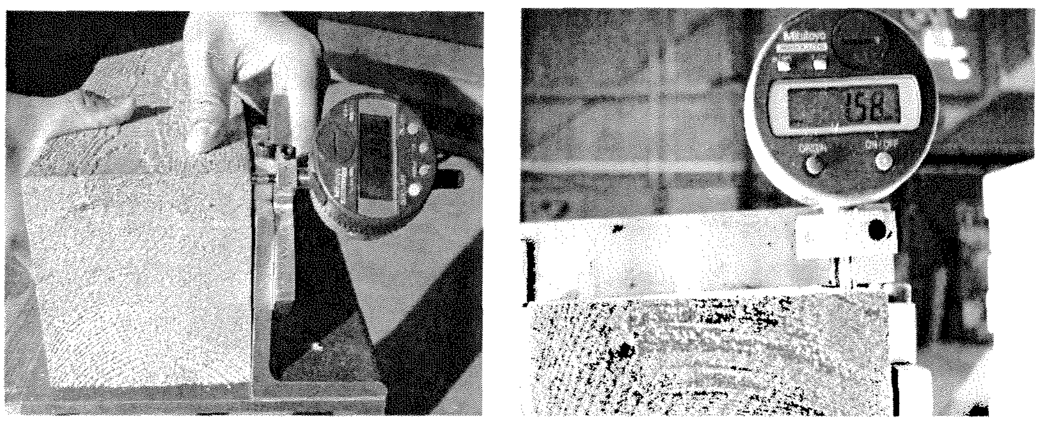


Figure 3.9: Twist and diamonding measuring tools

The weight of each specimen was recorded to calculate its current moisture content. The cross-sections of the specimens were coated using polyvinyl acetate (PVA) before drying to prevent significant moisture loss through the ends and achieve a simulation of longer specimens.

3.2 Drying experiment

3.2.1 Dry kiln used

The conventional heat-and-vent kiln used for this research study was a 900mm aluminum experimental kiln located at Forintek Canada Corp which is shown in Figure 3.10. The kiln has a volume of 0.73m^3. The heat is supplied by either two heater coils (3kW and 4kW) and/or by low pressure steam from a small boiler. For this project, the heat was supplied by steam. The air velocity was held between 2.5 and 3.0m/s (500 to 600ft/min), which was about 60% fan capacity. The kiln was equipped with a load cell that measured the wood weight constantly during the drying process. The same aluminum stickers, weighing 8.94kg and being 19mm thick each, were used for each drying run to sticker each load of 42 specimens.

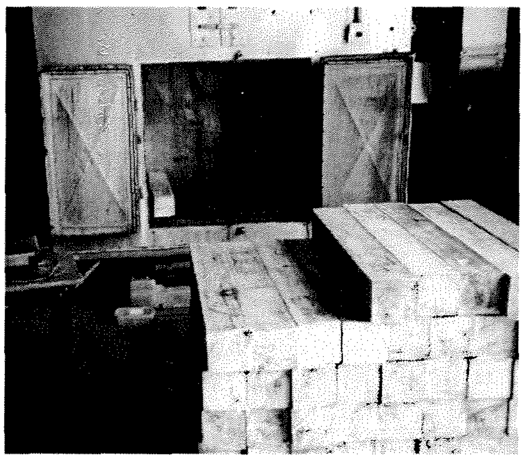


Figure 3.10: Loading of green specimens into the kiln, cross section are covered in glue

The specimens were loaded into the kiln with the front end pointing towards the kiln door and the label side pointing up. Each load was stickered and consisted of six rows with seven specimens each which were stacked tight from edge to edge (Figure 3.12). The computer software monitored the weight of the load, wet-bulb temperature, two dry-bulb temperatures, wood temperature, air velocity and equilibrium moisture content during the drying process and automatically stopped the kiln upon completion of each drying run. In addition, the location and direction of each specimen in the kiln were recorded.

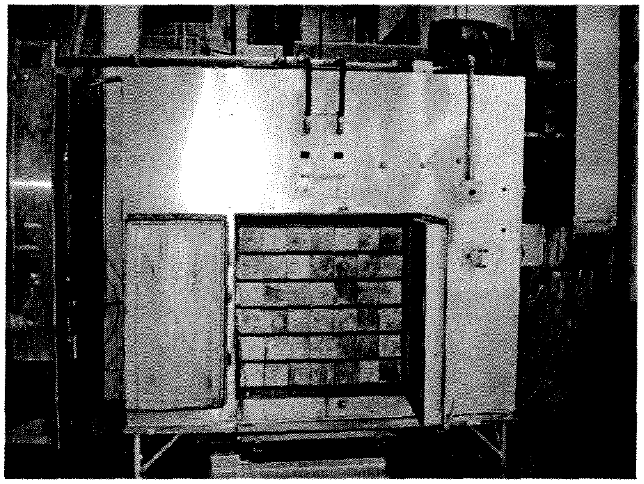


Figure 3.11: Kiln loaded with specimens, ready for drying

3.2.2 Drying schedules

The drying schedule used in the past to dry hem-fir (western hemlock and amabilis fir) was now used as a "Control" for drying hemlock exclusively; this "Control" schedule was developed by the Wood Drying Group of the University of British Columbia (Hao and Avramidis, 2004; Hao and Avramidis, 2006). The drying consists of eight steps using a pre-determined number of hours for each step, hence a time based schedule. In step nine, the drying process is switched to a moisture content based schedule; drying the timber to the target moisture content without a change in settings. The target moisture content was set to 12%. The last step is a conditioning step and was time based. After completing a drying run, the timbers cooled down for twelve hours inside the kiln with the doors closed.

Schedule "I" was a variation of the "Control" schedule. The same dry-bulb temperature was reached in the last step. The EMC was reduced more aggressively, which increased the length of the drying process. Schedule "II" was considered an aggressive drying schedule because it reached a higher dry-bulb temperature in the final step of drying, as well as having a steep reduction in EMC. Furthermore, the final temperature was kept under 93°C to avoid the development of honeycomb. Table 3.2 and Figures 3.13 to 3.15 illustrate all three drying schedules in more detail.

The target moisture content for each of the nine runs was set to 12%, which is the average equilibrium moisture content in Japan from October to May. This target moisture content was chosen to avoid additional moisture loss from the specimens during post-drying storage time.

Table 3.2: Drying schedules used for the "Control" run and the 8 experimental runs

	"Control"				Schedule "I"				Schedule "II"			
Step	EMC [%]	WB [°C]	DB [°C]	hours	EMC [%]	WB [°C]	DB [°C]	hours	EMC [%]	WB [°C]	DB [°C]	hours
1	25.5	48.9	48.9	12	25.5	48.9	48.9	12	25.5	48.9	48.9	12
2	20.8	50.6	51.7	24	15.2	54.4	57.8	24	17.2	60.6	62.8	24
3	17.5	52.8	55.0	24	9.7	46.1	54.4	24	13.9	64.4	68.3	24
4	16.2	55.0	57.8	24	6.8	46.1	60.0	24	10.7	64.4	71.1	24
5	12.7	56.7	61.7	24	5.8	46.1	62.8	24	6.2	64.4	79.4	24
6	10.8	58.9	65.6	24	5.1	51.7	71.1	24				
7	8.8	60.6	70.0	24								
8	7.8	62.8	73.9	24								
9	7.0	65.0	77.8	till 12%	4.3	54.4	77.8	till 12%	4.7	64.4	85.0	till 12%
Optional conditioning: EMC: 12.3%, WB: 66.7°C, DB: 71.7°C, time: 12hours												
Optional storage: EMC: 12%, T: 20°C, H: 65%, time: 7 days												

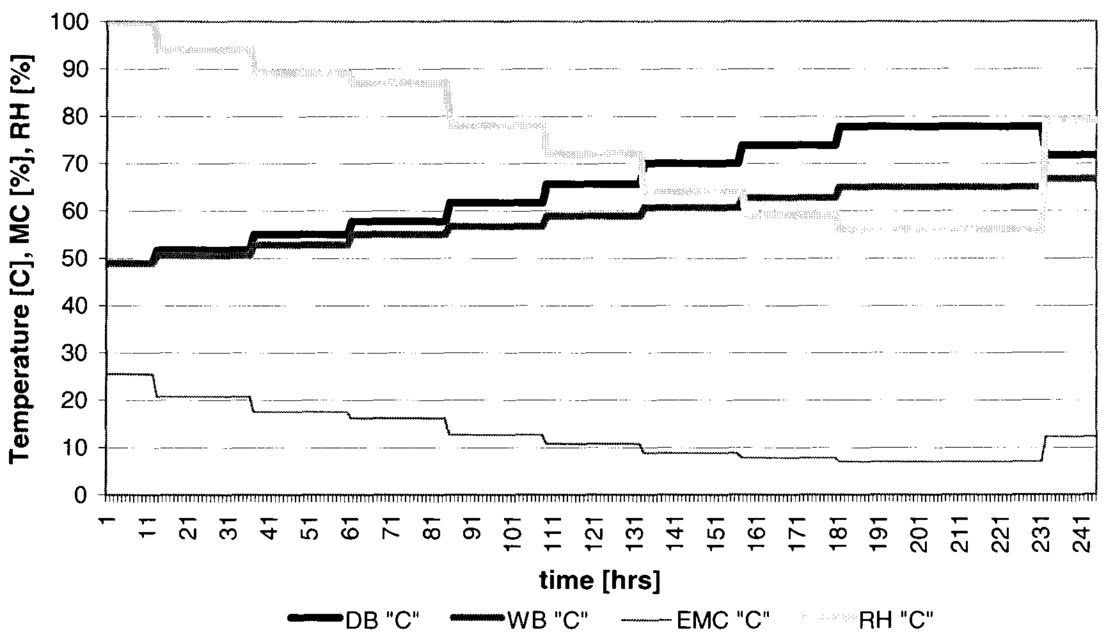


Figure 3.12: "Control" schedule

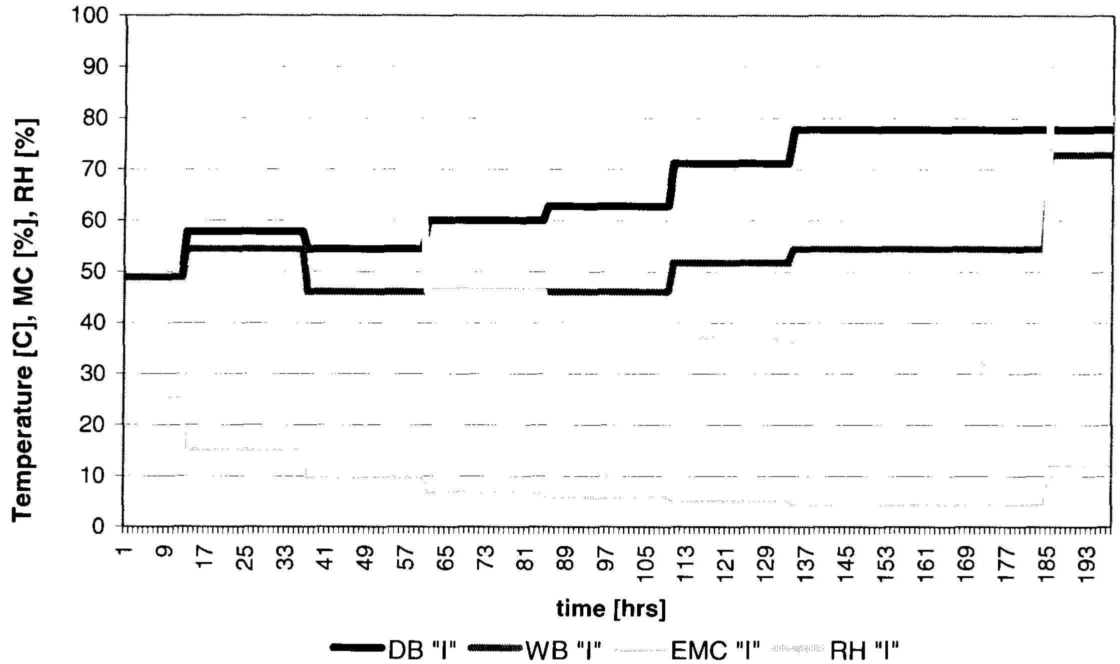


Figure 3.13: Schedule "I" schedule

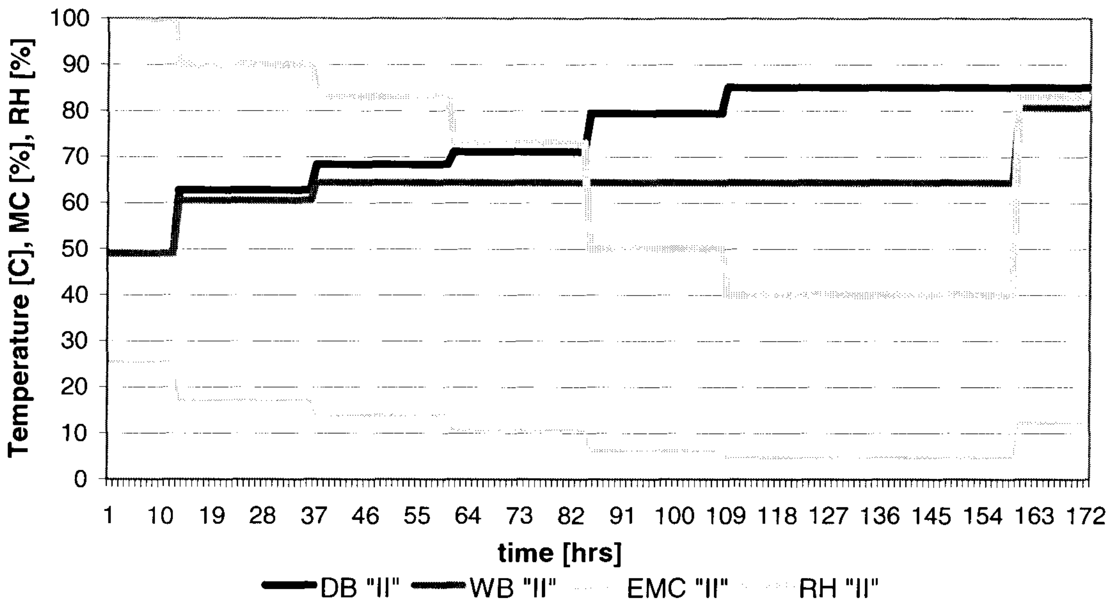


Figure 3.14: Schedule "II" schedule

Schedule "I" and "II" were executed with an option of conditioning and/or storage. Detailed combinations of the eight experimental runs and the "Control" run can be seen in Table 3.3.

Table 3.3: Code used for the nine drying runs

Run number	Schedule used	Conditioning	Storage	Run name
1	"Control"	Yes	No	"C"
2	"I"	Yes	No	"I c ns"
3	"I"	No	No	"I nc ns"
4	"II"	No	No	"II nc ns"
5	"I"	Yes	Yes	"I c s"
6	"I"	No	Yes	"I nc s"
7	"II"	Yes	Yes	"II c s"
8	"II"	No	Yes	"II nc s"
9	"II"	Yes	No	"II c ns"

3.3 Post-drying protocol

3.3.1 Post-drying measurements

After kiln drying was completed, the specimens of runs 5, 6, 7 and 8 were visually examined for checks and splits while they were taken out of the kiln. The length of each new check was measured and recorded and the after drying weight was obtained for each specimen. Next, the specimens were taken to the controlled climate room for one week of storage and afterwards, diamonding, twist and the weight of each specimen was measured and recorded. Diamonding and twist were measured using the same tools and protocol used in the pre-drying measurements. The specimens of the other runs had all measurements taken right after unloading the kiln and before being cut (details in section 3.4.3).

3.3.2 Post-drying storage

In Japan, the timbers are stored undercover for 7 to 12 days to reduce internal moisture gradients, in addition to stresses resulting from drying. The EMC in Vancouver differs from those in Japan; therefore, in order to simulate the outside storage a climate chamber was used. The dried timbers were stored in a climate chamber set to an EMC of 12% (H: 65%, T: 20°C). This EMC is equivalent to that in Japan (Kobe and Nagasaki area) from October to May. The timbers were stacked using wooden sticks (Figure 3.16). Each specimen was kept in the same position it was positioned in during drying.

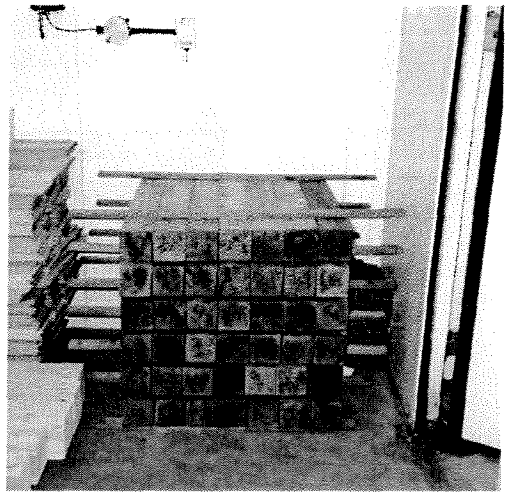
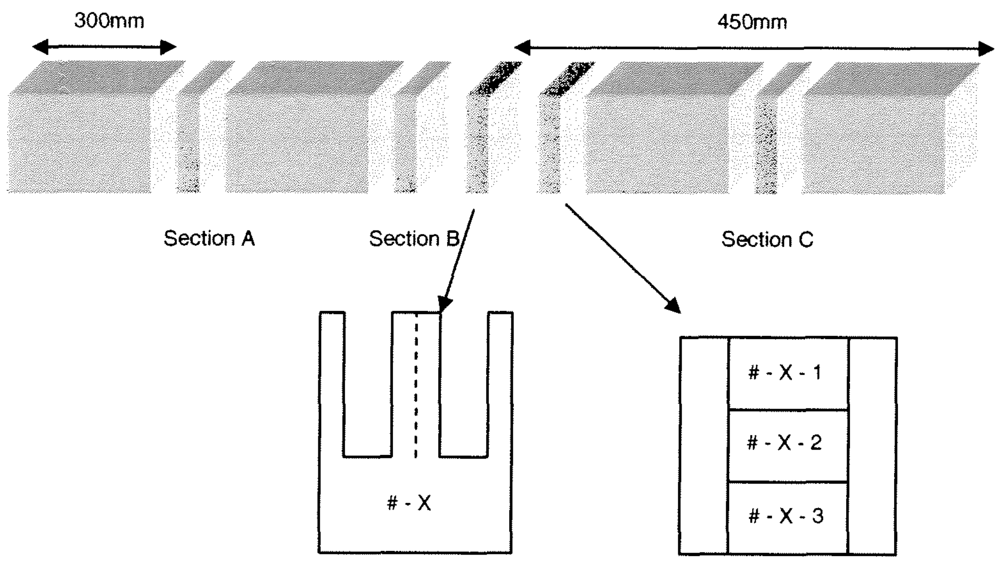


Figure 3.15: Dried specimens in the climate room for their seven day storage after drying

3.3.3 Post-drying and post-storage cutting

The drying specimens that were placed into storage were removed and cut after their seventh day of storage. The non-storage runs were cut immediately after they were unloaded from the kiln. Each specimen was cut using the same sectioning pattern and in the same position, which was the front end of the specimen. This was cut first and the side surface that had the label written on was always up. The first 300mm cutting was discarded. Then, a 25mm section was cut for moisture content measurements, which was labeled as section A. Another 100mm piece was cut and discarded and then three 25mm sections were cut for moisture content, prong test and core/shell moisture content; always in this order. After discarding another 100mm cutting, the last section for the average moisture content was cut. For a detailed cutting plan see Figure 3.17.



Section for...	Label	Dimension [mm]	Quantity
.. average moisture content of each specimen	# - X – A # - X – B # - X – C	112.5 x 112.5 x 25	(42*3)*9=1134
.. prong test for each specimen	# - X	112.5 x 112.5 x 25	42*9=378
.. moisture content of shell of each specimen	# - X – 1 # - X – 3		42*2*9=756
.. moisture content of specimen core	# - X - 2		42*9=378

Figure 3.16: Cutting pattern and labelling for dried specimens and sections (# = board number 1 to 96, X = specimen number 1 to 4)

After cutting, each section was immediately labeled using a permanent marker with the specimen label and the section label. The side of the section that was labeled always pointed to the front of the specimen while the top of each section represented the upper side of the specimen. While labeling the sections for the prong test, the prongs were drawn using the template shown in Figure 3.18. The prongs always pointed upwards and were approximately the same length.

The cutting pattern for the core/shell measurements was drawn on the sections with a permanent marker using the template, also shown in Figure 3.15.

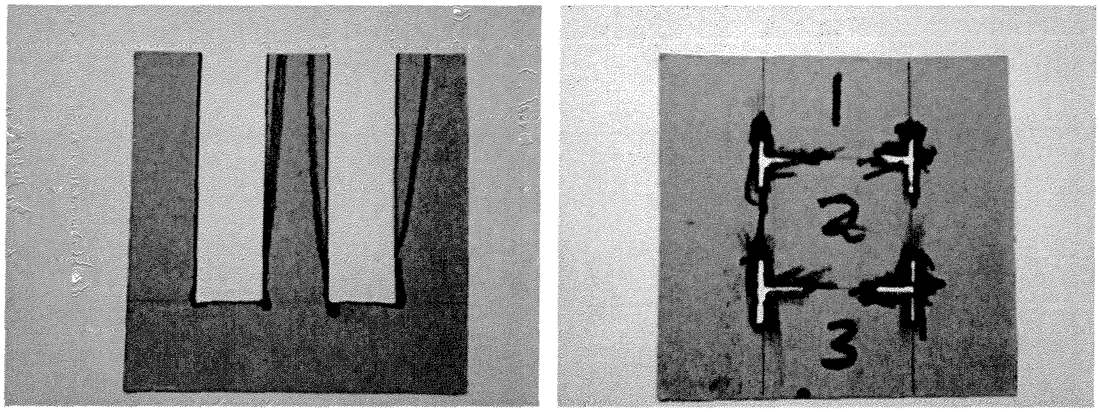


Figure 3.17: Templates used to cut prongs and shell/core equal

The pieces for the shell moisture content represented the upper and lower side of each specimen. The sections for the moisture content measurements had their weight taken and recorded immediately after cutting and labeling.

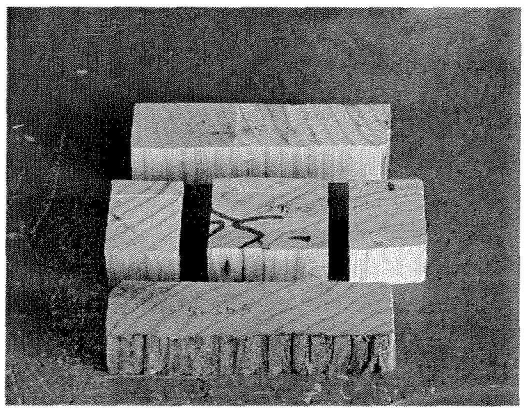


Figure 3.18: Section cut into core and shell parts

The pieces for core/shell moisture content (Figure 3.19) were cut using a small band saw (Figure 3.20) and weighed right after.

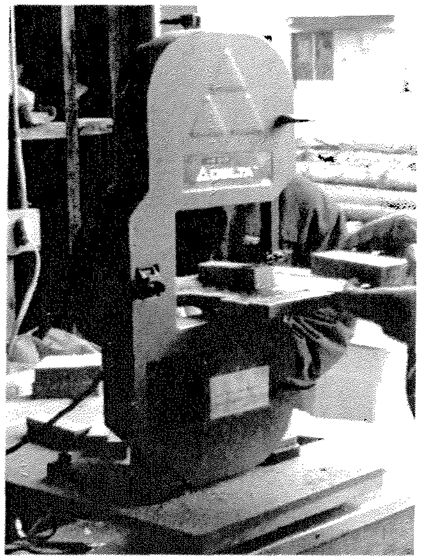


Figure 3.19: Small band saw used to cut sections
into core/shell specimens and cutting of prongs.

The downward cuts for the prongs were made and then the prongs were taken out using a hammer and chisel, as seen in Figure 3.21. The distance of the cut prong tips was then measured and recorded.

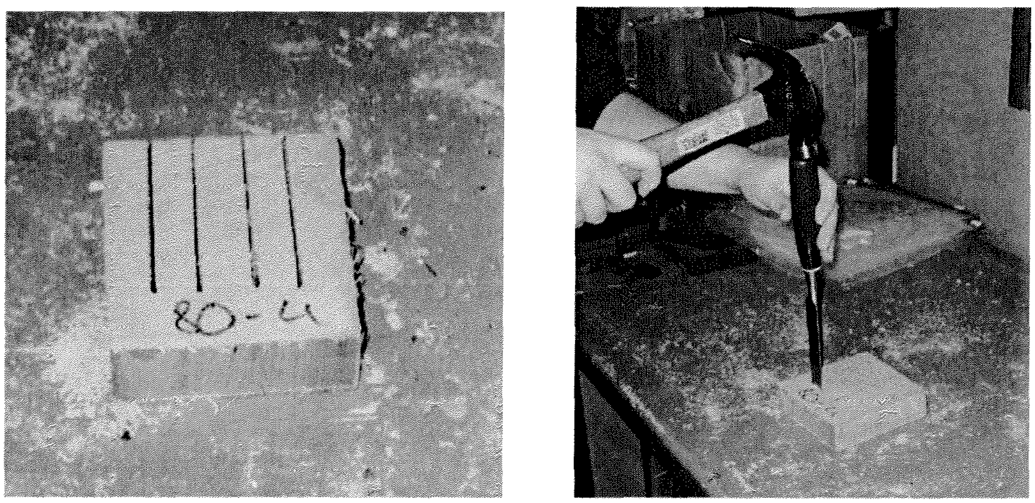


Figure 3.20: Section with cut prongs to be taken out -
a chisel is used to take out the wood in between the prongs

After allowing the prongs to dry at room temperature for 24 hours, their tip distance was measured again along with the length of the prongs. The numbers were used to calculate casehardening using Fuller's equation (2). The sections designated for average moisture content and core/shell moisture content were weighed again after oven drying for 24 hours and then their moisture content calculated.

Section B of each specimen was scanned and visually sorted into four different pith location categories (**A**, **B**, **C** and **D**) representing the presence or absence of juvenile wood. The classification of specimens in terms of the presence of pith in the cross section is shown in Figure 3.22.

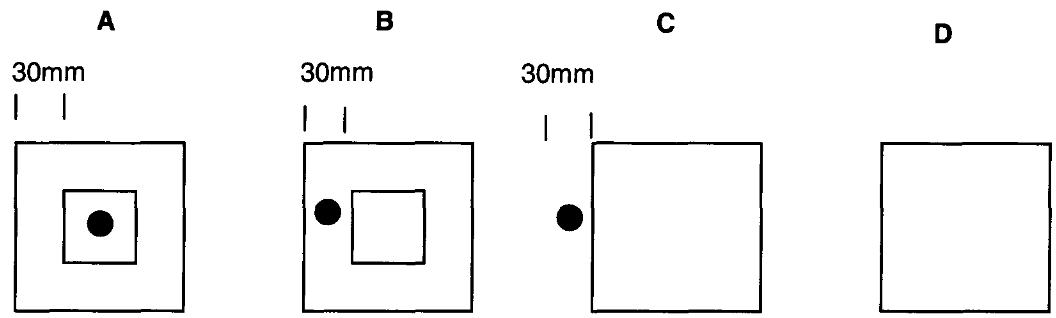


Figure 3.21: Pith location categories, the dark dots represent the pith

3.4 Data analysis

The data obtained from the pre- and post-drying measurements, as well as the information gathered, during drying was used to compare the drying times, stresses induced during drying (casehardening), quality (checks, twist and diamonding) as well as the moisture content distribution within and between the runs. The moisture profile of each specimen was used to investigate moisture content differences in core and shell and to compare the runs.

The experimental design for this experiment is an incomplete factorial design. The experiment has 3 factors (drying schedule, conditioning, and storage) with 2 levels for each factor (schedule I and II, conditioning: yes or no, storage: yes or no), which is a 2x2x2 factorial with 8 runs. In addition, there is the "Control" run, which lies outside the factorial design by not being exposed to any treatments that were set up by the factors. This ninth run for the control is what makes the design an incomplete factorial.

Strictly speaking, this experiment does not contain repetitions, since each treatment combination was used only once and no runs were duplicated. Each run contained forty-two specimens, which were the experimental unit, but they are likely to have similar measurements because they are close in space or time and received the same treatment during the same drying run. They, therefore, cannot be called repetitions. Because the observations were not acquired by random sampling, they are designated as pseudoreplications. Timber drying research would be very time consuming and expensive if each run was repeated to achieve real replications.

In order to link the green values to the final values, a t-test was performed to test for significant differences. For all t-tests, the ANOVA and the ANCOVA were executed, the level of significance (type I error) was set to be 0.05.

Analysis of Variance (ANOVA) was used to search for differences between the drying runs for parameters like final moisture content, shell moisture content, and casehardening. For the ANOVA Table and equations used, see Table 3.4 to Table 3.6.

Table 3.4: Labels for treatment levels used in the ANOVA

Run #	**Run name**	**Labels**	**A**	**B**	**C**
1	**“I nc ns”**	**(1)**	0	0	0
2	**“II nc ns”**	**a**	1	0	0
3	**“I c ns”**	**b**	0	1	0
4	**“II c ns”**	**ab**	1	1	0
5	**“I nc s”**	**c**	0	0	1
6	**“II nc s”**	**ac**	1	0	1
7	**“I c s”**	**bc**	0	1	1
8	**“II c s”**	**abc**	1	1	1
9	**“C”**				

Table 3.5: ANOVA Table for 2^3 incomplete factorial design

Source of Variation	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Squares (MS)	F_o	F_{crit}
Treatment	8 = k-1	SS_{TR}	$MS_{TR} = SS_{TR}$ / DF	MS_{TR} / MS_E	
"Control" vs all	1	SS_1	MS_C vs O/DF	MS_C vs O/MS_E	
Residual	7	SS_2	$MS_{res.}$/DF	MS_{res}/MS_E	
A (schedule)	1	SS_A	$MS_A = SS_A$ / DF	MS_A / MS_E	
B (conditioning)	1	SS_B	$MS_B = SS_B$ / DF	MS_B / MS_E	
C (storage)	1	SS_C	$MS_C = SS_C$ / DF	MS_C / MS_E	
AB	1	SS_{AB}	$MS_{AB} = SS_{AB}$ / DF	MS_{AB} / MS_E	
AC	1	SS_{AC}	$MS_{AC} = SS_{AC}$ / DF	MS_{AC} / MS_E	
BC	1	SS_{BC}	$MS_{BC} = SS_{BC}$ / DF	MS_{BC} / MS_E	
ABC	1	SS_{ABC}	$MS_{ABC} = SS_{ABC}$ / DF	MS_{ABC} / MS_E	
Experimental Error	369 = k*(n-1)	SS_E	$MS_E = SS_E$ / DF		
Total	377 = (k-1)+(k*(n-1))	SS_T			

Table 3.6: Additional information needed to use the ANOVA Table

treatments	k = 9
pseudoreplications	n = 42
Probability level	$\alpha = 0.05$
F_{crit}	F(k-1), (k*(n-1)), alpha = 3.974
Sum of Squares for Treatments	$SS_{TR} = SS_1 + SS_2$
Sum of Squares Residual	$SS_2 = SS_A + SS_B + SS_C + SS_{AB} + SS_{AC} + SS_{BC} + SS_{ABC}$
Sum of Squares Total	$SS_T = SS_{TR} + SS_E$
Null Hypothesis	H_0: no difference between mean of runs
Alternative Hypothesis	H_a: at least one is different
Rule of Rejection for H_o	If $F_{calc} > F_{crit}$: reject H_o

The results will reveal if there is a difference, but they will not show which of the treatments is different from the other. In order to detect differences between treatments, the Bonferroni test was implemented. This test is used when there are multiple outcome measures and, in addition, it uses an adjusted alpha-level to raise its standard of proof when simultaneously investigating a wide range of hypotheses. The following equation was used to calculate the Bonferroni critical difference:

$$CD = t * \sqrt{\frac{2MSE}{n}} \tag{4}$$

Table 3.7: Additional information needed to use the Bonferroni test

CD	Critical difference
Replications	n = 42
Adjusted probability level	$\alpha = 0.002083$
Mean Squares for Experimental Error	MSE
t	2.8832
n	42
Degrees of freedom	369
Rule significant difference	If actual difference > CD

Due to the significant influence of the difference in final moisture contents, a different statistical approach was called for when comparing core moisture content, twist, and diamonding. In order to eliminate the effects of the differences in final moisture content on the experimental results, it was necessary to use the Analysis of Covariance (ANCOVA). Computer software called SAS was used to calculate the ANCOVA Tables shown in the "Results and Discussion" section.

For meaningful comparisons the level of significance had to be calculated using the following equation:

$$\alpha = \frac{0.05}{\frac{9!}{7!*2!}} = 0.00138 \qquad (5)$$

An overview flowchart of the experimental set up is shown in Figure 3.23.

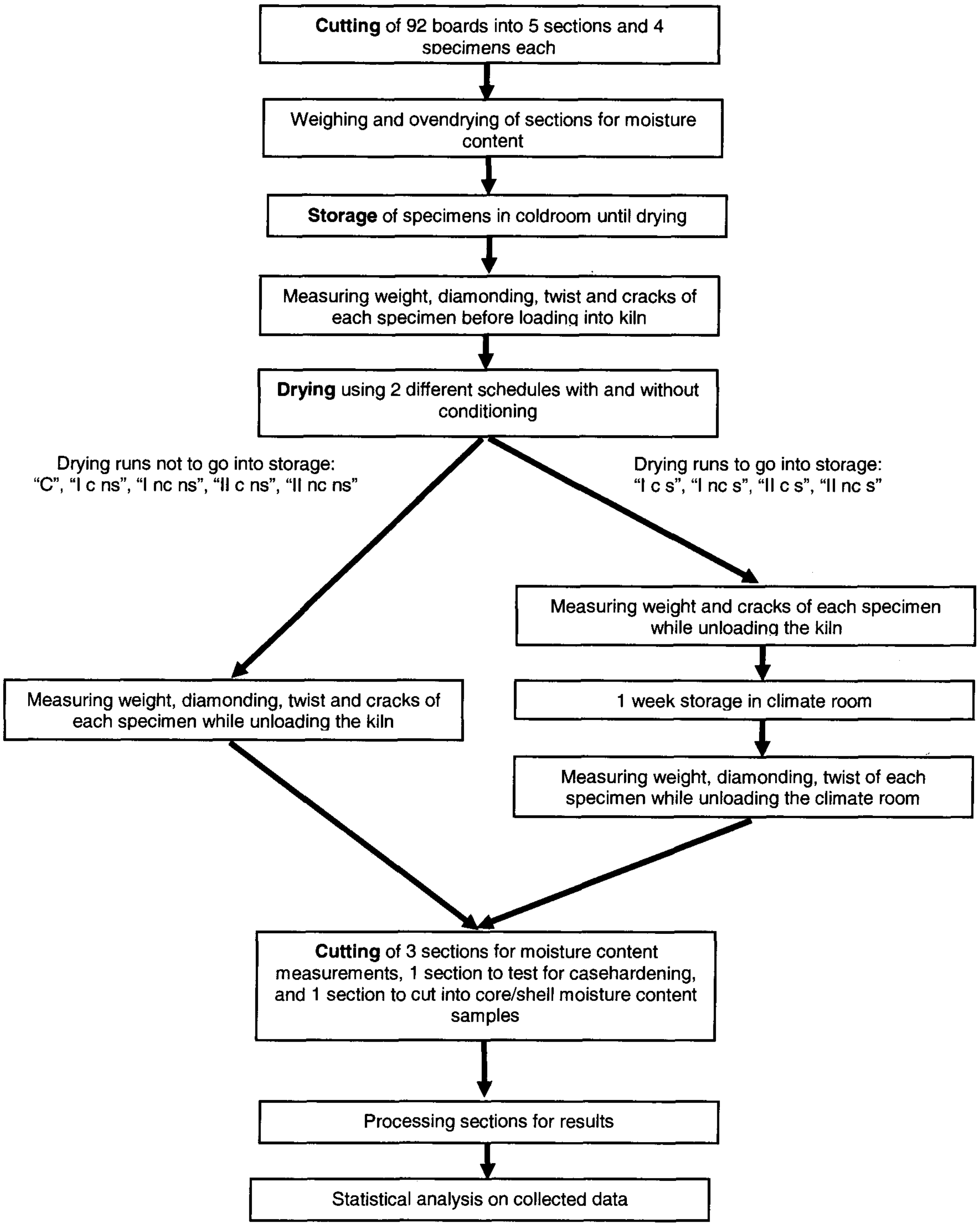


Figure 3.22: Experimental flowchart

4. Results and Discussion

4.1 Basic density

The average basic density of the 384 specimens was 380kg/m^3, and varied from 198kg/m^3 to 570kg/m^3 with a standard deviation of 44kg/m^3. Three timbers, namely 58, 60 and 69, had a considerably lower density (averages of 295, 292, and 200kg/m^3) than the majority of the timbers. These timbers might have been fir that was mixed in with the hemlock.

These results are comparable to findings that other researchers have reported for western hemlock, such as Zhang et al. (1996), who reported a range from 316 to 563kg/m^3 and Li et al. (1997), whose specimens ranged from 261 to 540kg/m^3. The hemlock Wallace (2001) used gave basic density averages of 389kg/m^3 and 455kg/m^3. Avramidis and Oliveira (1993) and Zhang et al. (1996) discovered an influence of basic density on drying time, in addition to core and shell moisture content differences. In order to minimize the influence of basic density on the drying of the specimens, the specimens were statistically sorted into 9 groups with almost identical basic density averages and standard deviations. Table 4.1 shows basic density values and their standard deviations for each drying run.

Table 4.1: Comparison of basic density [kg/m^3] for all 9 drying runs

	Mean	St. Dev.	Min	Max
All 384 specimens	380	44	198	570
"Control"	380	46	204	494
"I c s"	380	45	285	483
"I c ns"	382	37	306	479
"I nc ns"	384	39	298	496
"I nc s"	379	40	299	472
"II c s"	385	32	338	479
"II c ns"	387	43	288	504
"II nc ns"	377	47	290	516
"II nc s"	383	45	308	597
Min of all 9 runs	377	32		
Max of all 9 runs	387	47		

Each of the nine groups had 42 specimens with a total of 378 out of the original 384 specimens used for this experiment. The average basic density of the nine groups ranged from 377 to 387kg/m^3 and the standard deviations ranged from 32 to 47 kg/m^3. The t-Tests in Table 7.2 in the Appendix illustrate no significant differences between average basic densities of the nine drying runs.

4.2 Initial moisture content

The average green moisture content of the 384 specimens ranged from 33.5% to 168.3%, with the majority of specimens ranging from 60% to 100%, as illustrated in Figure 4.3.

These moisture content results fall within the range of Nielson et al. (1985) who reported 55% for heartwood and 143% for sapwood when considering western hemlock. Wallace (2001) confirmed moisture contents of 75.3% and 59.5% respectively. These specimens showed an average of 79.7% and a standard deviation of 24.5. The high variation in green moisture content may be attributed to the occurrence of wet pockets and high sapwood moisture content (Kozlik, 1970). As mentioned previously, the nine drying runs were sorted statistically to achieve an equal average moisture content and standard deviation for each run. The t-Tests performed, as seen in Table 7.2 in the Appendix, demonstrate no significant difference between the average initial moisture contents of the nine drying runs. The purpose was to minimize the influence of the green moisture content on the drying time. As a result, the nine drying runs showed initial moisture contents ranging from 77.3% to 81.2% with standard deviations from 20.3 to 30.1, respectively; see Table 4.2 for details.

Table 4.2: Initial moisture content [%] for each drying run

	Mean	St. Dev.	Min	Max
All 384specimens	78.7	24.5	33.5	168.3
"Control"	77.3	30.0	34.2	168.4
"I c s"	79.5	23.6	46.6	149.9
"I c ns"	78.1	20.3	49.6	140.6
"I nc ns"	80.1	27.0	43.2	155.7
"I nc s"	80.7	25.4	43.4	158.2
"II c s"	79.1	21.2	48.1	156.6
"II c ns"	81.2	24.3	47.3	151.5
"II nc ns"	78.6	25.8	33.5	143.9
"II nc s"	78.1	24.3	40.8	148.4
Min of all 9 runs	77.3	20.3		
Max of all 9 runs	81.2	30.1		

4.3 Drying times

The actual drying times for the nine runs ranged from 229 hours to 528 hours. The drying schedule used for the "Control" was the mildest schedule and it took the longest to finish, which was expected. The runs using schedule "II" finished the fastest. Hao and Avramidis (2004) used the "Control" schedule and experienced drying times of 574.9, 391.6 and 293.6 hours with target moisture contents of 12, 15 and 20% respectively, which confirms to the drying times of this study.

In order to compare the drying times of the nine runs, the drying times had to be normalized. This was necessary due to the fact that each run had different initial and final moisture contents. The drying times became comparable when counting only the hours of drying from the lowest green moisture content to the highest final moisture content that the nine runs had in common. This way all nine runs had the same start and end points for their moisture contents. These normalized drying times ranged from 154 to 264 hours (Table 4.3).

Table 4.3: Drying times for each drying run [hrs]

	"Control"	"I c s"	"I c ns"	"I nc ns"	"I nc s"	"II c s"	"II c ns"	"II nc ns"	"II nc s"
Absolute Drying Time	528.17	297.50	325.13	314.83	292.67	264.33	299.67	229.17	292.67
Normalized Drying Time	264.67	244.00	256.50	234.33	235.50	165.83	166.00	173.83	154.17

The "Control" run was still the slowest run; however, it was very closely followed by the drying runs using schedule "I", while schedule "II" demonstrated a significantly faster drying time. Figure 4.1 clearly shows a difference in drying times between schedule "I" and schedule "II", which is due to the more aggressive schedule "II". The drying times were influenced by the drying schedules, as well as, by experimental and equipment related errors that could not be avoided.

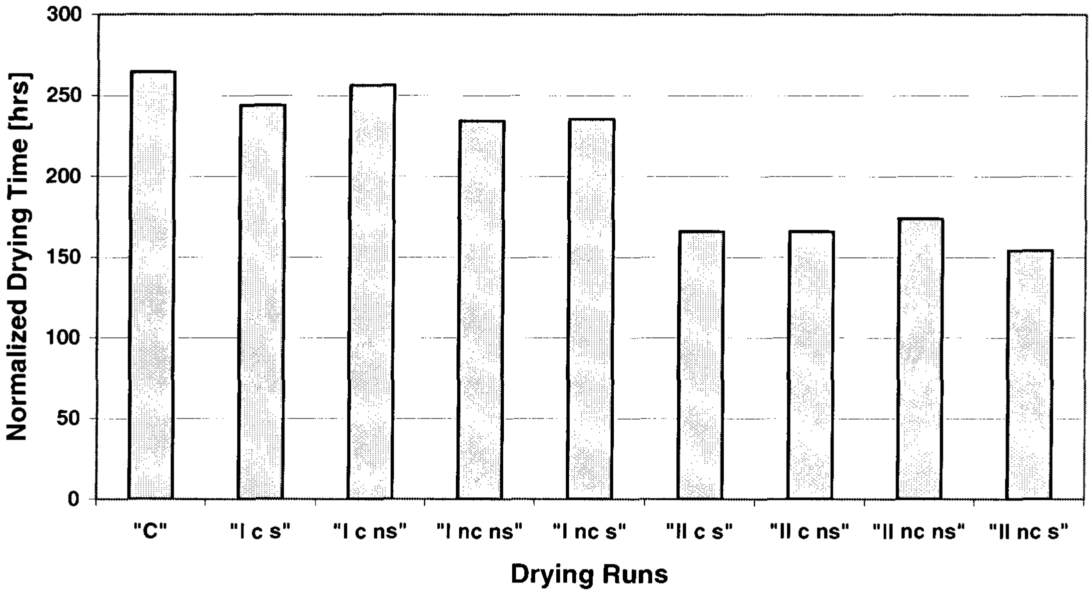


Figure 4.1: Normalized drying times for all nine runs

4.4 Drying curves

The drying curves for this study indicate that the moisture contents decreased with time. The steepness of the slope illustrates the speed of drying during the different phases of the drying process. At the beginning of the drying process the slope is very steep, because the free water evaporates fast and the speed of drying is high. Towards the end of the process, the drying rate is decreased and the slope flattens out. The drying slows down after the free water is evaporated and only the bound water remains. Removing bound water takes more energy than removing free water from the timber, thus, the slow rate.

See Appendix Figure 7.1 to Figure 7.8 for the drying curves of the experimental runs. All nine drying curves have been normalized by moving green moisture contents for each run to the same starting point. As a result, the slopes and lengths of the runs can be compared directly. Normalizing drying curves is a fairly accurate approximation and this procedure can be accepted as appropriate based on experiences provided by Avramidis and Hao (2004), Bradic, (2005) and Sackey (2003).

As seen in Figure 4.2, at the very beginning all schedules start off similarly, due to the warm up period but soon after they split according to the individual drying schedules. The "Control" has the flattest slope and hence, the mildest drying. Schedule "I" shows a steeper slope at the beginning, then later in the drying run, it overlaps with the "Control" run. By using this schedule, the drying is much harsher at the beginning, but finishes rather mildly. Schedule "II" is a harsher drying schedule overall, which shows in the steeper slope during the entire drying time. Both runs that did not include a conditioning phase were finished faster. Each drying curve changes with the schedule used and is unique. The drying curves of each run were not only influenced by variations in the timber, but experimental and equipment related errors, like power outages or accidental shuting of the steam.

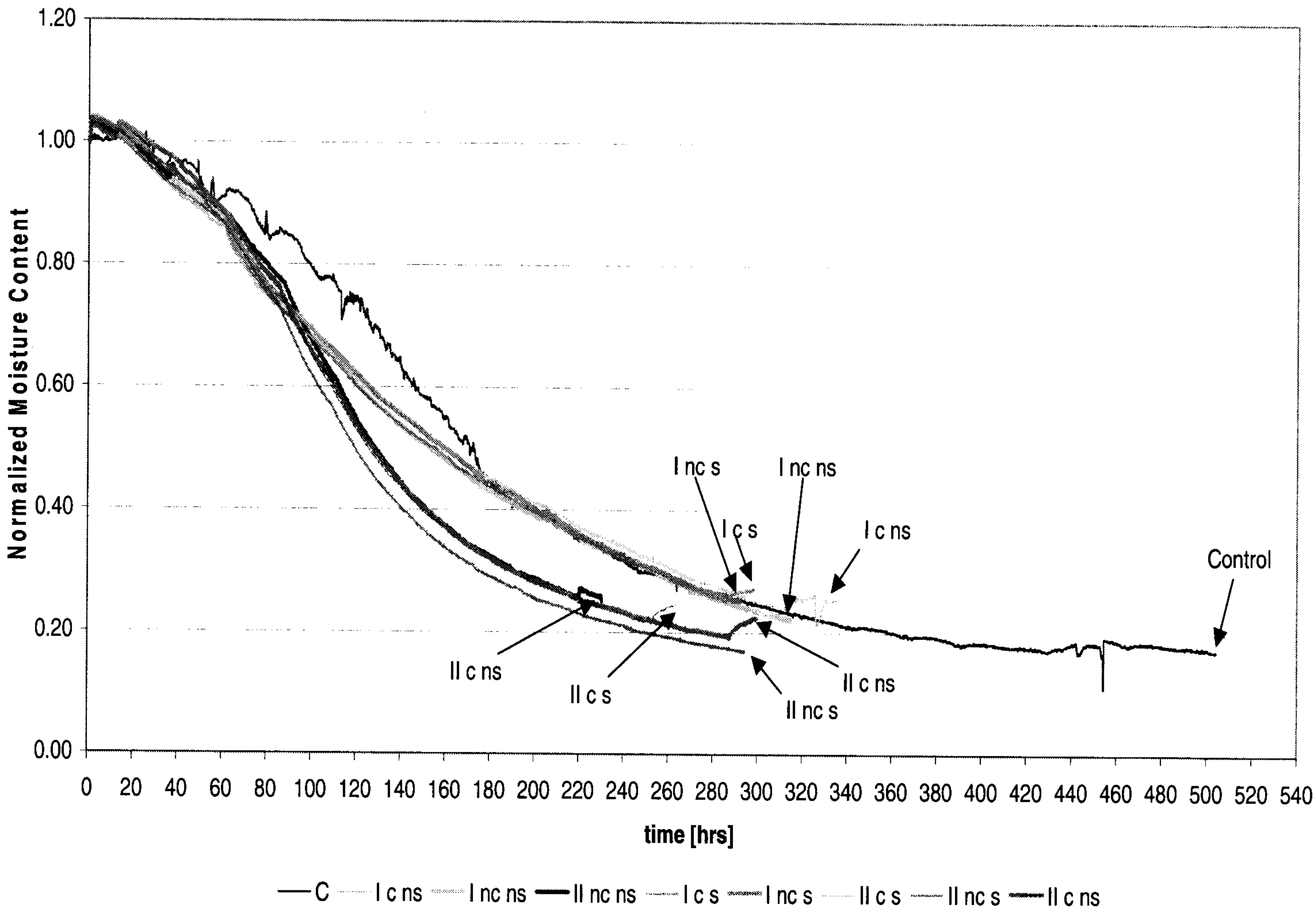


Figure 4.2: Normalized drying curves for all runs

4.5 Final moisture contents

The results of the final moisture contents for all the nine runs ranged from 10.9% to 17.0% and averaged 14.1%, while the target moisture content was set to 12%. The averages, standard deviations, as well as, minimum and maximum values for each drying run are shown in Table 4.4.

Table 4.4: Comparison of the final moisture contents [%]

	Mean	St. Dev.	Min	Max
"Control"	10.87	2.19	7.39	20.00
"I c s"	17.02	4.17	11.49	27.53
"I c ns"	14.94	5.01	8.78	27.44
"I nc ns"	14.36	6.26	8.36	39.53
"I nc s"	16.05	4.72	10.26	28.02
"II c s"	14.26	3.43	10.15	25.93
"II c ns"	12.15	3.42	7.30	25.85
"II nc ns"	15.94	5.70	10.15	42.24
"II nc s"	11.09	3.39	7.12	24.15
Min of all 9 runs	10.87	2.19	-	-
Max of all 9 runs	17.02	6.26	-	-

The wide distribution of final moisture contents between the runs provided a problematic situation when comparing lumber qualities. The discrepancy is to some extent related to equipment error. It also should be noted that the effect of the timber plays a significant role in the results of the final moisture contents. The lack of uniformity in the final moisture contents has been observed by other researchers and in addition, could be due to wet pockets which are found in hemlock (Kozlik and Hamlin, 1972; Zhang et al., 1996 and Bradic and Avramidis, 2007). The final moisture content gives important information about the timber because of its influence on the timber's shape stability in the future. Timbers with final moisture contents below target could develop unacceptable degradation while higher final moisture contents could negatively affect the commercial value of the final product. The statistical analysis of the lumber's quality parameters had to be adjusted to eliminate the influence of the final moisture contents.

ANOVA (Table 4.5) was performed on the final moisture content measurements. This statistical analysis showed an apparent significant influence of the treatments on the final moisture content. A difference between the treatment runs and the "Control" run was also evident. The interaction of schedule, conditioning and storage shows significant influence on the final moisture content as does the interaction of conditioning and storage and the interaction of schedule and storage. Furthermore, the interaction of schedule and storage was statistically significant. Consequently, the drying schedule had a significant influence on the final moisture content.

Table 4.5: ANOVA for the final moisture content

Source of Variation	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Squares (MS)	F_o	Significantly Different?
Treatment	7	1673.18	239.0263	12.2130	**Yes**
"Control" vs all	1	486.84	486.8444	24.8753	**Yes**
A (schedule)	1	417.89	417.8890	21.3520	**Yes**
B (conditioning)	1	4.53	4.5315	0.2315	No
C (storage)	1	5.62	5.6200	0.2871	No
A*B	1	24.72	24.7181	1.2629	No
A*C	1	223.21	223.2061	11.4047	**Yes**
B*C	1	283.35	283.3471	14.4776	**Yes**
A*B*C	1	227.03	227.0275	11.5999	**Yes**
Experimental Error	369	7221.83	19.5713		
Total	377	8895.01			

The four runs that were put into post-drying storage had their moisture contents measured before and after storage. Pre-storage, the moisture contents ranged from 6.3 to 40%, while post-storage, the final moisture contents ranged from 7.1 to 28.0%, which can be seen in Table 4.6.

Table 4.6: Moisture contents before and after storage [%]

	"I c s"		"I nc s"		"II c s"		"II nc s"	
	Before storage (M_{KD})	**After storage (M_{final})**	**Before storage (M_{KD})**	**After storage (M_{final})**	**Before storage (M_{KD})**	**After storage (M_{final})**	**Before storage (M_{KD})**	**After storage (M_{final})**
Mean	20.5	17.0	18.2	16.1	16.0	14.3	11.6	11.1
st. dev.	6.9	4.2	7.9	4.7	5.4	3.4	5.1	3.4
Min	10.7	11.5	9.1	10.3	10.0	10.2	6.3	7.1
Max	39.4	27.5	40.2	28.0	35.0	25.9	33.2	24.2

Each of the four runs lost moisture during storage which was due to the relatively high post-drying moisture contents compared to the conditions of the climatized storage room. The average moisture content loss during storage ranged from 0.5 to 3.5%, with three out of four runs showing no significant moisture content loss while in storage. Run “I c s” had a significant loss in moisture content during storage; however, this run also showed the highest moisture content after drying, so a higher moisture loss was to be expected.

Table 4.7: t-Test for significant difference of moisture content pre- and post-storage

Run	**M loss [%]**	t_{calc}	t_{crit}	**sig. diff.**
“I c s”	3.5	2.726	1.989	**Yes**
“I nc s”	2.1	1.737	1.989	No
“II c s”	1.7	1.763	1.989	No
“II nc s”	0.5	0.495	1.989	No

Runs that used schedule “II” for drying lost less moisture than runs dried with schedule “I”; ultimately, this was due to their lower average post-drying moisture content after drying (please see Figure 4.3).

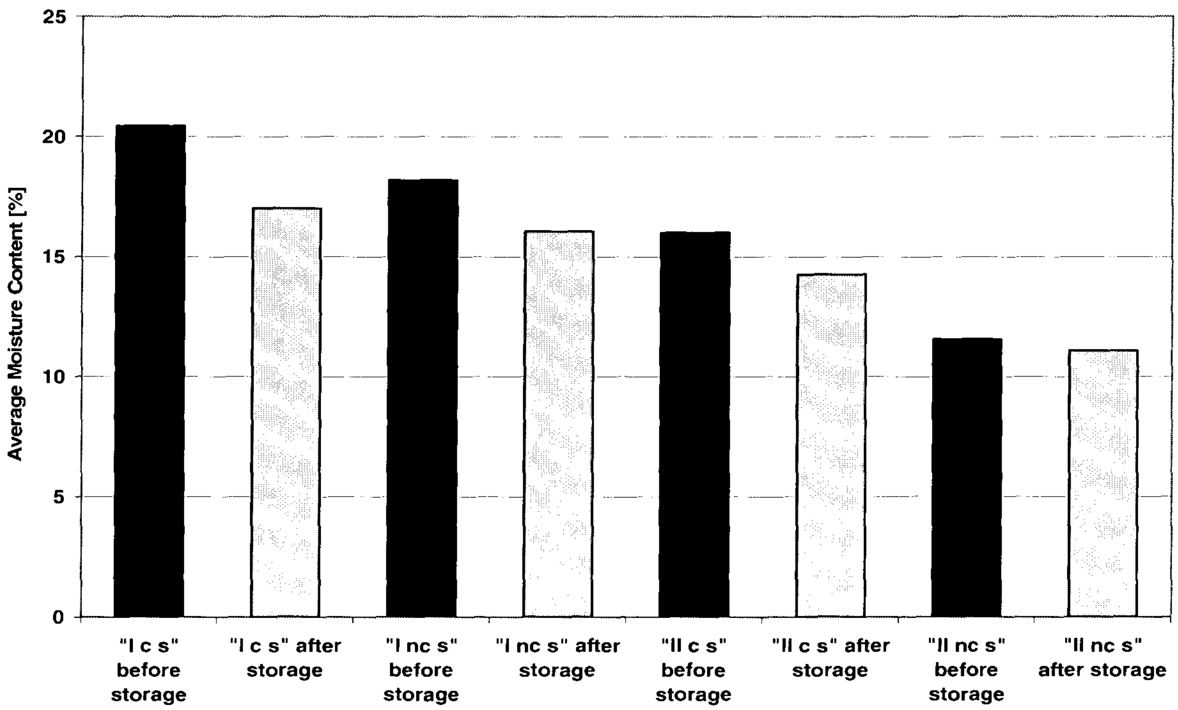


Figure 4.3: Comparison of the average moisture contents before (dark grey) and after (light grey) storage

The timber's cores had average moisture contents of 21.7%, ranging from 14.9 to 28.56% for the nine runs, as shown in Table 4.8 and illustrated in Figure 4.4.

Table 4.8: Comparisons of the core moisture contents [%]

	Mean	St. Dev.	Min	Max
"Control"	14.98	4.80	8.03	31.23
"I c s"	25.75	11.02	13.90	65.90
"I c ns"	26.73	15.70	11.23	96.10
"I nc ns"	24.73	12.82	11.29	69.65
"I nc s"	23.78	9.52	12.56	52.27
"II c s"	21.92	8.50	12.59	44.42
"II c ns"	19.20	9.88	8.26	53.74
"II nc ns"	28.58	5.21	12.15	34.84
"II nc s"	16.69	8.96	8.15	57.41
Min of all 9 runs	14.98	4.80		
Max of all 9 runs	28.58	12.82		

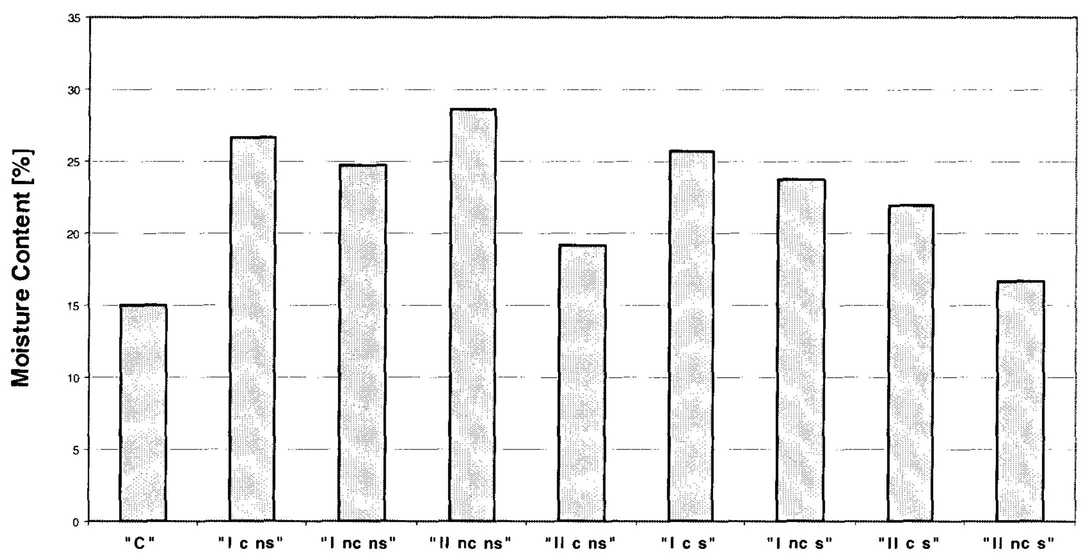


Figure 4.4: Final moisture contents of the core for all nine drying runs

Close examination of the core moisture contents for the nine experimental runs revealed that they are more uniform when using schedule "I" than when using schedule "II". This could be attributed to the different average final moisture contents. Moreover, the treatments with the seven day storage period had lower core moisture contents. The final core moisture contents were influenced by the overall final moisture contents of the lumber and therefore, the ANCOVA had to be used to eliminate this influence.

Table 4.9: ANCOVA results for core moisture contents ($\alpha = 0.05$)

Source	DF	Type III SS	Mean Square	F value	Pr > F	
X (M_{final})	1	31038.7315	31.0387	311.77	<0.0001	Need to adjust for M_{final}
Treatments	8	1331.0308	166.3788	1.67	0.1039	
Contrast	**DF**	**Contrast SS**	**Mean Square**	**F value**	**Pr > F**	
"Control" vs All	1	32.2582	32.2582	0.32	0.5696	
A (schedule)	1	75.0944	75.0944	0.75	0.3857	
B (conditioning)	1	23.3454	23.3454	0.23	0.6285	
C (storage)	1	920.0948	920.0948	9.24	0.0025	sig. diff.
A*B	1	68.6868	68.6868	0.69	0.4067	
A*C	1	200.4595	200.4595	2.01	0.1568	
B*C	1	2.2088	2.2088	0.02	0.8817	
A*B*C	1	5.0456	5.0456	0.05	0.8220	

When analyzing the results of the ANCOVA (Table 4.9), it becomes transparent that storage had a significantly positive influence on the core moisture contents. All other treatments did not show a significant influence on the core moisture contents during the course of this experiment.

According to Table 4.10, there are no significantly different meaningful comparisons for core moisture contents.

Table 4.10: Meaningful comparisons for core moisture content ($\alpha = 0.00138$)

Compared drying runs		probability	Significantly different
"I c ns"	"II c ns"	0.4270	No
"I c ns"	"I nc ns"	0.7162	No
"I c ns"	"I c s"	0.0162	No
"I nc ns"	"II nc ns"	0.7984	No
"I nc ns"	"I nc s"	0.0418	No
"I c s"	"II c s"	0.3926	No
"I c s"	"I nc s"	0.9869	No
"II c ns"	"II nc ns"	0.4954	No
"II nc ns"	"II nc s"	0.4177	No
"II c s"	"II nc s"	0.5416	No
"II c s"	"II c ns"	0.4496	No
"I nc s"	"II nc s"	0.1568	No

Table 4.10 continued: Meaningful comparisons for core moisture content (α = 0.00138)

"C"	**"I c s"**	0.3878	No
"C"	**"I nc s"**	0.3895	No
"C"	**"I c ns"**	0.1384	No
"C"	**"I nc ns"**	0.2566	No
"C"	**"II c s"**	0.9642	No
"C"	**"II nc s"**	0.5662	No
"C"	**"II c ns"**	0.4754	No
"C"	**"II nc ns"**	0.1738	No

Post-drying, the core generally shows a higher moisture content than the shell. This was also true for the present study. The difference in core and shell moisture contents are usually due to the fact that the drying starts in the surface layers and thus, the shell dries first while the core takes longer to dry. This can generate high moisture content gradients in thick timbers, which can be partially corrected with conditioning and storage as shown in this research.

For this experiment, the shell moisture contents ranged from 11.4 to 17.6% with a total average of 14.5%. The minimum and maximum moisture contents of the shell for the nine runs ranged from 6.1 to 35.2% as shown in Table 4.11. It should be noted, that schedule "I" had lower shell moisture contents than schedule "II" (Figure 4.5).

Table 4.11: Comparison of the shell moisture contents [%]

	Mean	**St. Dev.**	**Min**	**Max**
"Control"	11.39	2.74	7.52	24.02
"I c s"	17.58	4.55	11.87	35.22
"I c ns"	15.52	5.98	8.63	34.56
"I nc ns"	14.39	5.75	7.64	32.44
"I nc s"	16.12	4.62	10.23	35.39
"II c s"	15.04	2.76	11.01	22.07
"II c ns"	13.08	4.08	8.36	26.39
"II nc ns"	15.86	4.11	10.54	25.97
"II nc s"	11.54	3.10	6.06	22.74
Min of all 9 runs	11.39	2.74		
Max of all 9 runs	17.58	5.98		

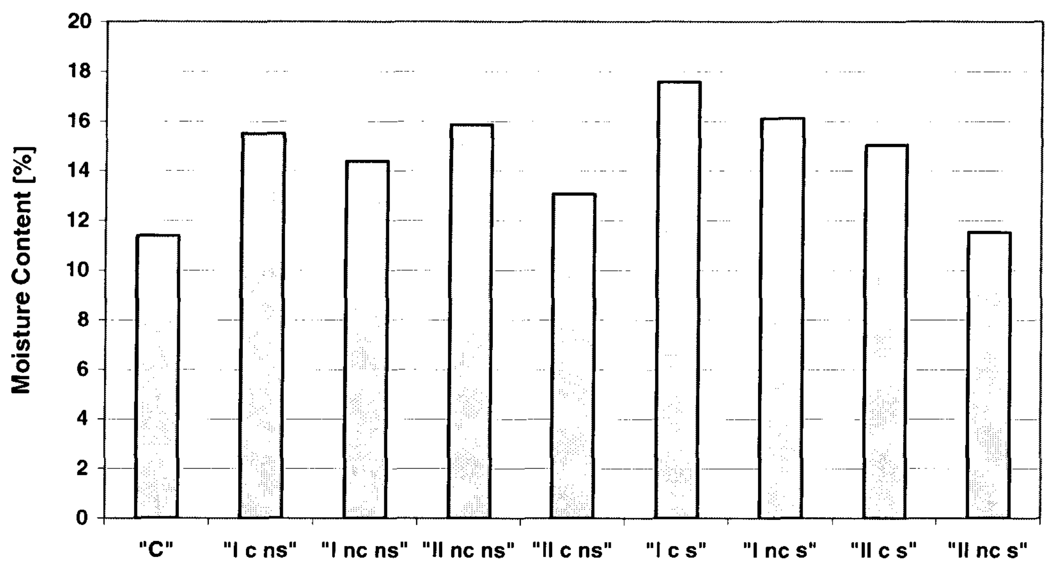


Figure 4.5: Final moisture contents of the shell for all nine drying runs

According to the statistics, the final moisture content did not influence the shell moisture contents; consequently, the ANOVA could be used.

Table 4.12: ANOVA results for shell moisture content (F_{crit} = 3.974)

Source of Variation	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Squares (MS)	F_o	sig. diff.
Treatment	7	1503.46	214.78	11.393	**Yes**
"Control" vs all	1	459.26	459.26	24.362	**Yes**
A (schedule)	1	343.45	343.45	18.218	**Yes**
B (conditioning)	1	56.99	56.99	3.023	No
C (storage)	1	10.83	10.83	0.574	No
A*B	1	18.38	18.38	0.975	No
A*C	1	198.87	198.87	10.549	**Yes**
B*C	1	229.65	229.65	12.182	**Yes**
A*B*C	1	185.98	185.98	9.865	**Yes**
Experimental Error	369	6956.19	18.85		
Total	377	8459.65			

Interpretation of the ANOVA results shown in Table 4.12 confirms that the interaction of all three treatments had a significant influence on the shell moisture content; as did the interaction of storage and conditioning and the interaction of schedule and storage. The main factor schedule also showed a significant influence: schedule "I" produced lower shell moisture contents than schedule did "II". The "Control" run had significantly different shell moisture contents when compared to the treatment runs.

When analysing the meaningful comparisons in Table 4.13, the "Control" run is significantly different from six of the treatment runs. The "Control" run showed a lower shell moisture content than both schedules "I" and "II" without conditioning or storage; the "Control" had lower shell moisture contents than both schedules with conditioning and storage. Moreover, the "Control" was lower in shell moisture content than schedule "I" either with conditioning or storage ("I nc s", "I c ns"). Run "II nc s" showed a significantly lower shell moisture content than either "II nc ns", "II c s" or "I nc s". But there seemed to be no logical pattern developing in the significantly different pairs in Table 4.13.

Table 4.13: Meaningful comparisons for the shell moisture content

		Critical Difference	**Actual Difference**	**Significantly Different**
"I c ns"	**"II c ns"**	2.73	2.44	No
"I c ns"	**"I nc ns"**	2.73	1.13	No
"I c ns"	**"I c s"**	2.73	3.19	**Yes**
"I nc ns"	**"II nc ns"**	2.73	1.47	No
"I nc ns"	**"I nc s"**	2.73	1.73	No
"I c s"	**"II c s"**	2.73	2.54	No
"I c s"	**"I nc s"**	2.73	1.46	No
"II c ns"	**"II nc ns"**	2.73	2.78	**Yes**
"II nc ns"	**"II nc s"**	2.73	4.32	**Yes**
"II c s"	**"II nc s"**	2.73	3.50	**Yes**
"II c s"	**"II c ns"**	2.73	1.96	No
"I nc s"	**"II nc s"**	2.73	4.58	**Yes**
"C"	**"I c s"**	2.73	6.19	**Yes**
"C"	**"I nc s"**	2.73	4.73	**Yes**
"C"	**"I c ns"**	2.73	4.13	**Yes**
"C"	**"I nc ns"**	2.73	3.00	**Yes**
"C"	**"II c s"**	2.73	3.65	**Yes**
"C"	**"II nc s"**	2.73	0.15	No
"C"	**"II c ns"**	2.73	1.69	No
"C"	**"II nc ns"**	2.73	4.47	**Yes**

The specimens were sorted into pith location classes as mentioned in detail in the "Materials and Methods". Most specimens (219 out of 378) did not show the pith located within the specimens' cross section or inside a 30mm perimeter around it (pith location **D**). For pith location **C** (pith located inside the 30mm perimeter around the cross section) there were 84 specimens, while 73 specimens showed the pith inside the first 30mm rim of their cross section (pith location **B**). Only two specimens had the pith located right in the middle of its cross section (pith location **A**). When examining Table 4.14, it gives the impression that every drying run had approximately the same distribution of pith locations.

Table 4.14: Amount of pith locations per drying run

	"Control"	"I c ns"	"I nc ns"	"II nc ns"	"I c s"	"I nc s"	"II c s"	"II nc s"	"II c ns"
A	0	0	0	0	0	1	0	1	0
B	8	9	10	11	8	8	5	6	8
C	11	12	11	9	7	9	10	6	9
D	23	21	21	22	27	24	27	29	25

The final moisture content for each specimen was sorted by its pith location and by drying runs (Figure 4.6). The moisture content of each pith location was influenced by the sapwood/juvenile wood content. Specimens with a higher content of mature wood showed higher final moisture contents, which was confirmed by Bradic (2005).

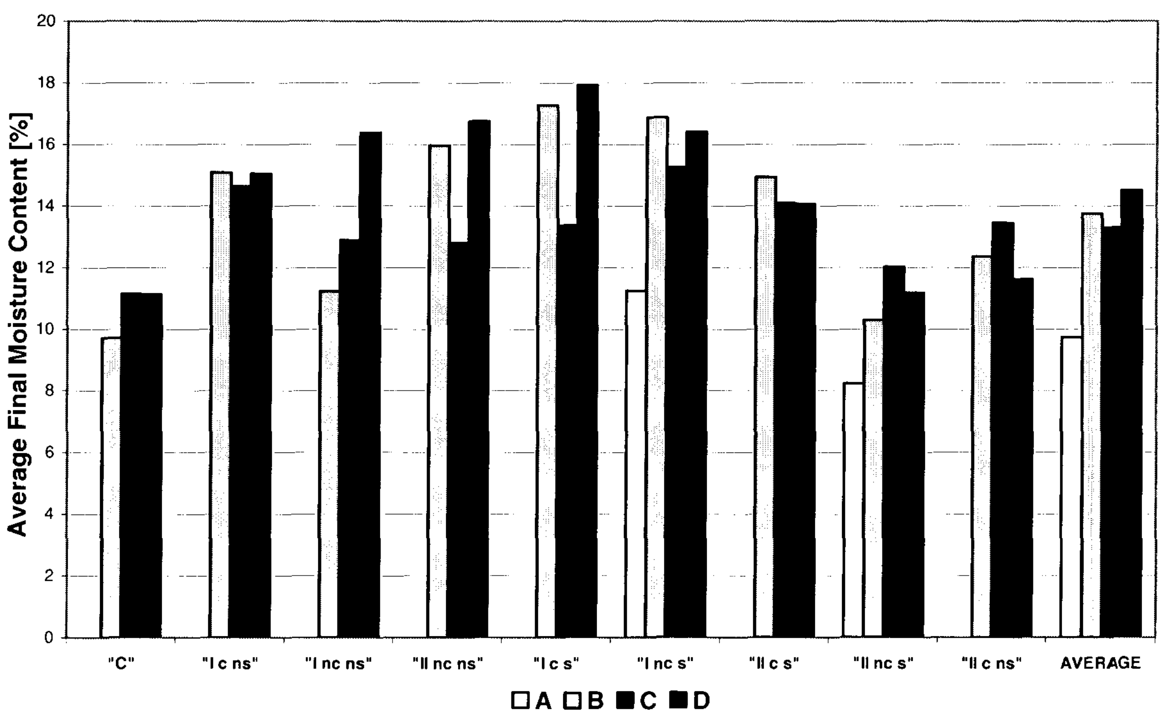


Figure 4.6: Average final moisture contents for each pith location sorted by run

Table 4.15 lists the average final moisture contents sorted by pith location and drying run, in addition to the average final moisture content of each pith location group. When considering these averages, it shows that the further the pith is distanced from the center of the cross section, the higher its final moisture content becomes, since the specimen moves further into the tree's sapwood. However, according to Bradic and Avramidis (2007), pith location does not have an influence on the final moisture content. The seven day storage seems to be able to lower the average final moisture content for each pith location.

Table 4.15: Final moisture content sorted by pith locations

		"C"	"I c ns"	"I nc ns"	"II nc ns"	"I c s"	"I nc s"	"II c s"	"II nc s"	"II c ns"	mean
A	**mean**						11.25		8.23		**9.74**
	max										**11.25**
	min										**8.23**
	st. dev.										**2.14**
B	**mean**	9.73	15.08	11.23	15.97	17.27	16.88	14.95	10.30	12.36	**13.75**
	max	12.24	27.44	16.06	42.24	26.46	27.92	21.92	12.11	19.21	**17.27**
	min	7.39	9.93	8.81	10.40	11.80	11.34	11.01	8.84	9.10	**9.73**
	st. dev.	2.19	5.34	4.08	8.96	4.81	5.93	4.30	1.22	3.31	**2.89**
C	**mean**	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	max	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	min	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	st. dev.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	mean	11.13	15.06	16.38	16.76	17.93	16.41	14.07	11.19	11.62	**14.51**
D	**max**	20.00	24.60	39.53	27.03	27.53	28.02	25.93	24.15	17.10	**17.93**
	min	8.91	8.79	9.37	10.88	12.55	10.26	10.52	7.63	8.56	**11.13**
	st. dev.	2.40	4.74	7.55	4.15	3.92	4.77	3.37	3.38	2.35	**2.62**

Table 7.3 in the Appendix indicates a possible correlation of the final moisture contents in regards to the location of the specimens in the kiln. Examination of the mean final moisture contents of the rows of each kiln load confirms that the lower rows show slightly higher moisture contents when compared to the upper rows of a kiln load.

4.6 Final moisture content distribution limits

During the evaluation of the final moisture content of a kiln run, it is customary in the wood industry to sort the timber into three groups of moisture content: on target, over-dried and under-dried. In terms of quality control, it is more convenient to look at those groups instead of a long list of individual moisture contents. The most common practice is to declare timbers with final moisture contents below 10% as over-dried and timbers with final moisture contents above 19% as under-dried. After applying this rule to the final moisture contents of the nine runs in this experiment, the specimens were sorted by numbers and percentages of over and under-dried timbers listed in Table 4.16.

Table 4.16: Absolute numbers and percentages of over- and under-dried specimens per run (over-dried is below 10% M, under-dried is above 19% M and target is between 10% and 19% M)

	"C"	"I c ns"	"I nc ns"	"II nc ns"	"I c s"	"I nc s"	"II c s"	"II nc s"	"II c ns"
Mean M_{final} [%]	10.9	14.9	14.4	15.9	17.0	16.1	14.3	11.1	12.2
St. Dev. [%]	2.2	5.0	6.3	5.7	4.2	4.7	3.4	3.4	3.4
Min [%]	7.4	8.8	8.4	10.2	11.5	10.3	10.2	7.1	7.3
Max [%]	20.0	27.4	39.5	42.2	27.5	28.0	25.9	24.2	25.9
ABSOLUTE	"C"	"I c ns"	"I nc ns"	"II nc ns"	"I c s"	"I nc s"	"II c s"	"II nc s"	"II c ns"
over-dried	15	5	8	0	0	0	0	17	13
under-dried	1	7	6	7	11	9	6	2	2
target	26	30	28	35	31	33	36	23	27
%	"C"	"I c ns"	"I nc ns"	"II nc ns"	"I c s"	"I nc s"	"II c s"	"II nc s"	"II c ns"
over-dried	35.7	11.9	19.1	0.0	0.0	0.0	0.0	40.5	30.9
under-dried	2.4	16.7	14.3	16.7	26.2	21.4	14.3	4.8	4.8
target	61.9	71.4	66.7	83.3	73.8	78.6	85.7	54.8	64.3

Most specimens of each of the nine runs fell into the target category, which was expected when considering that the range was from 10 to 19%. The graph in Figure 4.7 confirms this impression and also shows a relatively large number of under-dried specimens.

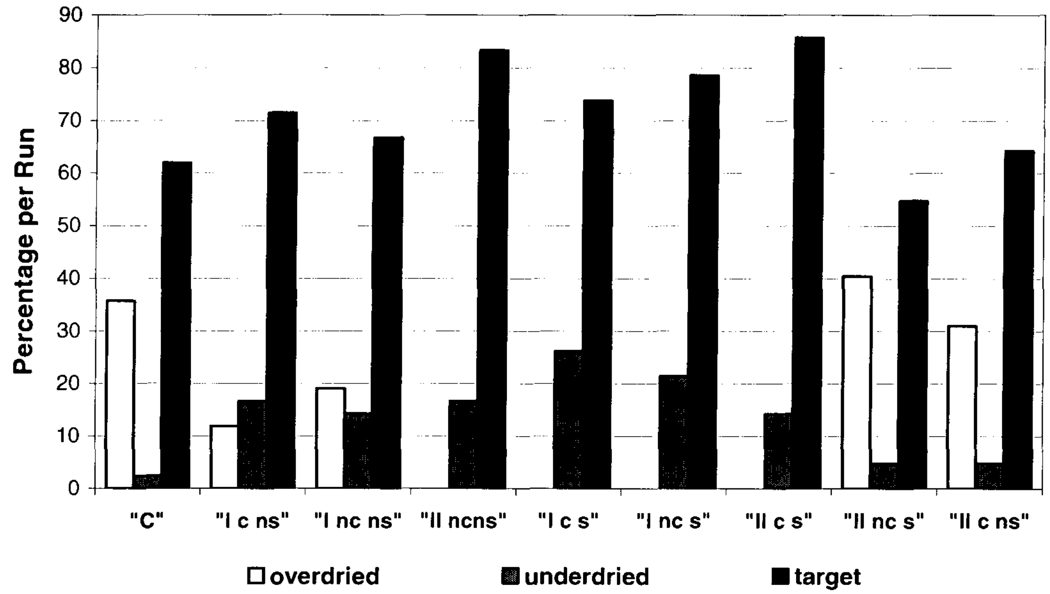


Figure 4.7: Percentages of over and under-dried specimens per run (over-dried is below 10%M, under-dried is above 19% M and target is between 10% and 19% M)

The aforementioned sorting rules might not be appropriate for this study when considering the wide range of final moisture contents. In order to sort moisture content groups, a different approach was used. Each run was analyzed individually when creating the three groups. The target was considered to be met when the final moisture content was within three percentage points of the average final moisture content of the individual run. The group of over-dried specimens was considered to be below the run's average moisture content, minus three percentage points, while the group of under-dried specimens was above the average, plus three percentage points. This method was used with each of the nine drying runs and the comparisons can be seen in Table 4.17 as absolute numbers of specimens for each group, along with percentages.

Table 4.17: Absolute numbers and percentages of over and underdried specimens per run

ABSOLUTE	"C"	"I c ns"	"I nc ns"	"II nc ns"	"I c s"	"I nc s"	"II c s"	"II nc s"	"II c ns"
over-dried	1	13	17	12	9	12	5	3	5
under-dried	2	9	8	7	8	9	7	5	4
target	39	20	17	23	25	21	30	34	33
%	"C"	"I c ns"	"I nc ns"	"II nc ns"	"I c s"	"I nc s"	"II c s"	"II nc s"	"II c ns"
over-dried	2.4	30.9	40.5	28.6	21.4	28.6	11.9	7.1	11.9
under-dried	4.8	21.4	19.1	16.7	19.1	21.4	16.7	11.9	9.5
target	92.9	47.6	40.5	54.8	59.5	50.0	71.4	80.9	78.6

This sorting procedure produced a higher percentage of over-dried specimens across all runs. This fact was due to the narrower range for the "on target group". Consequently, the percentage of specimens on target is smaller as well. As can be seen in Figure 4.8, two thirds of the runs had more over-dried than under-dried specimens. But in order to compare runs properly considering the final moisture content range, this approach was considered to be more appropriate. The drying runs using schedule "II" showed between 70 and 81% of timbers being on target which is reasonably close to 92% of the "Control". When considering the saving in drying time schedule "II" provides when compared to the "Control" this slightly lower percentage on target timbers becomes a very realistic trade off.

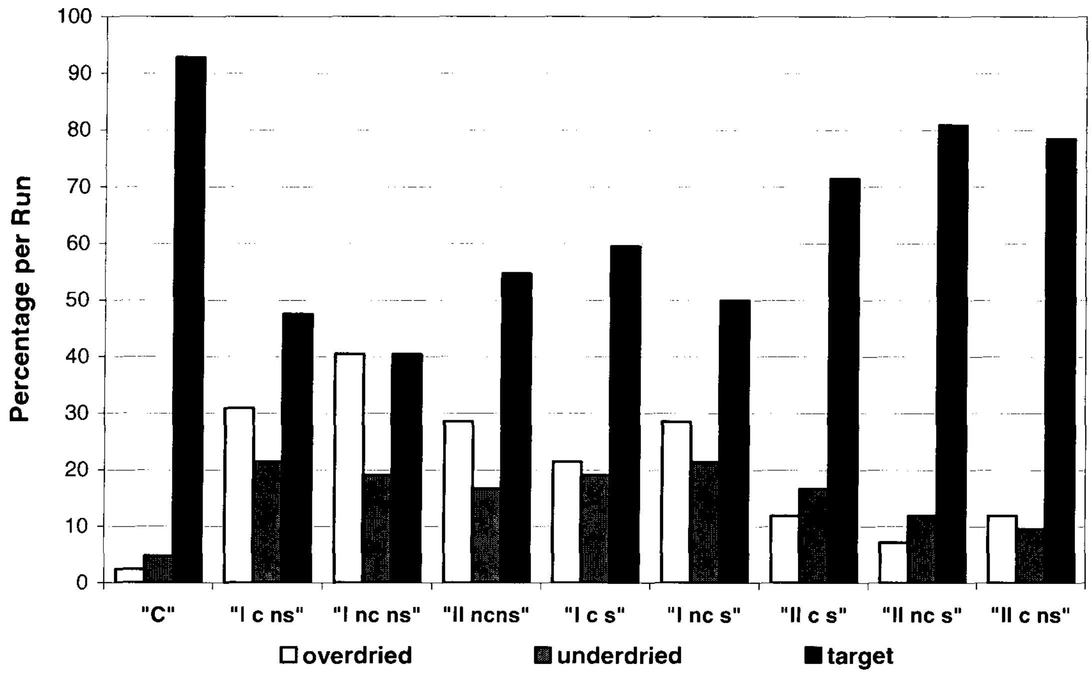


Figure 4.8: Percentages of over and under-dried specimens per run (over-dried was the mean of the run minus 3 percentage points, under-dried was the mean of the run plus 3 percentage points and target was the mean plus/minus 3 percentage points)

The four runs that were put into seven days of storage after drying was finished were sorted into the moisture content groups before and after storage. These drying runs were sorted using only the second method that was explained previously since it was considered to be more appropriate for this study; the results are shown in Table 4.18. The percentage of specimens in the target moisture content group increased considerably after the storage period, which is clearly illustrated in Figure 4.9. The number of over-dried specimens was visibly reduced after the timbers had been in storage for seven days. Also the number of under-dried timbers decreased, suggesting a further drying of the specimens during storage. The period of storage reduced the standard deviations of the final moisture contents for each run (see Table 4.6).

Table 4.18: Comparison of moisture contents, absolute numbers of specimens and percentages of over and under-dried specimens before and after post-drying storage

	"I c s"		"I nc s"		"II c s"		"II nc s"	
	Before storage (M_{KD}) [%]	After storage (M_{final}) [%]	Before storage (M_{KD}) [%]	After storage (M_{final}) [%]	Before storage (M_{KD}) [%]	After storage (M_{final}) [%]	Before storage (M_{KD}) [%]	After storage (M_{final}) [%]
mean	20.5	17.0	18.2	16.1	16.0	14.3	11.6	11.1
st. dev.	6.9	4.2	7.9	4.7	5.4	3.4	5.1	3.4
min	10.7	11.5	9.1	10.3	10.0	10.2	6.3	7.1
max	39.4	27.5	40.2	28.0	35.0	25.9	33.2	24.2
ABSOLUTE								
over-dried	17	9	18	12	13	5	9	3
under-dried	12	8	10	9	9	7	6	5
target	13	25	14	21	20	30	27	34
%								
over-dried	40.5	21.4	42.9	28.6	30.6	11.9	21.4	7.1
under-dried	28.6	19.1	23.8	21.4	21.4	16.7	14.3	11.9
target	30.9	59.5	33.4	50.0	47.6	71.4	64.3	80.9

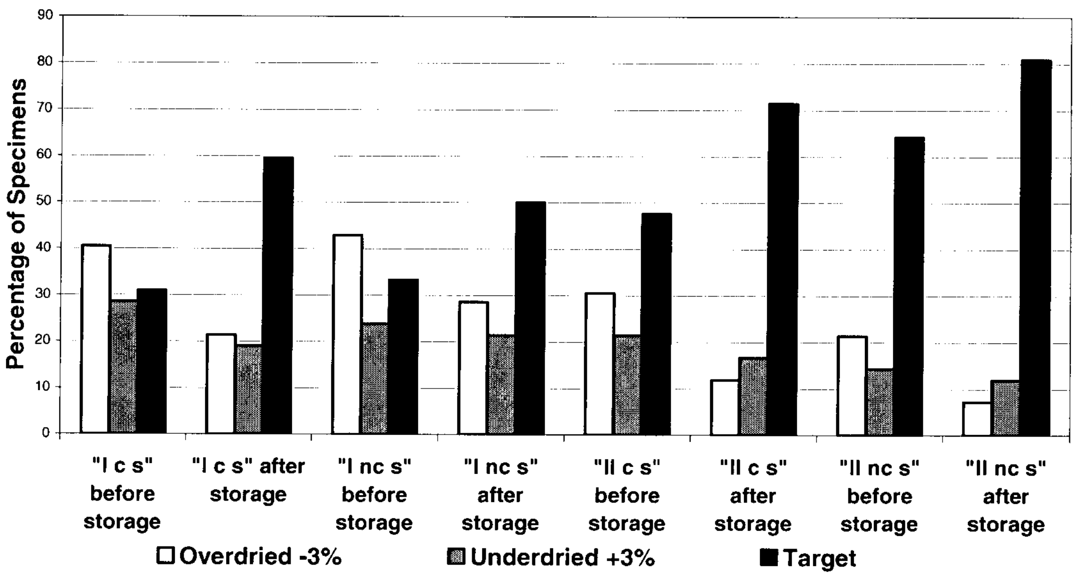


Figure 4.9: Percentage of over and under-dried specimens per run, measured before and after storage (over-dried is the mean of the run minus 3 percentage points, under-dried is the mean of the run plus 3 percentage points and target is the mean plus/minus 3 percentage points)

4.7 Drying defects

Defects that develop during the drying process determine the final quality of the kiln dried timber and significantly influence the commercial value of the final product. In this study the quality of the kiln dried timbers was determined by measuring checks, twist, diamonding and casehardening. In order to measure casehardening the timbers had to be cut, which is why casehardening could be evaluated only after the drying and storage process was finished. Checks, twist and diamonding were measured in the green stage of the timbers, as well as in the kiln dried stage. Given that the final moisture contents spanned such a wide range, it was necessary to use the ANCOVA for the evaluation of twist and diamonding. However, the final moisture content range did not have a statistical influence on the results of diamonding, so the ANOVA could be used here.

4.7.1 Checking

During drying the timbers develop surface checks when the drying stresses exceed the tensile strength perpendicular to the grain. Checks developed on all four sides of the timbers and for this analysis were added up to a total check length per timber. The length of every check on each specimen was measured before and after drying. When a t-Test was employed, there was a significant increase of checks during the drying process (for t-Test results see Table 4.19).

Table 4.19: Two sample t-Test comparison of pre- and post-drying checks assuming equal variance, (α=0.05)

Run	**checks**		
	t_{calc}	t_{crit}	**sig. diff.**
"C"	2.449	1.989	**Yes**
"I c ns"	3.547	1.989	**Yes**
"I nc ns"	4.176	1.989	**Yes**
"II nc ns"	3.932	1.989	**Yes**
"I c s"	5.639	1.989	**Yes**
"I nc s"	3.031	1.989	**Yes**
"II c s"	3.429	1.989	**Yes**
"II nc s"	3.122	1.989	**Yes**
"II c ns"	2.829	1.989	**Yes**

In Table 4.20, the absolute values in mm represent the sum of the length on all four sides of each specimen. The percentage represents the length of checks in relation to the total length of all specimens per run.

Table 4.20: Checking as measured before and after drying and the percentage of total check length to total specimens' length

	%		Absolute values [mm]		Difference [mm]
	length pre-drying	length post-drying	length pre-drying	length post-drying	post-drying minus pre-drying
"Control"	3.9	17.9	36	164	128
"I c ns"	0.8	18.5	7	169	162
"I nc ns"	2.3	32.7	21	299	277
"II nc ns"	0	60.4	0	552	552
"I c s"	0	32.3	0	296	296
"I nc s"	4.7	21.5	43	197	154
"II c s"	0	17.6	0	161	161
"II nc s"	0	12.9	0	118	118
"II c ns"	0	12.3	0	112	112

Figure 4.10 clearly shows a lower check length for the drying runs that used schedule "II" with either conditioning or storage. Only schedule "II" resulted in a lower percentage of checks when compared to the "Control", while schedule "I" developed more checks than the "Control" and than schedule "II". On the other hand, run "II nc ns" showed the highest check length, but it was reduced drastically when utilizing either the conditioning or the storage or both. Some specimens seemed to have developed a reduction in check length during drying and storage. This, of course, is not possible because the chemical bonds between the fibers do not reform during drying and storage. The checks are no longer visible to the naked eye but there is still a weakness within the timber.

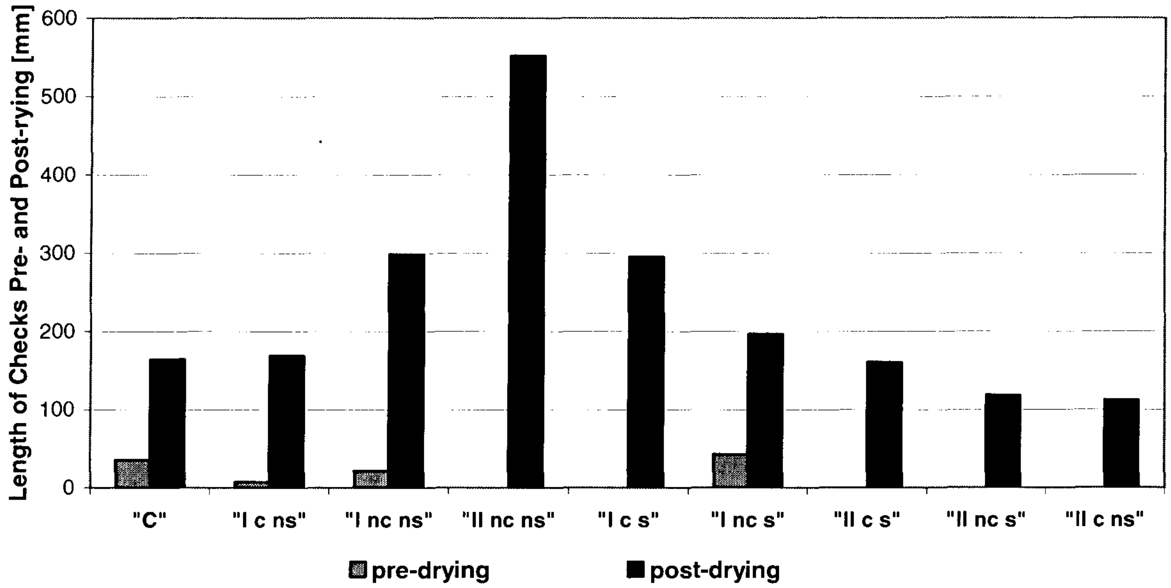


Figure 4.10: Length of checks [mm] pre- and post-drying

Figure 4.11 shows the difference of pre- and post-drying in length of checks or in other words, the increase of checks during drying. Schedule “II” with either conditioning and/or storage had the lowest increase which was only matched by the “Control”.

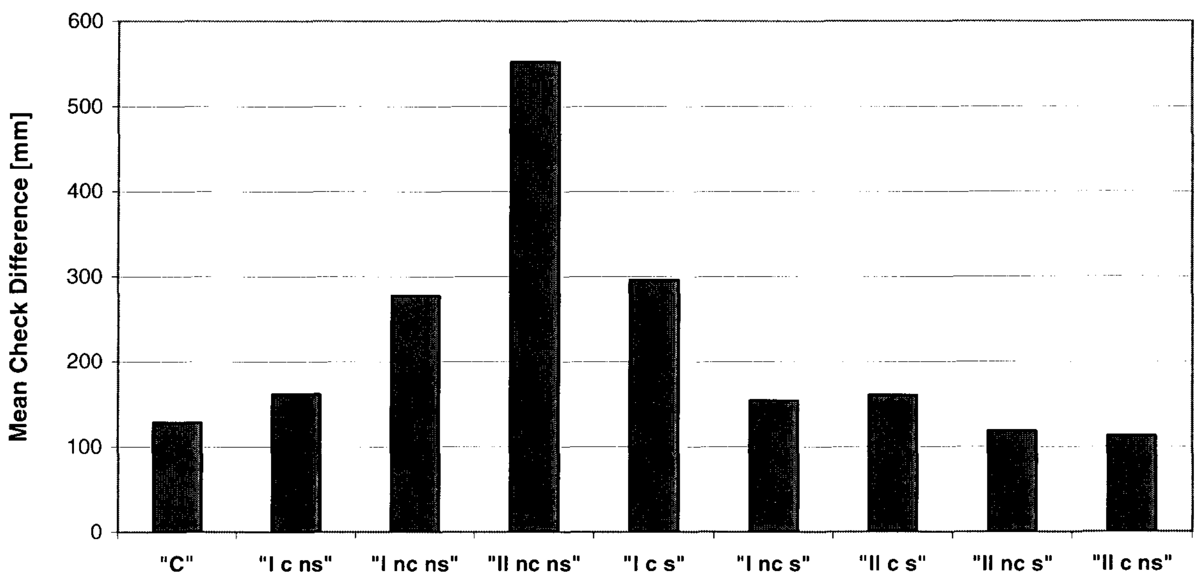


Figure 4.11: Checking differences (post-drying measurements minus pre-drying measurements)

The length of checks sorted by the pith location in Table 4.21 shows that the specimens with the pith located in its cross-section (**A** and **B**) show the longest checks, while the specimens with the pith located outside its cross section developed significantly less checks. Bradic and Avramidis (2007) confirmed that the length of checks was significantly influenced by pith location and specimens with the pith showing in its cross section (**A** and **B**) developed the longest checks. It was also discovered in the same study that neither slope of grain nor the amount of compression wood had an influence on the development of checks during drying. However, the length of checks was greatly influenced by the final moisture contents.

Table 4.21: Length of checks sorted by pith locations

		"C"	"I c ns"	"I nc ns"	"II nc ns"	"I c s"	"I nc s"	"II c s"	"II nc s"	"II c ns"	mean
A	**mean**						110		870		**490**
	max										**870**
	min										**110**
	st. dev.										**537**
B	**mean**	476	321	294	483	702	71	275	228	171	**336**
	max	905	900	900	1530	910	620	1200	760	910	**702**
	min	0	-310	-900	0	240	-900	0	0	0	**71**
	st. dev.	422	470	645	519	393	446	499	357	294	**190**
C	**mean**	[illegible]	189	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	max	900	720	[illegible]	280	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	min	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	st. dev.	346	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
D	**mean**	56	78	233	160	243	147	113	78	122	**137**
	max	900	660	900	910	910	820	1200	810	910	**243**
	min	-330	0	0	0	0	0	0	0	0	**56**
	st. dev.	238	177	347	277	286	214	292	187	275	**67**

Table 4.21 shows the mean check length sorted by pith location and drying run. When examining this table, it should be kept in mind that each run consisted mostly of pith locations outside of the specimens' cross-section (**C** and **D**), while pith location **A** was counted only twice which in turn accounts for its high mean.

There also might be a small correlation to length of checks and kiln location of the specimen. When referring to Table 7.4 in the Appendix, it seems that for most runs the length of checks increased in the top rows of the kiln load.

4.7.2 Twist

Twist was measured on every specimen before drying and after drying/storage. The t-Test was used to verify that the twist was different pre- and post-drying. As shown in Table 4.22, the twist was significantly increased during the majority of the drying runs. However, runs “II nc ns”, “II c s” and “I nc ns” did not show a significant increase of twist during drying. The last finding contradicts Hao and Avramidis (2004 and 2006), who found a significant increase in twist during all drying runs when using the “Control” schedule. Wallace et al. (2003) found an increase in twist in almost half of the dried timbers, but the changes were “considered acceptable”.

Table 4.22: Two sample t-Test comparison of pre- and post-drying twist, assuming equal variance (α=0.05)

Run	twist		
	t_{calc}	t_{crit}	sig. diff.
"C"	4.854	1.989	**Yes**
"I c ns"	2.499	1.989	**Yes**
"I nc ns"	0.791	1.989	No
"II nc ns"	0.466	1.989	No
"I c s"	2.168	1.989	**Yes**
"I nc s"	4.641	1.989	**Yes**
"II c s"	1.847	1.989	No
"II nc s"	5.654	1.989	**Yes**
"II c ns"	4.546	1.989	**Yes**

Since the twist of the dried specimens is greatly influenced by pre-existing twist, the difference of pre- and post-drying twist was calculated for a comparison. The pre-existing green twist ranged from 0.10 to 4.04mm, while the after drying twist ranged from 0 to 7.61mm. The difference of kiln dried to green twist ranged from 0.10 to 1.57mm, with a minimum of -2.68 to a maximum of 6.32mm (see Table 4.23). The negative values were due to a reduction of twist during the drying process in that particular specimen, which was also found by Bradic and Avramidis (2007) and by Hao and Avramidis (2004 and 2006), who ascribed it to the slope of grain. Bradic and Avramidis (2006) found a weak influence with the slope of grain on the twist development during drying. Hao and Avramidis (2006) also attributed lower final moisture contents with higher twist values.

Table 4.23: Twist measurements before and after drying and difference between pre- and post-drying

		"C"	"I c s"	"I c ns"	"I nc ns"	"I nc s"	"II c s"	"II c ns"	"II nc ns"	"II nc s"
twist green	**Mean**	1.10	1.24	1.15	1.06	1.24	1.14	1.24	1.27	1.06
	St. Dev.	0.58	0.64	0.41	0.72	0.65	0.69	0.69	0.67	0.84
	Min	0.22	0.20	0.19	0.21	0.31	0.10	0.34	0.27	0.17
	Max	2.42	2.87	1.89	3.80	3.12	3.48	3.24	2.85	4.04
twist KD	**Mean**	2.15	1.82	1.76	1.25	2.47	1.56	2.68	1.37	2.63
	St. Dev.	1.28	1.63	1.51	1.35	1.48	1.30	1.93	1.25	1.59
	Min	0.00	0.17	0.00	0.00	0.27	0.13	0.19	0.00	0.03
	Max	4.84	6.30	5.72	4.73	6.97	6.67	7.61	5.17	5.93
twist Diff.	**Mean**	1.05	0.59	0.60	0.21	1.23	0.42	1.44	0.10	1.57
	St. Dev.	1.26	1.62	1.63	1.74	1.55	1.35	1.78	1.34	1.65
	Min	-1.06	-2.17	-1.48	-2.68	-0.74	-1.24	-0.51	-2.85	-1.39
	Max	4.03	5.52	5.06	4.13	5.67	6.32	6.32	4.32	4.86

It can be seen from Figure 4.12 that run "II nc s" had the smallest twist pre-drying, but actually had the largest twist increase. It is in the group of highest twist difference together with runs "II c ns" and "I nc s"; all three runs with either no conditioning or no storage. The four runs with lowest twist difference contain three runs that used schedule "I" ("I c s", "I c ns", "I nc ns") and "II nc ns" as the fourth. It is interesting that three out of the four top runs did not utilize storage and the top two runs ("I nc ns", "II nc ns") did not go through conditioning or storage. The "Control" run showed a higher twist than most of the treatment runs ("I c s", "I c ns", "I nc ns", "II c s", "II nc ns") of which three did not include storage and two of those did not even include conditioning.

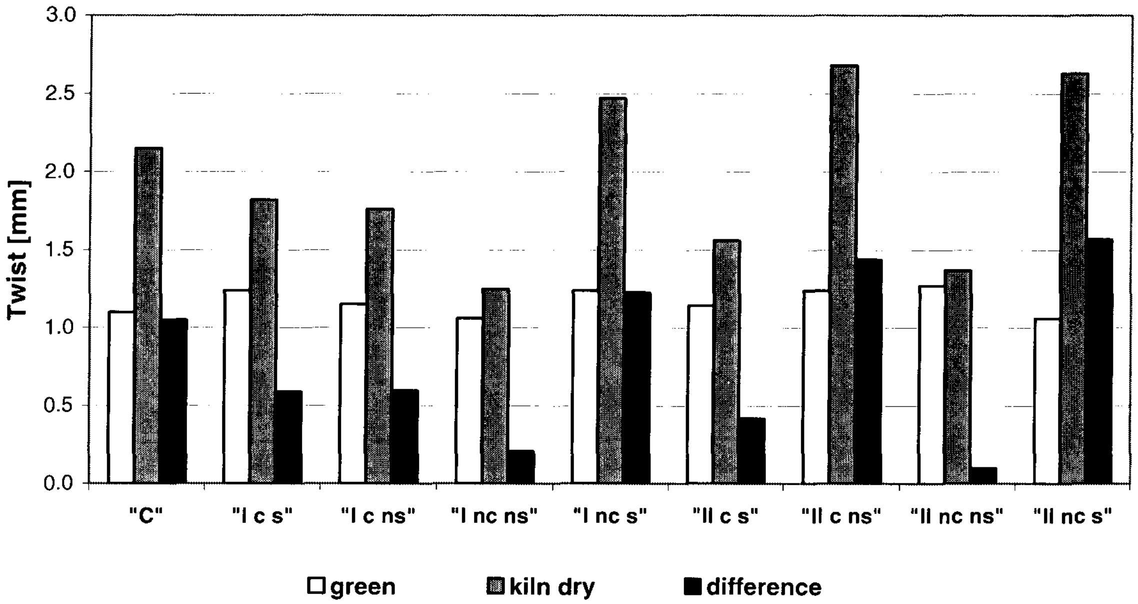


Figure 4.12: Twist before drying, after drying and the difference of pre- and post-drying for all 9 runs

ANCOVA was used to analyze twist in order to eliminate the influence of the final moisture contents. The results of the ANCOVA (Table 4.25) show a significant influence of the treatment combinations on the twist difference values. The interaction of schedule, conditioning and storage as well as, the interaction of conditioning and storage, showed a significant influence on twist. For the most part, the treatments seemed to have a positive influence on the twist when considering the significant differences of pre- and post-drying measurements. However, no single main factor had a significant influence during the drying process. Wallace (2001) found that storage had no significant effect on twist, which confirms the finding that storage, as a main factor, does not influence twist. The "Control" schedule did not show a significantly different twist when compared to the experimental drying runs.

Table 4.25: ANCOVA results for twist difference (α = 0.05)

Source	DF	Type III SS	Mean Square	F value	Pr > F	
X (M_{final})	1	11.5441	11.5441	4.59	0.0328	Need to adjust for X
Treatments	8	62.4680	7.8085	3.11	0.0021	**sig. diff.**
Contrast	**DF**	**Contrast SS**	**Mean Square**	**F value**	**Pr > F**	
"Control" vs all	1	1.6495	1.6495	0.66	0.4185	
A (schedule)	1	7.0837	7.0837	2.82	0.0941	
B (conditioning)	1	2.0510	2.0510	0.82	0.3670	
C (storage)	1	3.7981	3.7981	1.51	0.2198	
A*B	1	0.4577	0.4577	0.18	0.6699	
A*C	1	0.1559	0.1559	0.06	0.8035	
B*C	1	33.9276	33.9276	13.49	0.0003	**sig. diff.**
A*B*C	1	16.9561	16.9561	6.74	0.0098	**sig. diff.**

When evaluating the significantly different meaningful comparisons in Table 4.26, it becomes evident that only two of the possible pairings are significantly different from each other and none of the experimental runs is different from the "Control". The only runs that show a difference involve schedule "II". Run "II nc ns" developed significantly less twist than runs "II c ns" and "II nc s". It also had the overall least twist of all runs.

Table 4.26: Meaningful comparisons for twist difference (α=0.00138)

Compared drying runs		probability	Significantly different
"I c ns"	**"II c ns"**	0.0390	No
"I c ns"	**"I nc ns"**	0.2238	No
"I c ns"	**"I c s"**	0.8523	No
"I nc ns"	**"II nc ns"**	0.9086	No
"I nc ns"	**"I nc s"**	0.1980	No
"I c s"	**"II c s"**	0.4318	No
"I c s"	**"I nc s"**	0.9112	No
"II c ns"	**"II nc ns"**	0.0009	**Yes**
"II nc ns"	**"II nc s"**	0.0004	**Yes**
"II c s"	**"II nc s"**	0.0038	No
"II c s"	**"II c ns"**	0.0076	No
"I nc s"	**"II nc s"**	0.0290	No
"C"	**"I c s"**	0.5485	No
"C"	**"I nc s"**	0.4738	No
"C"	**"I c ns"**	0.4236	No
"C"	**"I nc ns"**	0.0458	No
"C"	**"II c s"**	0.1609	No
"C"	**"II nc s"**	0.1282	No
"C"	**"II c ns"**	0.2044	No
"C"	**"II nc ns"**	0.9086	No

Pith location seemed to have only a small influence on twist, since pith locations **B**, **C** and **D** increased twist during drying by less than 1mm, as demonstrated in Table 4.24. Bradic and Avramidis (2007) found pith location to have a significant influence on twist in interaction with either cutting season or target moisture content, but not as a main factor. Timbers closer to the pith have a higher slope of grain which could cause increased twisting during drying (Bradic and Avramidis, 2007). Hao and Avramidis (2006) also found timbers with pith locations, included in their cross section, posing some threat to the shape of the timber, in addition to the possibility of wet pockets and invisible grain defects. However, in regards to Figure 4.13, pith location **C** and **D** seemed to have the least twist difference in combination with schedule “I”.

Table 4.24: Twist difference [mm] sorted by pith locations

		“C”	**“I c ns”**	**“I nc ns”**	**“II nc ns”**	**“I c s”**	**“I nc s”**	**“II c s”**	**“II nc s”**	**“II c ns”**	**mean**
A	**mean**						-0.49		0.03		**-0.23**
	max										**0.03**
	min										**-0.49**
	st. dev.										**0.37**
B	**mean**	0.75	1.52	0.78	-0.44	0.89	1.18	1.09	1.27	0.67	**0.86**
	max	3.42	5.06	3.19	0.86	3.65	4.17	6.32	4.25	3.07	**6.32**
	min	-0.38	-0.75	-2.62	-1.78	-0.72	-0.74	-0.80	-1.39	-0.51	**-2.62**
	st. dev.	1.13	2.09	1.81	1.02	1.36	1.87	2.98	1.91	1.28	**0.56**
[redacted]											
D	**mean**	1.20	0.07	-0.13	0.42	0.78	1.27	0.34	1.61	1.64	**0.80**
	max	4.03	3.48	4.13	4.32	5.52	5.67	3.51	4.86	6.32	**6.32**
	min	-0.78	-1.48	-2.68	-2.20	-2.17	-0.68	-1.24	-1.32	-0.46	**-2.68**
	st. dev.	1.21	1.28	1.80	1.47	2.04	1.55	1.06	1.64	1.81	**0.66**

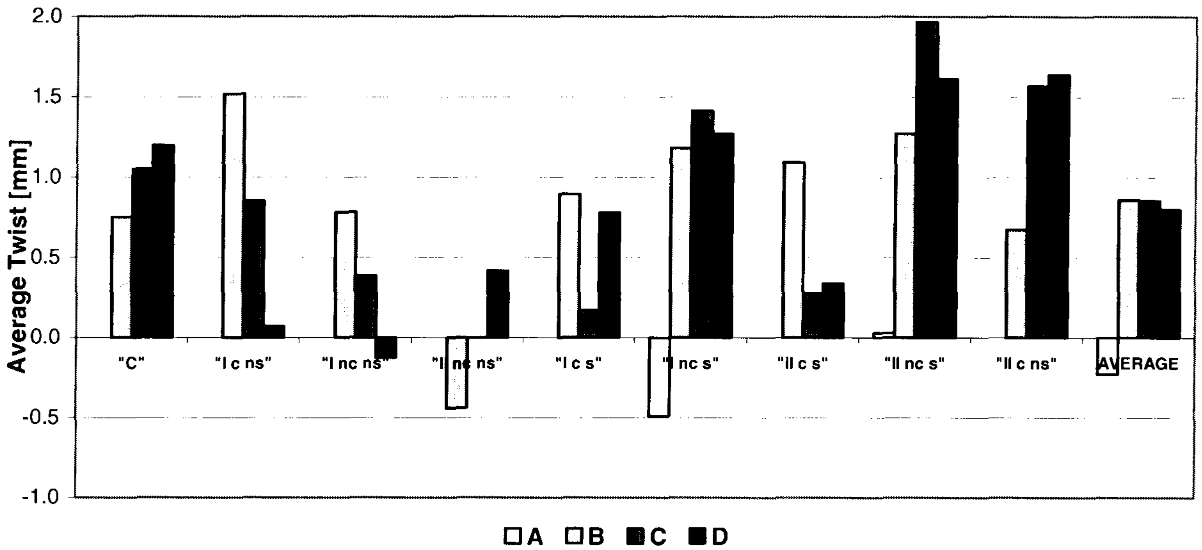


Figure 4.13: Mean twist difference sorted by pith location and drying run

In terms of physical location (Table 7.5 in the Appendix), during four out of the nine drying runs, the values for twist were higher in the top rows than in the bottom rows of the kiln load. The weight of the kiln load might help the timbers on the bottom to stay in shape. Hao and Avramidis (2004) found this to be true if the timber showed a high slope of grain.

4.7.3 Diamonding

Diamonding is one of the quality parameters that develops least during drying and can easily be corrected by planing the timbers. Diamonding was measured for each specimen pre-drying and post-drying/storage. After performing the t-Test on pre- and post-drying/storage values, it became clear that diamonding significantly increased during drying for six out of the nine runs. However, runs “I c ns” and “I nc ns” did not show a significant increase in diamonding and run “I nc s” even showed a significant decrease in diamonding during the drying process, as can be seen in Table 4.27. Hao and Avramidis (2006) found a significant increase in diamonding with decreasing final moisture content which Bradic and Avramidis (2006) contradicted. Hao and Avramidis (2004) found a significantly higher diamonding after drying when using the “Control” schedule which is also true for this experiment.

Table 4.27: Two sample t-Test comparison of pre- and post-drying diamonding assuming equal variance (α=0.05).

Run	diamonding		
	t_{calc}	t_{crit}	sig. diff.
"C"	3.235	1.989	**Yes**
"I c ns"	1.586	1.989	No
"I nc ns"	1.190	1.989	No
"II nc ns"	3.991	1.989	**Yes**
"I c s"	5.591	1.989	**Yes**
"I nc s"	3.990	1.989	**Yes** (reversed)
"II c s"	2.618	1.989	**Yes**
"II nc s"	5.045	1.989	**Yes**
"II c ns"	4.058	1.989	**Yes**

The green measurements ranged from 0 to 4.72mm for the 378 specimens. Taking into account only the means of the nine runs, diamonding ranged from 0.13 to 0.77mm. After drying, the variability of the measurements increased from 0 to 6.47mm between all specimens. The means of all runs varied from 0.19 to 1.57mm, as seen in Table 4.28. To make the diamonding measurements comparable, the pre-drying values were deducted from the after drying/storage measurements. This made it possible to compare the changes in diamonding that occurred during the drying process. After calculating the differences for all specimens, the range resulted from -4.72 to 6.08mm. The negative numbers were a result of decreasing diamonding during the drying process; a phenomenon that was also reported by Hao and Avramidis (2006).

Table 4.28: Diamonding measurements [mm] taken pre- and post-drying/storage and their difference between pre- and post-drying

		"C"	"I c s"	"I c ns"	"I nc ns"	"I nc s"	"II c s"	"II c ns"	"II nc ns"	"II nc s"
Diamonding pre-drying	Mean	0.46	0.28	0.56	0.51	0.77	0.14	0.37	0.54	0.13
	St. Dev.	0.44	0.26	0.33	0.43	0.90	0.24	0.47	0.33	0.21
	Min	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00
	Max	2.11	1.32	1.48	2.30	4.72	0.76	2.19	1.27	0.80
Diamonding post-drying	Mean	0.96	1.31	0.85	0.70	0.19	0.31	1.31	1.57	1.26
	St. Dev.	0.91	1.17	1.11	0.95	0.26	0.33	1.42	1.65	1.42
	Min	0.03	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00
	Max	3.33	4.99	5.39	5.00	1.28	1.08	6.47	6.08	5.22
Diamonding difference	Mean	0.50	1.03	0.28	0.19	-0.58	0.16	0.94	1.04	1.12
	St. Dev.	1.03	1.23	1.17	1.01	0.93	1.39	1.49	1.65	1.40
	Min	-1.03	-0.61	-1.10	-2.13	-4.72	-0.76	-0.86	-0.75	-0.80
	Max	3.13	4.48	3.91	4.54	0.59	1.02	6.08	5.56	5.22

From Figure 4.14 it becomes evident that three out of the four runs showing the largest kiln dry diamonding and diamonding difference used schedule "II" ("II c ns", "II nc ns", "II nc s", "I c s"). On the other hand, three out of the four runs with the smallest kiln dry measurements and diamonding differences were dried using schedule "I" ("I c ns", "I nc ns", "I nc s", "II c s").

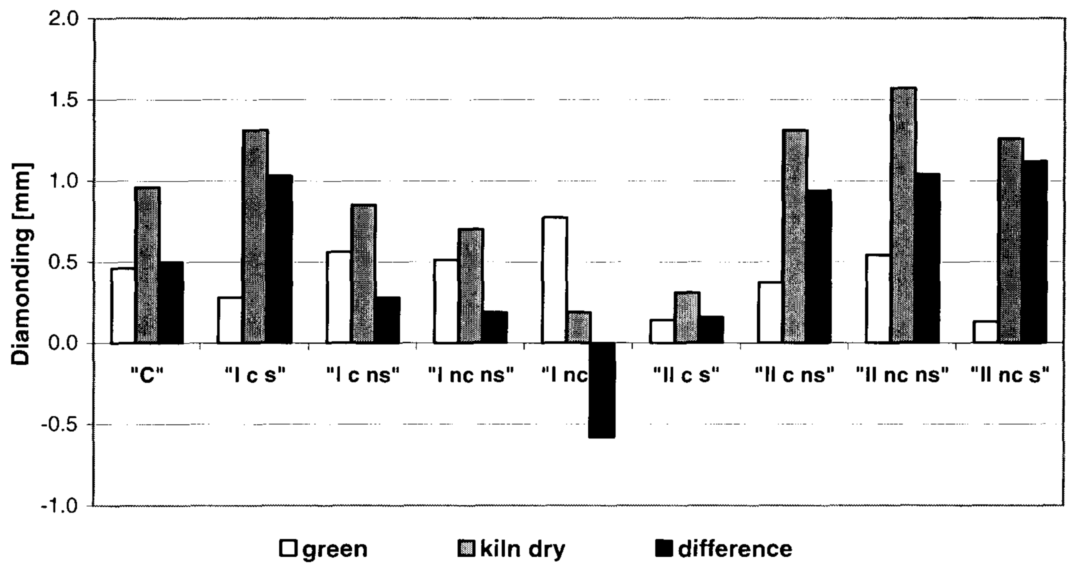


Figure 4.14: Diamonding pre- and post-drying and the resulting differences

ANCOVA had to be used in order to adjust for the final moisture contents when analyzing diamonding. In regards to the ANCOVA results shown in Table 4.30, the interaction of schedule and storage had a significant influence on the diamonding, in addition to the interaction of schedule and conditioning. However, none of the main effects had a significant influence. However, since the factor schedule shows up as significant in two interactions, it cannot be dismissed as a major influence. There were no significant differences when comparing the experimental runs to the "Control" run, which also becomes evident in Table 4.31.

Table 4.30: ANCOVA results for diamonding ($\alpha = 0.05$)

Source	DF	Type III SS	Mean Square	F value	Pr > F	
X (M_{final})	1	7.4118	7.4118	5.07	0.0249	Need to adjust for X
Treatments	8	58.3144	7.2893	4.99	<0.0001	
Contrast	**DF**	**Contrast SS**	**Mean Square**	**F value**	**Pr > F**	
"Control" vs all	1	4.0044	4.0044	2.74	0.0988	
A (schedule)	1	0.9480	0.9480	0.65	0.4212	
B (conditioning)	1	4.5823	4.5823	3.13	0.0775	
C (storage)	1	4.5402	4.5402	3.11	0.0789	
A*B	1	7.7876	7.7876	5.33	0.0216	**sig diff.**
A*C	1	31.5096	31.5096	21.55	<0.0001	**sig diff.**
B*C	1	2.5836	2.5836	1.77	0.1846	
A*B*C	1	1.5601	1.5601	1.07	0.3023	

Considering the meaningful comparisons in Table 4.31, there are only three pairings that are significantly different from each other. Using both schedules without conditioning or storage, the milder schedule "I" developed less diamonding. According to Bradic (2005), this is a positive confirmation for the quality of the drying schedule, since diamonding does not influence the use of the timber as construction lumber as much as it is an indicator for the quality of a drying schedule. When using conditioning and storage however, schedule "II" shows a significantly lower increase in diamonding when compared to schedule "I". The significantly lowest increase, which actually turned out to be a decrease, in diamonding showed run "I nc s". This significant decrease in diamonding is most likely not only due to the milder schedule "I" but also to the green timber quality in this specific run.

Table 4.31: Meaningful comparisons for diamonding differences (α=0.00138)

Compared drying runs		**probability**	**Significantly different**
"I c ns"	**"II c ns"**	0.0350	No
"I c ns"	**"I nc ns"**	0.3723	No
"I c ns"	**"I c s"**	0.0023	No
"I nc ns"	**"II nc ns"**	0.0008	**Yes**
"I nc ns"	**"I nc s"**	0.0008	**Yes**
"I c s"	**"II c s"**	0.0004	**Yes**
"I c s"	**"I nc s"**	0.9067	No
"II c ns"	**"II nc ns"**	0.4115	No
"II nc ns"	**"II nc s"**	0.7917	No
"II c s"	**"II nc s"**	0.0015	No
"II c s"	**"II c ns"**	0.0081	No
"I nc s"	**"II nc s"**	0.8002	No
"C"	**"I c s"**	0.0093	No
"C"	**"I nc s"**	0.0116	No
"C"	**"I c ns"**	0.7459	No
"C"	**"I nc ns"**	0.4583	No
"C"	**"II c s"**	0.3927	No
"C"	**"II nc s"**	0.0181	No
"C"	**"II c ns"**	0.0722	No
"C"	**"II nc ns"**	0.0111	No

Diamonding seems to have no obvious correlation with pith location, which was substantiated by the findings of Bradic (2005) and Bradic and Avramidis (2007). According to Bradic and Avramidis (2006), the slope of grain does not have a significant influence on diamonding.

Table 4.29: Diamonding sorted by pith locations

		"C"	"I c ns"	"I nc ns"	"II nc ns"	"I c s"	"I nc s"	"II c s"	"II nc s"	"II c ns"	**mean**
A	**mean**						-0.06		0.02		**-0.02**
	max										**0.02**
	min										**-0.06**
	st. dev.										**0.06**
B	**mean**	0.44	0.64	0.54	1.26	1.06	-0.62	0.10	1.71	0.62	**0.64**
	max	1.75	3.91	2.18	5.56	4.48	0.41	0.59	3.80	2.97	**5.56**
	min	-0.49	-1.10	-0.80	-0.62	-0.61	-2.57	-0.39	0.30	-0.54	**-2.57**
	st. dev.	0.79	1.91	0.96	2.04	1.70	0.80	0.39	1.38	1.21	**0.67**
[redacted]											
D	**mean**	0.56	-0.04	-0.02	0.63	0.83	-0.41	0.21	1.03	0.92	**0.41**
	max	2.94	2.42	1.41	3.04	3.04	0.59	1.02	5.22	6.08	**6.08**
	min	-1.03	-1.08	-2.13	-0.75	-0.15	-2.25	-0.76	-0.80	-0.86	**-2.13**
	st. dev.	1.05	0.84	0.69	1.26	0.87	0.66	0.41	1.47	1.66	**0.50**

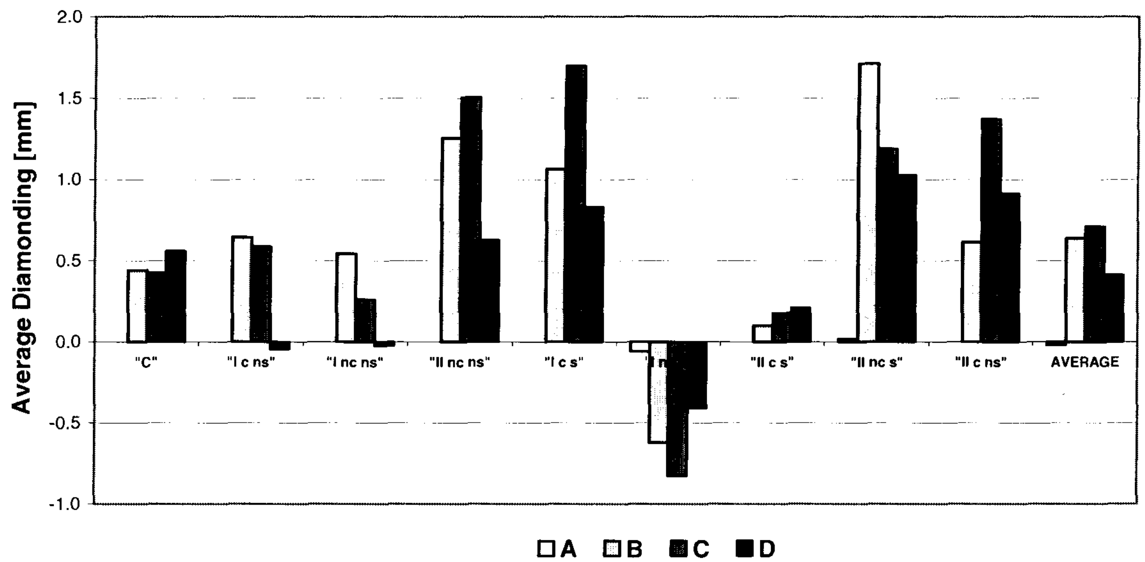


Figure 4.15: Mean diamonding differences sorted by pith location and drying run

In terms of physical location (Table 7.6 in the Appendix), it was apparent that four out of the nine runs showed increased diamonding in the top rows of the kiln load. This might have something to do with the weight of the load functioning as a counter measure or simply with the distribution of pith locations across the load.

4.7.4 Casehardening

Casehardening was measured for every specimen after drying/storage using the measurements of the prongs as described in the "Materials and Methods". The average of the nine runs spanned from 0.0014 to 0.0031mm^{-1}, while the values of the specimens ranged from 0.00009 to 0.00535mm^{-1}, as shown in Table 4.32.

Table 4.32: Casehardening [mm^{-1}] means for each drying run

	"C"	"I c s"	"I c ns"	"I nc ns"	"I nc s"	"II c s"	"II c ns"	"II nc ns"	"II nc s"
Mean	0.0018	0.00245	0.00195	0.00197	0.00311	0.00165	0.0014	0.00264	0.00201
St. Dev.	0.00083	0.00094	0.00093	0.00062	0.0011	0.00078	0.00097	0.00097	0.00077
Min	0.00026	0.00066	0.00046	0.001	0.00053	0.00024	0.00009	0.00094	0.00069
Max	0.00417	0.00473	0.00383	0.00371	0.00535	0.00355	0.00433	0.00481	0.00386

Figure 4.16 confirms that runs “II c s” and “II c ns” show the lowest casehardening followed by the “Control” run which all used conditioning in their drying process. It was surprising that the harsher schedule “II” was used for the two runs that developed the smallest casehardening. Runs “I nc s” and “II nc ns” exhibit the highest casehardening measurements and did not utilize the conditioning option. The prong test used for casehardening does not show the stresses developed in the whole specimens but just the ones that developed in the section used to test and thus, the results could be misleading. There was an attempt to keep the prongs consistent but the slight difference in geometric shape might have influenced the casehardening results as well.

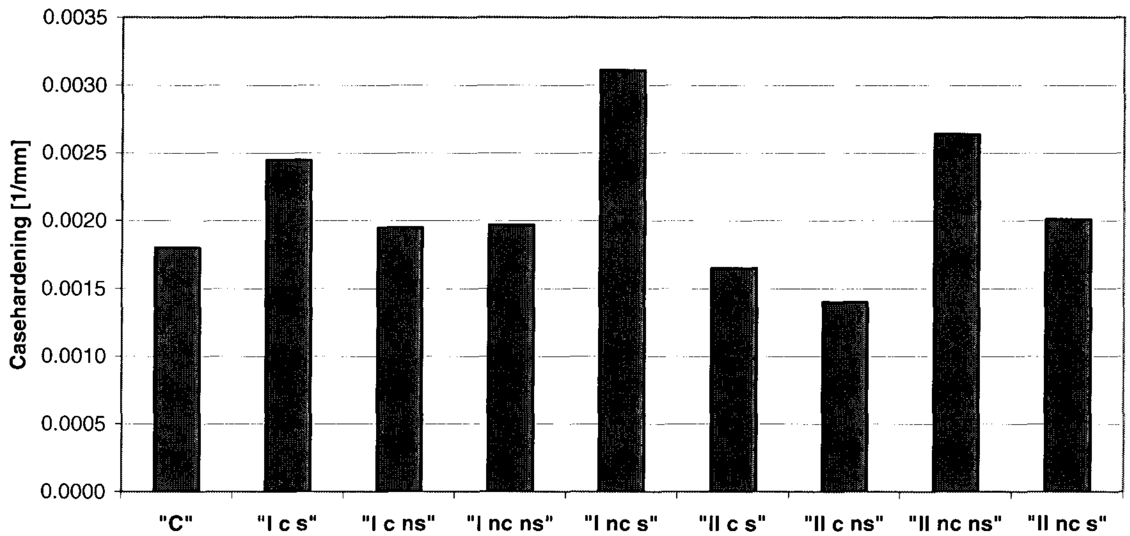


Figure 4.16: Casehardening [mm^{-1}] results for all 9 runs

The final moisture contents did not influence casehardening; accordingly, ANOVA was used to analyze the measurements. The results can be seen in Table 4.33. All treatments had a significant effect on casehardening; the interaction of schedule, storage and conditioning as well as the interaction of schedule and storage and the interaction of schedule and conditioning. Schedule, conditioning and storage also showed a significant influence on casehardening as main factors. It was to be expected that all factors would play a major role in casehardening. All tensions developed in the timbers became visible during the prong test. Furthermore, the treatment runs were significantly different from the "Control".

Table 4.33: ANOVA results for casehardening (F_{crit} = 3.974)

Source of Variation	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Squares (MS)	F_o	sig. diff.
Treatment	7	9.34294E-05	1.33471E-05	16.348	**Yes**
"Control" vs all	1	4.16771E-06	4.16771E-06	5.104	**Yes**
A (schedule)	1	1.86106E-05	1.86106E-05	22.795	**Yes**
B (conditioning)	1	2.4838E-05	2.4838E-05	30.423	**Yes**
C (storage)	1	8.7764E-06	8.7764E-06	10.750	**Yes**
A*B	1	3.46132E-06	3.46132E-06	4.239	**Yes**
A*C	1	2.12981E-05	2.12981E-05	26.087	**Yes**
B*C	1	2.87492E-07	2.87492E-07	0.352	No
A*B*C	1	1.19898E-05	1.19898E-05	14.686	**Yes**
Experimental Error	369	0.000301254	8.16E-07		
Total	377	0.000394683			

When examining the meaningful comparisons in Table 4.34 it is evident that out of the eight significant pairs, three of them are influenced each by schedule or conditioning and two of them by storage. Out of the two comparisons influenced by storage, interestingly, both schedules show better casehardening values when used without storage ("I nc ns" better than "I nc s", and "II nc ns" better than "II nc s"). Comparing both schedules without conditioning or storage directly, schedule "I" showed better results. When comparing the three pairs that differ in use of schedule, schedule "II" is better two out of the three pairs. Two out of the three pairings for conditioning show better results with conditioning than without. Upon comparing the "Control" run to the treatments, it turned out that the "Control" was significantly smaller than three of the treatment runs, namely "I c s", "I nc s", and "II nc ns". There seems to be no clear trend developing when trying to analyze the nine runs for casehardening, except that all the treatments had a significant influence on the stresses developed in these timbers during drying.

Table 4.34: Meaningful comparisons for casehardening

		Critical Difference	Actual Difference	Significantly Different
"I c ns"	**"II c ns"**	0.000568	0.000548	No
"I c ns"	**"I nc ns"**	0.000568	0.000021	No
"I c ns"	**"I c s"**	0.000568	0.0005075	No
"I nc ns"	**"II nc ns"**	0.000568	0.0006766	**Yes**
"I nc ns"	**"I nc s"**	0.000568	0.001146	**Yes**
"I c s"	**"II c s"**	0.000568	0.0007995	**Yes**
"I c s"	**"I nc s"**	0.000568	0.00066	**Yes**
"II c ns"	**"II nc ns"**	0.000568	0.0012461	**Yes**
"II nc ns"	**"II nc s"**	0.000568	0.0006317	**Yes**
"II c s"	**"II nc s"**	0.000568	0.0003584	No
"II c s"	**"II c ns"**	0.000568	0.000256	No
"I nc s"	**"II nc s"**	0.000568	0.0011011	**Yes**
"C"	**"I c s"**	0.000568	0.000649448	**Yes**
"C"	**"I nc s"**	0.000568	0.001309448	**Yes**
"C"	**"I c ns"**	0.000568	0.000149448	No
"C"	**"I nc ns"**	0.000568	0.000166448	No
"C"	**"II c s"**	0.000568	0.000150552	No
"C"	**"II nc s"**	0.000568	0.000209448	No
"C"	**"II c ns"**	0.000568	0.000149448	No
"C"	**"II nc ns"**	0.000568	0.000839448	**Yes**

The results might be influenced by the wood itself, as it is a naturally diverse material and can show uneven shrinkage of the specimens due to the occasional presence of compression wood, different sapwood and heartwood percentages, differences in slope of grain and varying pith locations. But as mentioned before, the results may vary with prong geometry and do not represent the stresses of the whole timber, but rather only from the cookie taken to cut the prongs.

4.8 Treatment effects

This last section discusses the quality parameters and compares the different runs under the aspect of these parameters. The results of the nine experimental runs will be discussed in conjunction with the three treatment factors; schedule, conditioning and storage, and are being compared to the "Control" run.

4.8.1 Schedule effects

Schedule “II” was a more severe drying schedule than both schedule “I” and the “Control”; although schedule “I”, after starting off harsher, levelled off towards the end of the schedule. When contrasting absolute and normalized drying times of both experimental schedules, schedule “II” dried the timber significantly faster than schedule “I”. Table 4.35 lists drying defects in terms of schedule effects for all runs.

Table 4.35: Direct comparisons of schedule effects

runs compared		M_{final} [%]		M_{shell} [%]		M_{core} [%]		casehardening [1/mm]		twist [mm]		diamonding [mm]	
“I c ns” “II c ns”	**mean**	14.94	12.15	15.52	13.08	26.73	19.20	0.00195	0.0014	0.60	1.44	0.28	0.94
	st. dev.	5.01	3.42	5.98	4.08	15.70	9.88	0.00093	0.00097	1.63	1.78	1.17	1.49
	min	8.78	7.30	8.63	8.36	11.23	8.26	0.00046	0.00009	-1.48	-0.51	-1.10	-0.86
	max	27.44	25.85	34.56	26.39	96.10	53.74	0.00383	0.00433	5.06	6.32	3.91	6.08
	sig. diff.												
“I nc ns” “II nc ns”	**mean**	14.36	15.94	14.39	15.86	24.73	28.58	**0.001967**	0.00264	0.21	0.10	**0.19**	1.04
	st. dev.	6.26	5.70	5.75	4.11	12.82	5.21	0.000621	0.00097	1.74	1.34	1.01	1.65
	min	8.36	10.15	7.64	10.54	11.29	12.15	0.000997	0.00094	-2.68	-2.85	-2.13	-0.75
	max	39.53	42.24	32.44	25.97	69.65	34.84	0.003711	0.00481	4.13	4.32	4.54	5.56
	sig. diff.							**Yes**				**Yes**	
“I c s” “II c s”	**mean**	17.02	12.15	17.58	13.08	25.75	19.20	0.00245	**0.0014**	0.59	1.44	1.03	**0.16**
	st. dev.	4.17	3.42	4.55	4.08	11.02	9.88	0.00094	0.00097	1.62	1.78	1.23	1.39
	min	11.49	7.30	11.87	8.36	13.90	8.26	0.00066	0.00009	-2.17	-0.51	-0.61	-0.76
	max	27.53	25.85	35.22	26.39	65.90	53.74	0.00473	0.00433	5.52	6.32	4.48	1.02
	sig. diff.							**Yes**				**Yes**	
“I nc s” “II nc s”	**mean**	16.05	11.09	16.12	**11.54**	23.78	16.69	0.00311	**0.00201**	1.23	1.57	-0.58	1.12
	st. dev.	4.72	3.39	4.62	3.10	9.52	8.96	0.0011	0.00077	4.55	1.65	0.93	1.40
	min	10.26	7.12	10.23	6.06	12.56	8.15	0.00053	0.00069	-0.74	-1.39	-4.72	-0.80
	max	28.02	24.15	35.39	22.74	52.27	57.41	0.00535	0.00386	5.67	4.86	0.59	5.22
	sig. diff.			**Yes**				**Yes**					

The treatment schedules had a significant influence on the final moisture content as a main factor. Another significant influence had the interaction of schedule, conditioning and storage and the interaction of schedule and storage. The drying schedule had an apparent significant effect on the final moisture contents. It was a similar situation for the higher moisture content loss during the storage period by the runs dried with schedule “II”. But schedule “I” experienced alike core moisture contents as opposed to schedule “II”. In terms of the shell moisture content, schedule “I” produced lower values than schedule “II”. The main factor schedule had a significant influence on the shell moisture content, as did the interaction of schedule and storage and the interaction of all treatments. Since schedule not only shows up as a main factor but also in two out of the three significant interactions, it had substantial influence.

On the subject of checks, schedule "II" developed the least checks during the drying process when used with either conditioning or storage. The "Control" developed only slightly more checks, while schedule "I" displayed a fairly consistent amount of checking. Once used without conditioning or storage, schedule "I" provided a much better result than schedule "II".

Concerning the development of twist, schedule "II" and schedule "I" did not develop significantly different increase in twist. Schedule had a significant influence on twist only in interaction with the other two treatments.

Regarding diamonding, two runs using schedule "I" showed no significant increase during drying and one schedule "I" run even significantly reversed its diamonding. In general, schedule "I" had the least diamonding development during drying, even though schedule was not a significant main factor; nevertheless, the interaction of schedule and storage had a significant influence.

The treatments had a significant influence on casehardening with schedule as a main factor. And they had a significant influence as interaction with conditioning or storage and as interaction with both conditioning and storage. Two out of three significant direct comparisons favour schedule "II" over schedule "I".

In summary, out of eight significant comparisons, both schedules are favoured equally. Generally, the choice of schedule had a significant influence on the results of this study.

4.8.2 Conditioning effects

The only noticeable effect conditioning had on the drying time was to prolong it for 12 hours when it was performed, which did not significantly change the overall trend. All treatments (schedule, conditioning and storage) had a significant effect on the final moisture contents, but conditioning was not a main factor. The interaction between conditioning and storage and the interaction of conditioning, storage and schedule proved to have a significant influence on the final moisture contents. In terms of core moisture content, the conditioning had no significant effect. However, for the shell moisture content it had an influence as interaction with storage and as interaction with storage and schedule. Conditioning had no significant influence when used with schedule "I", but influenced schedule "II".

The use of conditioning lessened the appearance of checks during drying. On the other hand, three out of four direct comparisons did not show a significant difference in twist. Conditioning stood out as having a significant influence on twist as interaction with storage and as the interaction with storage and schedule. But no clear pattern emerged. Surprisingly the harsher schedule "II nc ns" had developed significantly less twist than the run using "II c ns". Conditioning did not show a significant influence on diamonding; there was no significant difference when examining the meaningful comparisons. In combination with schedule, conditioning developed a significant influence on diamonding. With casehardening, two runs utilizing conditioning showed the lowest values. Conditioning had a major influence as a main factor and in the interaction with schedule, as well as the interaction of conditioning, storage and schedule. Please see Table 4.36 for the influence of conditioning on the shape deformations and moisture contents.

Table 4.36: Direct comparisons of conditioning effects

runs compared		M_{final} [%]		M_{shell} [%]		M_{core} [%]		casehardening [1/mm]		twist [mm]		diamonding [mm]	
"I c ns" "I nc ns"	mean	14.94	14.36	15.52	14.39	26.73	24.73	0.00195	0.001967	0.60	0.21	0.28	0.19
	st. dev.	5.01	6.26	5.98	5.75	15.70	12.82	0.00093	0.000621	1.63	1.74	1.17	1.01
	min	8.78	8.36	8.63	7.64	11.23	11.29	0.00046	0.000997	-1.48	-2.68	-1.10	-2.13
	max	27.44	39.53	34.56	32.44	96.10	69.65	0.00383	0.003711	5.06	4.13	3.91	4.54
	sig. diff.												
"II c ns" "II nc ns"	mean	12.15	15.94	**13.08**	15.86	19.20	28.58	**0.0014**	0.00264	1.44	**0.10**	0.94	1.04
	st. dev.	3.42	5.70	4.08	4.11	9.88	5.21	0.00097	0.00097	1.78	1.34	1.49	1.65
	min	7.30	10.15	8.36	10.54	8.26	12.15	0.00009	0.00094	-0.51	-2.85	-0.86	-0.75
	max	25.85	42.24	26.39	25.97	53.74	34.84	0.00433	0.00481	6.32	4.32	6.08	5.56
	sig. diff.			Yes				Yes		Yes			
"I c s" "I nc s"	mean	17.02	16.05	17.58	16.12	25.75	23.78	**0.00245**	0.00311	0.59	1.23	1.03	-0.58
	st. dev.	4.17	4.72	4.55	4.62	11.02	9.52	0.00094	0.0011	1.62	4.55	1.23	0.93
	min	11.49	10.26	11.87	10.23	13.90	12.56	0.00066	0.00053	-2.17	-0.74	-0.61	-4.72
	max	27.53	28.02	35.22	35.39	65.90	52.27	0.00473	0.00535	5.52	5.67	4.48	0.59
	sig. diff.							Yes					
"II c s" "II nc s"	mean	17.02	11.09	17.58	**11.54**	25.75	16.69	0.00245	0.00201	0.59	1.57	1.03	1.12
	st. dev.	4.17	3.39	4.55	3.10	11.02	8.96	0.00094	0.00077	1.62	1.65	1.23	1.40
	min	11.49	7.12	11.87	6.06	13.90	8.15	0.00066	0.00069	-2.17	-1.39	-0.61	-0.80
	max	27.53	24.15	35.22	22.74	65.90	57.41	0.00473	0.00386	5.52	4.86	4.48	5.22
	sig. diff.			Yes									

In general, conditioning did not affect diamonding in a significant way. But conditioning had a positive influence on casehardening. Conditioning seemed to have a positive influence on twist when interacting with schedule and storage. Overall, conditioning was a valuable step in the drying process.

4.8.3 Storage effects

Storage did not influence the kiln time directly, but it added seven days to the whole process. There was no influence of storage as a main factor but it did influence the final moisture content as interactions with schedule, with conditioning and together with schedule and conditioning. Each run lost a significant amount of moisture during storage. The core moisture content was influenced by storage as a main effect and as the only effect. The cores exhibited significantly decreased moisture contents after storage, but the meaningful comparison pairs did not show significant differences. This rather contradictory fact could be explained with the wide range of final moisture contents. The storage runs lost a significant amount of water during storage but compared to the non-storage runs they are not significantly different. The shell moisture contents were influenced by storage only as interactions, together with schedule, conditioning and together with both schedule and conditioning. These results are anticipated; since the timbers have been given time to even out the moisture gradient within them, as well as to lose accessible moisture after drying. Accordingly, the seven days of storage increased the number of specimens that fell within the target moisture content range and simultaneously reduced the number of over-dried specimens. The direct comparisons for the storage effect are displayed in Table 4.37.

Table 4.37: Direct comparisons of storage effects

runs compared		M_{final} [%]		M_{shell} [%]		M_{core} [%]		casehardening [1/mm]		twist [mm]		diamonding [mm]	
"I c s" "I c ns"	**mean**	17.02	14.94	17.58	**15.52**	25.75	26.73	0.00245	0.00195	0.59	0.60	1.03	0.28
	st. dev.	4.17	5.01	4.55	5.98	11.02	15.70	0.00094	0.00093	1.62	1.63	1.23	1.17
	min	11.49	8.78	11.87	8.63	13.90	11.23	0.00066	0.00046	-2.17	-1.48	-0.61	-1.10
	max	27.53	27.44	35.22	34.56	65.90	96.10	0.00473	0.00383	5.52	5.06	4.48	3.91
	sig. diff.			**Yes**									
"I nc s" "I nc ns"	**mean**	16.05	14.36	16.12	14.39	23.78	24.73	0.00311	**0.001967**	1.23	0.21	**-0.58**	0.19
	st. dev.	4.72	6.26	4.62	5.75	9.52	12.82	0.0011	0.000621	4.55	1.74	0.93	1.01
	min	10.26	8.36	10.23	7.64	12.56	11.29	0.00053	0.000997	-0.74	-2.68	-4.72	-2.13
	max	28.02	39.53	35.39	32.44	52.27	69.65	0.00535	0.003711	5.67	4.13	0.59	4.54
	sig. diff.							**Yes**				**Yes**	
"II c s" "II c ns"	**mean**	17.02	12.15	17.58	13.08	25.75	19.20	0.00245	0.0014	0.59	1.44	1.03	0.94
	st. dev.	4.17	3.42	4.55	4.08	11.02	9.88	0.00094	0.00097	1.62	1.78	1.23	1.49
	min	11.49	7.30	11.87	8.36	13.90	8.26	0.00066	0.00009	-2.17	-0.51	-0.61	-0.86
	max	27.53	25.85	35.22	26.39	65.90	53.74	0.00473	0.00433	5.52	6.32	4.48	6.08
	sig. diff.												
"II nc s" "II nc ns"	**mean**	11.09	15.94	**11.54**	15.86	16.69	28.58	**0.00201**	0.00264	1.57	**0.10**	1.12	1.04
	st. dev.	3.39	5.70	3.10	4.11	8.96	5.21	0.00077	0.00097	1.65	1.34	1.40	1.65
	min	7.12	10.15	6.06	10.54	8.15	12.15	0.00069	0.00094	-1.39	-2.85	-0.80	-0.75
	max	24.15	42.24	22.74	25.97	57.41	34.84	0.00386	0.00481	4.86	4.32	5.22	5.56
	sig. diff.			**Yes**				**Yes**		**Yes**			

The amount of visible checks seemed to be reduced after storage. In terms of twist, the results were quite different; in direct comparison, only run "II nc ns" showed a significantly lower twist when compared to its paired run. Nonetheless, the interaction of storage and conditioning and the interaction of storage, conditioning and schedule exhibited a significant influence on twist. Storage exhibited a significant influence of diamonding when interacting with schedule or with conditioning. There was no clear trend developing yet in terms of diamonding. On the other hand, storage had a major effect on casehardening as a main factor and as the interaction with schedule and with both schedule and conditioning. Both significant comparisons, however, favour storage and no storage equally.

Overall, storage decreased the core moisture content and reduced diamonding when interacting with schedule. It showed an influence as interaction for twist and as main factor and interaction for casehardening. In addition, storage increased the number of specimens in the target moisture content group and reduced the over-dried specimens by moving the final moisture content distribution towards the target moisture content.

4.8.4 Comparison of all treatments to the "Control" run

The drying time of the "Control" was slower than both, schedules "I" and "II", because it used a considerably milder drying schedule. The final moisture content was significantly lower than the treatment runs, which could be attributed to the wide moisture content variation. The "Control" was not significantly different when considering the core moisture contents. However, it was significantly lower in the shell moisture contents in six out of eight comparisons. Over 90% of its specimens fell into the on-target group, which was more than most treatment runs. This could also be attributed to the wide spread of final moisture contents. The "Control" was in the group of the smallest increase of checks together with schedule "II" with either conditioning and/or storage. The "Control" had less of an increase in checks during drying than seven out of the eight treatments. Twist did not develop significantly different from any of the eight treatment runs, but visually it was in the group of four with the highest increase in twist. For diamonding, the "Control" showed no significant difference to any of the treatment runs. Visually, the "Control" had less increase than four out of eight treatment runs, which were mostly schedule "II' without either conditioning and/or storage. For casehardening, the "Control" was the third lowest and was significantly different from the treatment runs.

Table 4.38: Direct comparisons of treatment runs to "Control" run

runs compared		M final [%]		M shell [%]		M core [%]		casehardening [1/mm]		twist [mm]		diamonding [mm]	
"I c s" "C"	**mean**	17.02	10.87	17.58	**11.39**	25.75	14.98	0.00245	**0.001801**	0.59	1.05	1.03	0.50
	st. dev.	4.17	2.19	4.55	2.74	11.02	4.80	0.00094	0.000834	1.62	1.26	1.23	1.03
	min	11.49	7.39	11.87	7.52	13.90	8.03	0.00066	0.000263	-2.17	-1.06	-0.61	-1.03
	max	27.53	20.00	35.22	24.02	65.90	31.23	0.00473	0.004173	5.52	4.03	4.48	3.13
	sig. diff.			**Yes**				**Yes**					
"I nc s" "C"	**mean**	16.05	10.87	16.12	**11.39**	23.78	14.98	0.00311	**0.001801**	1.23	1.05	-0.58	0.50
	st. dev.	4.72	2.19	4.62	2.74	9.52	4.80	0.0011	0.000834	4.55	1.26	0.93	1.03
	min	10.26	7.39	10.23	7.52	12.56	8.03	0.00053	0.000263	-0.74	-1.06	-4.72	-1.03
	max	28.02	20.00	35.39	24.02	52.27	31.23	0.00535	0.004173	5.67	4.03	0.59	3.13
	sig. diff.			**Yes**				**Yes**					
"I nc ns" "C"	**mean**	14.36	10.87	14.39	**11.39**	24.73	14.98	0.001967	0.001801	0.21	1.05	0.19	0.50
	st. dev.	6.26	2.19	5.75	2.74	12.82	4.80	0.000621	0.000834	1.74	1.26	1.01	1.03
	min	8.36	7.39	7.64	7.52	11.29	8.03	0.000997	0.000263	-2.68	-1.06	-2.13	-1.03
	max	39.53	20.00	32.44	24.02	69.65	31.23	0.003711	0.004173	4.13	4.03	4.54	3.13
	sig. diff.			**Yes**									
"I c ns" "C"	**mean**	14.94	10.87	15.52	**11.39**	26.73	14.98	0.00195	0.001801	0.60	1.05	0.28	0.50
	st. dev.	5.01	2.19	5.98	2.74	15.70	4.80	0.00093	0.000834	1.63	1.26	1.17	1.03
	min	8.78	7.39	8.63	7.52	11.23	8.03	0.00046	0.000263	-1.48	-1.06	-1.10	-1.03
	max	27.44	20.00	34.56	24.02	96.10	31.23	0.00383	0.004173	5.06	4.03	3.91	3.13
	sig. diff.			**Yes**									
"II c s" "C"	**mean**	17.02	10.87	17.58	**11.39**	25.75	14.98	0.00245	0.001801	0.59	1.05	1.03	0.50
	st. dev.	4.17	2.19	4.55	2.74	11.02	4.80	0.00094	0.000834	1.62	1.26	1.23	1.03
	min	11.49	7.39	11.87	7.52	13.90	8.03	0.00066	0.000263	-2.17	-1.06	-0.61	-1.03
	max	27.53	20.00	35.22	24.02	65.90	31.23	0.00473	0.004173	5.52	4.03	4.48	3.13
	sig. diff.			**Yes**									
"II nc s" "C"	**mean**	11.09	10.87	11.54	11.39	16.69	14.98	0.00201	0.001801	1.57	1.05	1.12	0.50
	st. dev.	3.39	2.19	3.10	2.74	8.96	4.80	0.00077	0.000834	1.65	1.26	1.40	1.03
	min	7.12	7.39	6.06	7.52	8.15	8.03	0.00069	0.000263	-1.39	-1.06	-0.80	-1.03
	max	24.15	20.00	22.74	24.02	57.41	31.23	0.00386	0.004173	4.86	4.03	5.22	3.13
	sig. diff.												
"II nc ns" "C"	**mean**	15.94	10.87	15.86	**11.39**	28.58	14.98	0.00264	**0.001801**	0.10	1.05	1.04	0.50
	st. dev.	5.70	2.19	4.11	2.74	5.21	4.80	0.00097	0.000834	1.34	1.26	1.65	1.03
	min	10.15	7.39	10.54	7.52	12.15	8.03	0.00094	0.000263	-2.85	-1.06	-0.75	-1.03
	max	42.24	20.00	25.97	24.02	34.84	31.23	0.00481	0.004173	4.32	4.03	5.56	3.13
	sig. diff.			**Yes**				**Yes**					
"II c ns" "C"	**mean**	12.15	10.87	13.08	11.39	19.20	14.98	0.0014	0.001801	1.44	1.05	0.94	0.50
	st. dev.	3.42	2.19	4.08	2.74	9.88	4.80	0.00097	0.000834	1.78	1.26	1.49	1.03
	min	7.30	7.39	8.36	7.52	8.26	8.03	0.00009	0.000263	-0.51	-1.06	-0.86	-1.03
	max	25.85	20.00	26.39	24.02	53.74	31.23	0.00433	0.004173	6.32	4.03	6.08	3.13
	sig. diff.												

When comparing the "Control" to the eight treatment runs it becomes apparent that the "Control" exhibited less casehardening than three out of the eight treatment runs, but on the other hand, none of the treatment runs showed a significant difference in twist or diamonding when compared to the "Control".

5. Conclusions and Future Recommendations

The drying of timbers is one of the most important operations during the production process in terms of costs and time invested. But, on the other hand, it can add significant value to the finished product. The drying process is rather unpredictable due to the many variables that influence the outcome of each drying run. In order to achieve a consistent drying quality the industry has to rely on the skills and experience of the kiln operator. To get a handle on the endless drying possibilities more research is necessary and hopefully this study will contribute to this research.

When considering the objective and results of this investigation, the following conclusions can be made:

1. Storage decreased the final and the core moisture contents significantly when interacting with the other factors. More importantly, storage increased the number of timbers in the target moisture content group and reduced the amount of over-dried timbers. Storage had significant influence on diamonding, also in interaction with the drying schedule and with conditioning, but no clear trend could be established with the current data. There was also a significant influence on twist, in interaction with conditioning and with both, conditioning and schedule. However, three out of four runs that experienced the smallest increase in twist did not use storage. Statistically, storage had significant influence on casehardening as a main factor and in interactions with schedule and with both, schedule and conditioning.

2. The conditioning significantly influenced the final moisture content in interaction with storage and in interaction together with both schedule and storage. It did not show any effect on core moisture content. Nevertheless, conditioning had a positive influence on the shell moisture content when used with the harsher schedule "II". Conditioning had a significant influence on the shell moisture content in interaction with storage and with both, storage and

schedule. Conditioning visibly decreased the appearance of checks. The development of twist did not significantly increase when conditioning was excluded during drying. However, conditioning had a significant influence in interaction with storage and together with both, storage and schedule. One run each with and without conditioning did not show a significant increase in diamonding during drying. In direct comparison conditioning did not have any influence on diamonding. It only exhibited a significant influence in interaction with schedule. The three runs that displayed the lowest values for casehardening all used conditioning. Conditioning influenced casehardening not only as a main factor but also in interaction with schedule and together with schedule and storage.

3. The harshest schedule, schedule "II", was the fastest, followed by schedule "I" and the "Control". Schedule proved to be a main influence on the final moisture content, as well as in interaction with storage. The core moisture content was level and steady when using schedule "I" and it also developed lower shell moisture contents than schedule "II". The treatment schedules proved to be a main influence on the shell moisture content and also had a significant influence in interaction with storage and with both storage and conditioning. Schedule "II" used with conditioning and/or storage developed fewer checks than schedule "I" with the same treatments. On the other hand, schedule "I" without conditioning and storage showed better results in terms of checks than schedule "II" under the same conditions; however, both runs did not develop a significant increase in twist. In terms of twist, schedule showed no significant influence. Schedule had a significant influence on twist in interaction with storage and conditioning. In regards to diamonding, schedule "I" developed no significant increase during drying in two out of four times. In one of the drying runs schedule "I" even reversed the pre-existing diamonding significantly. Schedule only had a significant influence on diamonding in interaction with storage. For casehardening, schedule proved to be a significant influence as a main factor and in interaction with

conditioning and with storage and in a combined interaction with conditioning and storage. Drying runs utilizing schedule “II” developed less casehardening in two out of three runs.

4. The “Control” was the mildest schedule in this study and consequently the significantly slowest drying run. It experienced significantly lower final moisture contents than the treatment runs, which was due to the high variability in final moisture contents. However, its core moisture content did not show a difference but its shell moisture contents were significantly lower in six out of eight treatments. Over 90% of the timbers in the “Control” run were on target in terms of final moisture content. The “Control” developed less increase in checks in seven out of eight treatment runs. In terms of twist, the “Control” developed no significantly higher twist than any of the eight runs. There were no significant differences in diamonding either. Its casehardening development is significantly different from the treatment runs; the “Control” showed the third lowest casehardening measurements.

In summary, conditioning reduced the casehardening, as did the harsher schedule “II”, while the milder schedule “I” developed less twist and diamonding. The “Control” did not develop significant values in shape distortions than the treatment runs, except for casehardening, but it took considerably longer drying times. If the harsher schedule “II” is used for drying, it would reduce the kiln time and free it for the next drying run. If the timber was put into storage after drying, the core and shell moisture contents would be levelled out and the casehardening reduced. To reduce twist, diamonding and checks, the timber could be planed, which leads to a significant reduction in these distortions (Hao and Avramidis, 2004; Hao and Avramidis, 2006; Bradic and Avramidis, 2007). In terms of shape distortions, the experimental schedules were not that much different from the “Control” and they took considerably less drying time. The casehardening measurements are different, but they might not be valid for the entire piece of timber they were taken from. Using one of the experimental schedules, the timber would dry faster and would still provide good quality fiber for building materials.

There is still more research necessary to develop our knowledge of wood drying and the economic consequences of the new experimental schedules and methods. For future research, it is recommended to continue the investigation into new schedules as well as, the conditioning and storage options for conventional kiln drying of hemlock squares. All, however, seem to have a beneficial influence on kiln dried western hemlock baby-squares and might be tried for other species. It would be advisable to repeat the experimental runs more than once for each treatment in order to achieve statistically stronger results. The input from advanced statistical methods to explore the interactions of the treatments in more detail might be advisable. Also, the use of an industrial size kiln that fits specimens longer than 900mm would be worthwhile. It might be useful to investigate the influence of the kiln location of each timber on the developing drying distortions, as well as, the influence that additional weight has on these deformations, especially in larger kilns. However, it would be advisable to ensure that the final moisture contents fall in a narrower range, for easier comparison of the timber quality.

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7. Appendix

Table 7.1: Average moisture content and basic density values for each run and their standard deviations in comparison

	M green [%]	*St. Dev.*	Basic Density [kg/m3]	*St. Dev.*
Run 1	78.1	*20.3*	382.0	*36.92*
Run 2	78.7	*22.6*	382.2	*52.17*
Run 3	79.5	*23.6*	379.5	*44.72*
Run 4	78.6	*25.8*	377.4	*46.87*
Run 5	78.1	*24.3*	383.1	*45.17*
Run 6	79.1	*27.4*	379.1	*48.54*
Run 7	78.7	*22.9*	380.3	*43.37*
Run 8	80.6	*25.4*	379.5	*39.69*
Run 9	77.3	*30.1*	379.8	*45.92*
AVRG	*78.7*	*24.7*	*380.3*	*44.82*
St. Dev.	*0.93*	*2.87*	*1.8*	*4.53*
min	*77.3*	*20.3*	*377.4*	*36.9*
max	*80.6*	*30.1*	*383.1*	*52.2*

Table 7.2: T-test to compare moisture content and basic density averages of drying runs, using α = 0.05

Moisture Content				**Basic Density**			
comparisons	**probability calculated**	**alpha**	**sig. diff.**	**comparisons**	**probability calculated**	**alpha**	**sig. diff.**
1-2	0.392	0.05	no	**1-2**	0.450	0.05	no
1-3	0.327	0.05	no	**1-3**	0.440	0.05	no
1-4	0.396	0.05	no	**1-4**	0.353	0.05	no
1-5	0.437	0.05	no	**1-5**	0.405	0.05	no
1-6	0.409	0.05	no	**1-6**	0.392	0.05	no
1-7	0.243	0.05	no	**1-7**	0.459	0.05	no
1-8	0.260	0.05	no	**1-8**	0.433	0.05	no
1-9	0.498	0.05	no	**1-9**	0.452	0.05	no
2-3	0.438	0.05	no	**2-3**	0.496	0.05	no
2-4	0.500	0.05	no	**2-4**	0.418	0.05	no
2-5	0.458	0.05	no	**2-5**	0.374	0.05	no
2-6	0.493	0.05	no	**2-6**	0.451	0.05	no
2-7	0.345	0.05	no	**2-7**	0.491	0.05	no
2-8	0.363	0.05	no	**2-8**	0.493	0.05	no
2-9	0.411	0.05	no	**2-9**	0.495	0.05	no
3-4	0.440	0.05	no	**3-4**	0.415	0.05	no
3-5	0.396	0.05	no	**3-5**	0.360	0.05	no
3-6	0.435	0.05	no	**3-6**	0.451	0.05	no
3-7	0.399	0.05	no	**3-7**	0.486	0.05	no
3-8	0.419	0.05	no	**3-8**	0.497	0.05	no
3-9	0.356	0.05	no	**3-9**	0.490	0.05	no

Table 7.2 Continued: T-test to compare moisture content and basic density averages of drying runs, using $\alpha = 0.05$

Moisture Content				Basic Density			
comparisons	**probability calculated**	**alpha**	**sig. diff.**	**comparisons**	**probability calculated**	**alpha**	**sig. diff.**
4-5	0.460	0.05	no	**4-5**	0.287	0.05	no
4-6	0.493	0.05	no	**4-6**	0.466	0.05	no
4-7	0.350	0.05	no	**4-7**	0.408	0.05	no
4-8	0.366	0.05	no	**4-8**	0.414	0.05	no
4-9	0.412	0.05	no	**4-9**	0.407	0.05	no
5-6	0.468	0.05	no	**5-6**	0.322	0.05	no
5-7	0.310	0.05	no	**5-7**	0.383	0.05	no
5-8	0.325	0.05	no	**5-8**	0.349	0.05	no
5-9	0.447	0.05	no	**5-9**	0.371	0.05	no
6-7	0.350	0.05	no	**6-7**	0.442	0.05	no
6-8	0.365	0.05	no	**6-8**	0.452	0.05	no
6-9	0.422	0.05	no	**6-9**	0.443	0.05	no
7-8	0.478	0.05	no	**7-8**	0.482	0.05	no
7-9	0.287	0.05	no	**7-9**	0.495	0.05	no
8-9	0.296	0.05	no	**8-9**	0.486	0.05	no

Table 7.3: Final moisture content for each specimen by location in kiln and with pith location

								mean
RUN	**10.56**	**11.64**	**7.93**	**13.35**	**9.49**	**10.32**	**10.60**	**10.56**
"C"	**9.42**	**9.07**	**8.98**	**7.39**	[illegible]	**15.70**	**10.72**	**9.91**
	12.29	**9.22**	**10.33**	**8.91**	**8.95**	**9.75**	**13.06**	**10.36**
	9.62	**12.01**	**11.58**	**10.15**	**10.38**	[illegible]	**11.37**	**10.57**
	11.75	**12.24**	**10.85**	**9.84**	**9.76**	**10.64**	**11.12**	**10.88**
	11.50	**10.92**	**13.70**	**12.32**	**10.49**	**11.55**	**20.00**	**12.93**
mean	**10.85**	**10.85**	**10.56**	**10.33**	**9.53**	**11.14**	**12.81**	
								mean
RUN	**11.13**	**11.99**	**19.89**	**9.70**	**12.35**	**14.88**	**13.35**	**13.33**
"I c ns"	**9.80**	**10.97**	**11.95**	**8.79**	[illegible]	**17.24**	**24.60**	**13.16**
	17.60	[illegible]	**14.39**	**12.00**	[illegible]	**15.78**	[illegible]	**14.70**
	11.35	[illegible]	**17.13**	**10.74**	[illegible]	[illegible]	**27.44**	**15.07**
	16.75	**11.11**	**9.93**	**13.17**	**12.55**	**10.36**	[illegible]	**14.33**
	23.57	**12.50**	**13.20**	**20.34**	**21.63**	**24.00**	**18.13**	**19.05**
mean	**15.04**	**12.55**	**14.42**	**12.46**	**12.76**	**16.51**	**20.86**	
								mean
RUN	[illegible]	**16.06**	**9.86**	**11.75**	**12.16**	**8.75**	**14.39**	**11.61**
"I nc ns"	**11.81**	**20.22**	**10.83**	**8.81**	**9.37**	**9.47**	[illegible]	**11.74**
	14.47	**15.80**	**10.87**	**18.69**	**11.18**	[illegible]	**10.49**	**14.43**
	11.94	**11.47**	**24.82**	**10.75**	**30.45**	**13.82**	**10.43**	**16.24**
	[illegible]	**18.21**	**11.33**	**9.42**	**24.67**	**9.70**	**13.15**	**13.95**
	10.33	**17.19**	**15.95**	**16.84**	**39.53**	**11.97**	[illegible]	**18.28**
mean	**11.35**	**16.49**	**13.94**	**12.70**	**21.23**	**12.20**	**12.71**	

Table 7.3 Continued: Final moisture content for each specimen by location in kiln and with pith location

								mean
RUN "II nc ns"	15.15	[redacted]	[redacted]	10.59	12.41	17.86	15.39	13.11
	14.30	20.73	13.40	13.66	21.07	10.40	12.98	15.22
	16.17	[redacted]	18.11	15.71	[redacted]	11.70	14.11	14.96
	12.63	[redacted]	11.49	17.95	18.42	23.23	10.88	15.30
	11.66	20.34	13.54	15.71	42.24	12.97	22.33	19.83
	[redacted]	18.60	15.14	13.74	27.03	[redacted]	16.18	17.26
mean	13.99	15.51	13.64	14.56	23.24	15.38	15.31	

								mean
RUN "I c s"	12.13	26.46	17.81	14.96	[redacted]	13.03	[redacted]	15.90
	11.80	16.53	15.46	16.84	[redacted]	12.55	16.34	14.83
	[redacted]	19.58	20.25	15.85	15.58	21.90	13.06	16.82
	27.53	22.71	[redacted]	26.58	20.99	15.04	16.15	20.28
	[redacted]	16.54	16.30	18.56	[redacted]	14.88	19.90	16.29
	18.16	18.30	14.20	25.27	17.08	19.06	13.91.	18.68
mean	15.92	20.02	16.17	19.68	16.09	16.08	15.45	

								mean
RUN "I nc s"	10.49	10.26	[redacted]	27.92	18.92	21.69	[redacted]	16.83
	11.34	14.69	[redacted]	[redacted]	[redacted]	[redacted]	*11.25*	14.29
	15.47	21.05	10.52	23.49	23.88	28.02	15.47	19.70
	12.28	13.73	15.48	11.87	13.54	[redacted]	14.35	14.02
	13.91	13.15	13.14	12.85	15.12	13.01	27.15	15.48
	16.03	14.05	[redacted]	[redacted]	19.43	21.50	15.04	16.06
mean	13.25	14.49	13.60	17.27	18.21	18.99	16.64	

								mean
RUN "II c s"	13.70	17.79	11.64	[redacted]	14.46	10.85	13.70	13.51
	10.52	12.59	11.45	12.81	11.54	[redacted]	13.07	11.73
	11.74	12.05	13.01	19.23	[redacted]	[redacted]	13.04	13.48
	20.37	14.31	12.19	14.21	[redacted]	[redacted]	11.01	13.48
	13.07	[redacted]	25.93	14.50	12.95	13.30	[redacted]	14.93
	[redacted]	19.05	[redacted]	14.18	14.02	13.90	21.92	16.19
mean	13.59	15.39	14.86	14.56	14.37	12.12	14.96	15.73

								mean
RUN "II nc s"	7.63	8.40	15.65	8.84	9.92	*8.23*	8.66	9.62
	12.19	10.92	[redacted]	10.19	7.77	11.04	13.95	10.45
	9.40	11.03	8.65	[redacted]	9.70	9.00	10.85	9.90
	10.92	10.15	9.73	8.54	12.15	9.71	12.11	10.47
	9.43	[redacted]	10.91	[redacted]	10.19	11.54	10.55	12.11
	9.58	17.85	15.24	10.90	24.15	10.08	[redacted]	14.00
mean	9.86	13.26	11.22	10.02	12.31	9.93	11.06	

Table 7.3 Continued: Final moisture content for each specimen by location in kiln and with pith location

								mean
RUN "II c ns"	11.27	9.86		9.10	16.96		9.75	11.30
	10.64		8.56		9.81	10.69	14.00	10.49
	9.32	8.74	12.03	9.33		13.80	10.23	11.12
	10.80	9.19	19.21		9.78	13.33	11.52	11.98
	13.34	10.30	9.28		11.90	16.13		14.53
	12.26	14.76	10.60	13.66		12.20	17.10	13.51
mean	11.27	10.88	11.44	10.73	12.80	13.22	14.74	

Pith Location	A	B		D

Table 7.4: Checks for each specimen by location in kiln and with pith location

								mean
RUN "C"	0	0	900	900	905	[illegible]	0	386
	0	0	490	0	[illegible]	[illegible]	0	-14
	0	360	0	-330	0	0	500	76
	-150	[illegible]	0	[illegible]	610	[illegible]	0	66
	0	0	900	0	0	0	[illegible]	129
	[illegible]	[illegible]	0	[illegible]	0	[illegible]	0	129
mean	-25	60	382	245	259	-105	83	

								mean
RUN "I c ns"	320	0	0	[illegible]	0	-310	[illegible]	104
	0	0	0	320	[illegible]	660	0	226
	0	[illegible]	0	340	[illegible]	0	[illegible]	106
	[illegible]	[illegible]	0	0	[illegible]	[illegible]	900	207
	700	700	0	0	0	0	[illegible]	200
	0	0	0	0	0	[illegible]	900	129
mean	170	183	0	110	192	58	420	

								mean
RUN "I nc ns"	[illegible]	900	0	[illegible]	[illegible]	[illegible]	0	259
	0	[illegible]	0	0	900	540	[illegible]	429
	600	460	0	900	0	[illegible]	-900	311
	0	[illegible]	900	640	0	260	900	386
	[illegible]	0	0	900	0	[illegible]	0	129
	0	400	0	0	660	0	[illegible]	151
mean	100	503	150	407	260	472	50	

								mean
RUN "II nc ns"	0	[illegible]	[illegible]	0	820	0	910	247
	0	0	200	0	0	600	0	114
	670	[illegible]	0	0	[illegible]	0	400	153
	780	[illegible]	0	170	910	580	0	387
	280	0	0	1530	0	0	0	259
	[illegible]	0	140	0	250	[illegible]	910	186
mean	288	45	57	283	330	197	370	

Table 7.4 Continued: Checks for each specimen by location in kiln and with pith location

RUN "I c s"							mean
250	812	0	460	[illegible]	0	[illegible]	217
910	0	0	0	[illegible]	0	910	260
[illegible]	760	400	0	0	220	430	259
700	140	[illegible]	230	910	0	0	283
[illegible]	380	260	910	[illegible]	240	770	366
0	910	100	320	130	590	670	389
mean 310	500	127	320	173	175	463	

RUN "I nc s"							mean
0	0	[illegible]	240	0	0	[illegible]	116
0	140	[illegible]	[illegible]	[illegible]	[illegible]	*110*	60
0	180	240	180	520	290	110	217
220	0	0	820	-180	[illegible]	0	143
370	620	0	0	450	0	-900	77
0	340	[illegible]	[illegible]	0	0	450	169
mean 98	213	160	247	132	100	-38	

RUN "II c s"							mean
0	1200	0	[illegible]	200	0	0	200
0	0	0	900	0	[illegible]	0	129
0	400	0	300	[illegible]	[illegible]	1200	357
0	0	0	0	[illegible]	[illegible]	250	357
0	[illegible]	0	0	0	250	[illegible]	129
[illegible]	0	[illegible]	0	0	0	0	79
mean 0	317	83	200	167	117	242	

RUN "II nc s"							mean
0	550	220	0	0	*870*	0	234
0	760	[illegible]	0	0	0	0	109
0	0	0	[illegible]	810	0	0	116
230	0	0	0	0	250	0	69
0	[illegible]	0	[illegible]	0	0	0	57
0	270	0	610	0	0	[illegible]	126
mean 38	330	37	102	135	187	0	

RUN "II c ns"							mean
0	0	[illegible]	0	910	[illegible]	0	130
0	[illegible]	0	[illegible]	910	280	0	170
0	0	0	0	[illegible]	910	0	171
0	0	360	[illegible]	0	480	0	120
0	0	0	[illegible]	0	0	[illegible]	0
100	0	0	480	[illegible]	0	0	83
mean 17	0	60	80	352	278	0	

Pith Location				
	A	B	C	D

Table 7.5: Twist for each specimen by location in kiln and with pith location

								mean
RUN "C"	-0.22	0.15	0.09	2.86	1.06	[illegible]	-0.44	0.75
	1.77	2.18	0.51	1.66	[illegible]	[illegible]	0.19	1.51
	0.69	1.00	2.66	2.15	2.08	0.96	0.28	1.40
	-0.78	[illegible]	-0.16	[illegible]	-0.13	[illegible]	1.38	0.21
	-0.18	-0.38	3.42	4.03	0.55	1.22	[illegible]	1.31
	[illegible]	[illegible]	0.71	[illegible]	2.26	[illegible]	2.00	1.26
mean	0.05	1.35	1.21	1.69	1.26	1.32	0.66	

								mean
RUN "I c ns"	-0.77	-0.25	-1.23	[illegible]	-0.70	2.61	[illegible]	0.73
	3.48	-0.75	-0.11	0.09	[illegible]	0.00	-1.33	0.81
	-1.03	[illegible]	0.02	2.79	[illegible]	-1.48	[illegible]	0.02
	[illegible]	[illegible]	-0.07	1.52	[illegible]	[illegible]	-0.50	0.08
	-0.75	5.06	3.08	-0.24	-0.06	0.21	[illegible]	1.14
	-1.00	1.00	2.81	-0.35	0.91	[illegible]	2.17	0.83
mean	-0.06	0.83	0.75	1.10	0.59	0.32	0.71	

								mean
RUN "I nc ns"	[illegible]	2.36	0.48	[illegible]	[illegible]	[illegible]	0.20	0.51
	4.13	[illegible]	0.73	-1.40	3.89	3.19	[illegible]	1.79
	1.77	-0.21	0.85	1.87	0.40	[illegible]	3.00	1.08
	-0.84	[illegible]	-0.31	-0.62	-2.65	0.25	0.03	-0.82
	[illegible]	-1.12	0.90	1.47	-1.32	[illegible]	-1.37	-0.04
	-2.62	-0.90	-2.23	-2.68	-1.48	-1.52	[illegible]	-1.30
mean	0.49	-0.30	0.07	-0.05	-0.03	0.17	1.08	

								mean
RUN "II nc ns"	2.11	[illegible]	[illegible]	0.58	0.42	-0.81	-0.07	0.40
	-0.70	-0.55	-0.34	0.01	0.18	0.86	-2.20	-0.39
	0.72	[illegible]	1.36	1.25	[illegible]	-0.04	0.48	0.38
	-0.43	[illegible]	-1.78	-1.02	0.81	-0.04	1.98	-0.07
	0.03	1.52	-1.60	-0.03	-1.15	4.32	-0.17	0.42
	[illegible]	1.25	-2.15	-0.53	2.60	[illegible]	-1.73	-0.01
mean	0.37	0.06	-0.53	0.04	0.48	0.71	-0.29	

								mean
RUN "I c s"	3.65	0.70	0.02	-0.09	[illegible]	4.39	[illegible]	1.47
	-0.72	4.69	5.52	-0.63	[illegible]	0.48	0.86	1.57
	[illegible]	0.50	-0.81	1.12	-1.17	-0.08	0.50	-0.10
	-2.17	0.19	[illegible]	-0.28	-0.40	0.32	1.06	-0.10
	[illegible]	-1.19	-0.20	0.31	[illegible]	0.86	2.17	0.13
	0.11	0.40	1.09	-0.23	-1.77	2.44	1.80	0.55
mean	-0.05	0.88	1.03	0.03	-0.29	1.40	1.09	

Table 7.5 Continued: Twist for each specimen by location in kiln and with pith location

								mean
RUN "I nc s"	3.85	0.40	[illegible]	-0.74	3.59	-0.15	[illegible]	1.24
	-0.72	2.11	[illegible]	[illegible]	[illegible]	[illegible]	*-0.49*	0.69
	0.60	3.43	-0.26	0.16	-0.11	0.63	1.45	0.84
	1.58	0.32	1.86	1.73	1.44	[illegible]	1.96	1.59
	0.06	2.52	5.67	3.21	1.03	0.53	0.19	1.89
	0.72	4.17	[illegible]	[illegible]	-0.68	0.07	-0.61	1.17
mean	1.02	2.16	2.27	0.96	1.08	0.53	0.63	

								mean
RUN "II c s"	0.49	-0.80	-1.24	[illegible]	0.04	-0.63	-0.34	-0.31
	-0.33	0.01	2.16	0.96	1.42	[illegible]	0.54	0.59
	-0.2	0.19	1.35	0.31	[illegible]	[illegible]	0.28	0.37
	-0.78	-1.19	3.51	0.65	[illegible]	[illegible]	-0.48	0.37
	0.33	[illegible]	-0.24	0.31	6.32	-1.04	[illegible]	0.24
	[illegible]	0.60	[illegible]	0.63	-0.31	1.68	0.06	1.32
mean	-0.21	-0.04	0.86	0.53	1.22	0.03	0.45	

								mean
RUN "II nc s"	1.63	2.13	1.38	1.89	0.52	*0.03*	3.29	1.55
	-0.42	-0.08	[illegible]	2.26	0.29	2.36	-1.32	0.54
	3.73	4.86	1.22	[illegible]	-0.90	0.38	2.18	1.85
	2.60	2.66	2.85	2.42	3.78	3.85	1.55	2.82
	1.41	0.87	-0.30	2.03	3.87	1.52	-1.23	1.17
	-1.39	0.01	0.73	4.25	1.27	0.79	[illegible]	1.49
mean	1.26	1.74	1.09	2.39	1.47	1.49	1.54	

								mean
RUN "II c ns"	2.15	2.00	[illegible]	-0.10	0.16	[illegible]	-0.46	0.72
	2.76	[illegible]	-0.02	[illegible]	-0.13	0.29	0.31	1.47
	4.61	1.96	1.06	0.82	[illegible]	0.19	-0.37	1.24
	6.32	-0.04	0.59	[illegible]	5.90	1.32	-0.51	1.96
	3.11	3.07	0.09	2.55	1.19	1.70	[illegible]	1.69
	2.45	0.24	1.81	2.42	2.52	-0.19	1.68	1.56
mean	3.57	1.37	0.52	1.99	1.67	0.84	0.12	

Pith Location				
	A	B	C	D

Table 7.6: Diamonding for each specimen by location in kiln and with pith location

RUN "C"							mean
-0.18	0.17	-0.49	0.05	0.05	[illegible]	2.08	0.41
-0.78	-0.30	0.72	-0.31	[illegible]	[illegible]	1.28	0.07
0.08	1.68	-0.03	-0.03	1.16	1.31	0.04	0.60
2.94	[illegible]	0.00	[illegible]	1.50	[illegible]	-1.03	0.79
1.63	0.49	1.75	0.61	-0.78	-0.45	[illegible]	0.43
[illegible]	[illegible]	1.12	[illegible]	1.97	[illegible]	0.14	0.71
mean 0.89	0.15	0.51	0.09	0.52	0.97	0.38	

RUN "I c ns"							mean
-0.70	-0.73	0.81	[illegible]	3.91	2.87	[illegible]	1.10
0.02	0.64	0.61	-0.61	[illegible]	-0.82	0.17	-0.07
-1.08	[illegible]	-0.64	-0.80	[illegible]	-0.42	[illegible]	-0.29
[illegible]	[illegible]	0.11	2.42	[illegible]	[illegible]	-0.85	0.74
-1.10	-0.73	2.37	-0.36	1.23	0.04	[illegible]	0.25
0.71	-0.45	-0.65	0.06	-0.51	[illegible]	-0.63	-0.02
mean -0.28	-0.08	0.44	0.13	1.26	0.44	0.09	

RUN "I nc ns"							mean
[illegible]	0.22	0.16	[illegible]	[illegible]	[illegible]	1.41	0.86
0.34	[illegible]	0.34	0.23	-2.13	-0.80	[illegible]	-0.37
0.57	-0.26	1.68	0.08	-0.91	[illegible]	2.18	0.40
0.71	[illegible]	0.44	-0.16	-0.54	-0.19	1.54	0.23
[illegible]	0.76	0.00	-0.63	0.63	[illegible]	0.59	0.26
-0.26	0.09	-0.35	-0.26	-0.39	-0.37	[illegible]	-0.24
mean 0.29	0.06	0.38	0.63	-0.63	-0.28	0.89	

RUN "II nc ns"							mean
3.03	[illegible]	[illegible]	2.53	1.60	1.10	2.81	2.55
3.32	0.00	-0.25	2.13	-0.53	5.56	-0.17	1.44
-0.53	[illegible]	0.68	0.54	[illegible]	2.48	3.04	1.33
-0.62	[illegible]	2.67	-0.08	-0.04	-0.50	0.83	0.32
-0.61	0.07	-0.56	-0.22	0.18	0.24	-0.49	-0.20
[illegible]	2.05	-0.75	-0.18	-0.38	[illegible]	-0.12	0.79
mean 1.45	1.55	0.80	0.79	0.08	1.62	0.98	

RUN "I c s"							mean
4.48	0.47	1.81	0.01	[illegible]	1.98	[illegible]	2.11
-0.33	1.30	0.28	-0.11	[illegible]	0.70	1.17	0.37
[illegible]	1.25	-0.15	-0.11	0.53	0.26	0.35	0.61
1.35	1.17	[illegible]	-0.09	-0.61	0.11	0.83	0.78
[illegible]	3.04	0.84	-0.09	[illegible]	-0.22	0.62	0.81
2.46	3.49	0.27	1.97	1.93	0.44	0.05	1.52
mean 1.86	1.79	0.96	0.26	0.68	0.55	1.13	

Table 7.6 Continued: Diamonding for each specimen by location in kiln and with pith location

								mean
RUN "I nc s"	-0.06	-0.21	[illegible]	0.09	-0.46	-0.33	[illegible]	-1.04
	-0.60	-1.01	[illegible]	[illegible]	[illegible]	[illegible]	*-0.06*	-0.44
	0.07	0.59	0.03	0.39	-0.46	0.22	-0.25	0.08
	-1.41	-0.56	-0.41	-0.55	-0.36	[illegible]	0.10	-0.47
	-2.25	0.41	-0.92	-1.08	-0.52	-0.47	-0.41	-0.75
	0.26	-2.57	[illegible]	[illegible]	0.00	-1.62	-0.46	-0.84
mean	-0.67	-0.56	-1.10	-0.46	-0.34	-0.46	-0.44	

								mean
RUN "II c s"	-0.37	-0.39	0.32	[illegible]	0.35	0.09	0.52	0.15
	0.22	0.00	0.04	0.37	0.18	[illegible]	0.13	0.20
	0	-0.24	0.76	0	[illegible]	[illegible]	-0.76	-0.07
	0.35	0.00	-0.34	0.95	[illegible]	[illegible]	-0.11	-0.07
	0.39	[illegible]	0.03	-0.10	0.59	0.85	[illegible]	0.22
	[illegible]	0.46	[illegible]	0.23	0.56	1.02	-0.02	0.25
mean	0.16	-0.03	0.14	0.33	0.28	0.47	-0.04	

								mean
RUN "II nc s"	0.26	0.13	1.09	3.80	-0.51	*0.02*	-0.04	0.68
	0.74	1.71	[illegible]	1.27	3.51	-0.39	0.86	1.10
	3.27	0.18	0.10	[illegible]	0.00	0.07	0.74	0.84
	0.14	5.22	1.56	-0.80	4.04	0.66	2.78	1.94
	0.35	[illegible]	2.60	[illegible]	0.22	0.94	3.12	1.59
	1.34	0.00	1.07	0.30	0.75	0.05	[illegible]	0.58
mean	1.02	1.65	1.07	1.22	1.34	0.23	1.33	

								mean
RUN "II c ns"	-0.51	1.55	[illegible]	0.61	-0.54	[illegible]	6.08	1.72
	-0.41	[illegible]	4.46	[illegible]	0.60	0.18.	0.99	1.41
	-0.48	0.04	1.19	1.42	[illegible]	-0.77	-0.10	0.20
	0.00	1.06	2.31	[illegible]	-0.39	-0.07	-0.31	0.77
	2.04	0.00	2.97	[illegible]	2.65	1.42	[illegible]	1.30
	-0.02	0.00	1.52	-0.86	[illegible]	0.83	-0.40	0.41
mean	0.10	0.75	2.32	0.83	0.70	0.96	1.04	

Pith Location	*A*	B	[illegible]	D

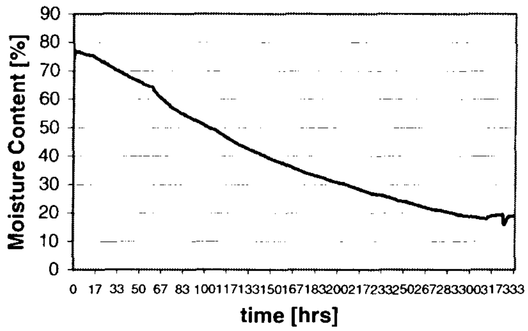

Figure 7.1: Drying curve for run "II c ns"

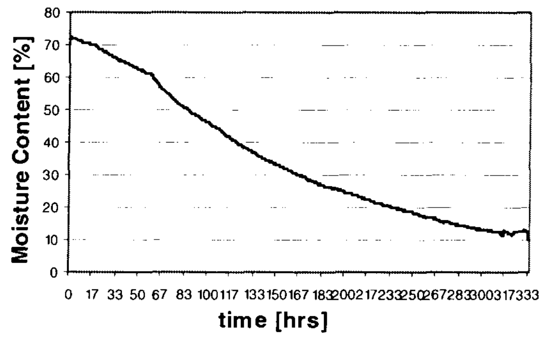

Figure 7.2: Drying curve for run "I c ns"

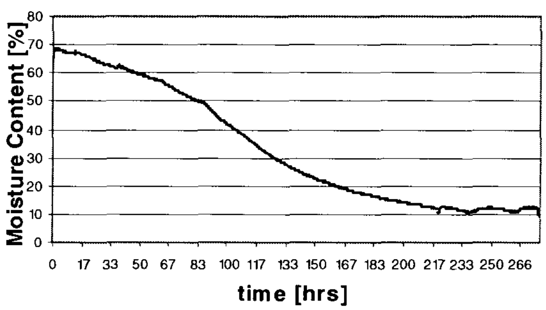

Figure 7.3: Drying curve for run "I nc ns"

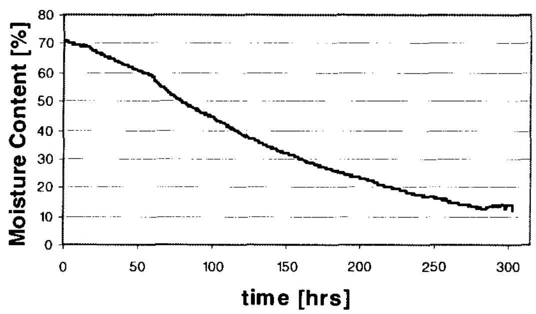

Figure 7.4: Drying curve for run "II nc ns"

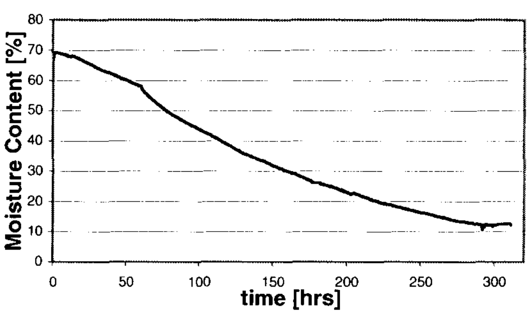

Figure 7.5: Drying curve for run "I c s"

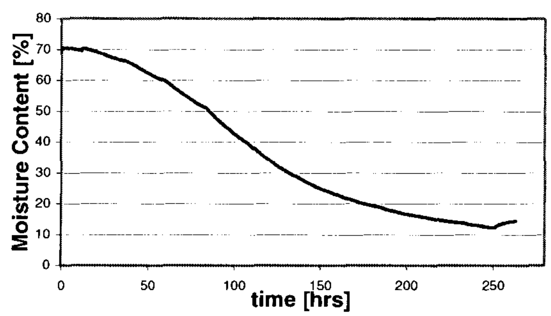

Figure 7.6: Drying curve for run "I nc s"

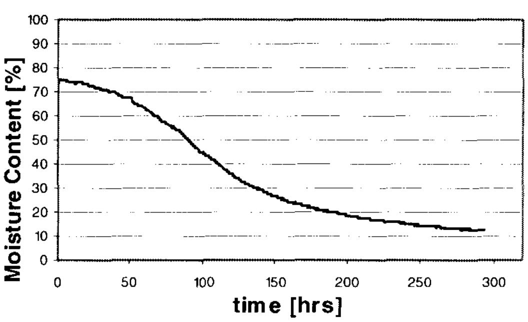

Figure 7.7: Drying curve for run "II c s"

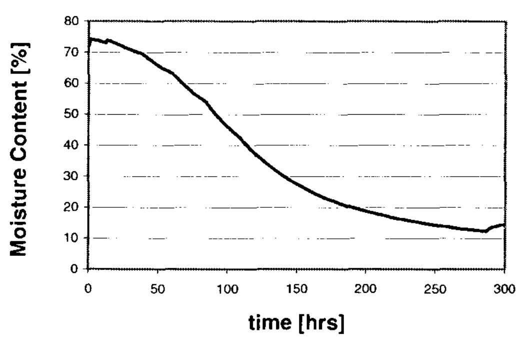

Figure 7.8: Drying curve for run "II nc s"

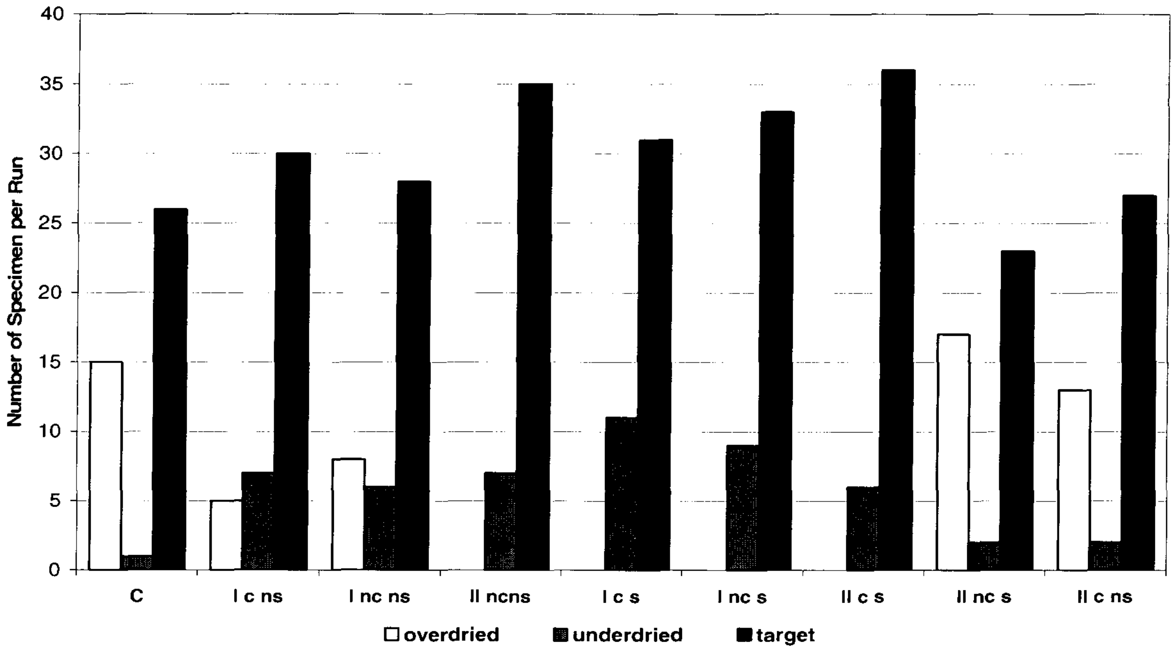

Figure 7.9: Absolute number of over and under-dried specimens per run (over-dried is below 10%M, under-dried is above 19% M and target is between 10% and 19% M)

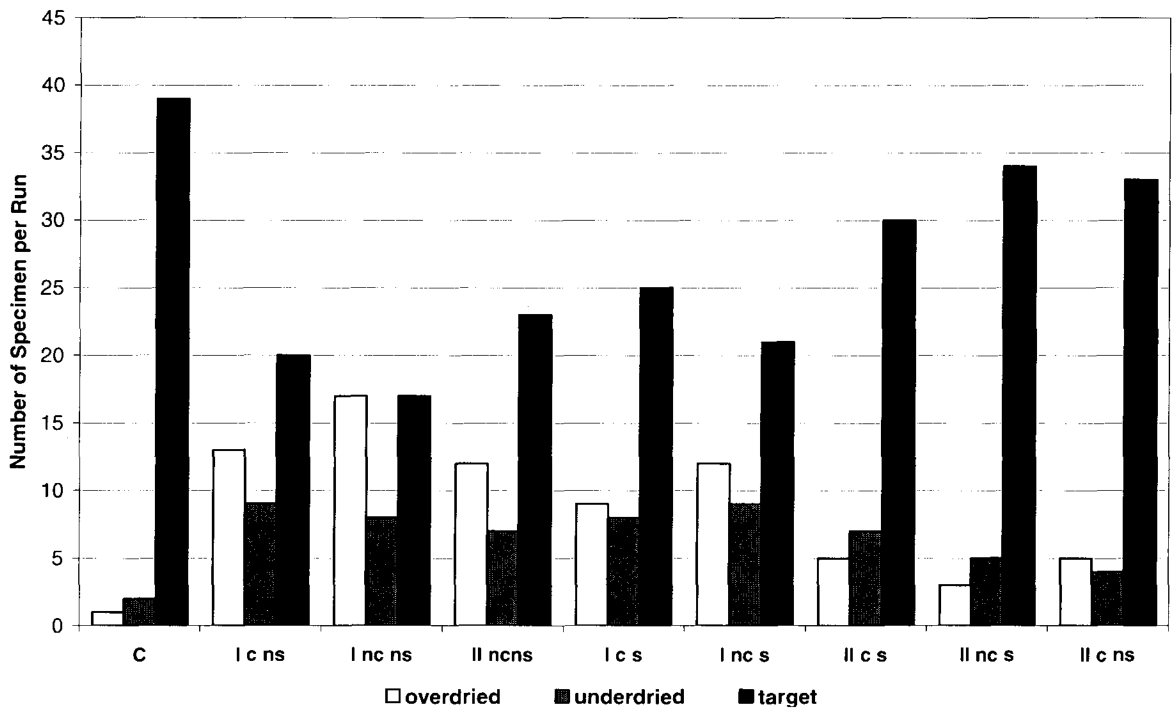

Figure 7.10: Absolute number of over and under-dried specimens per run (over-dried is the mean of the run minus 3 percentage points, under-dried is the mean of the run plus 3 percentage points and target is the mean plus/minus 3 percentage points)

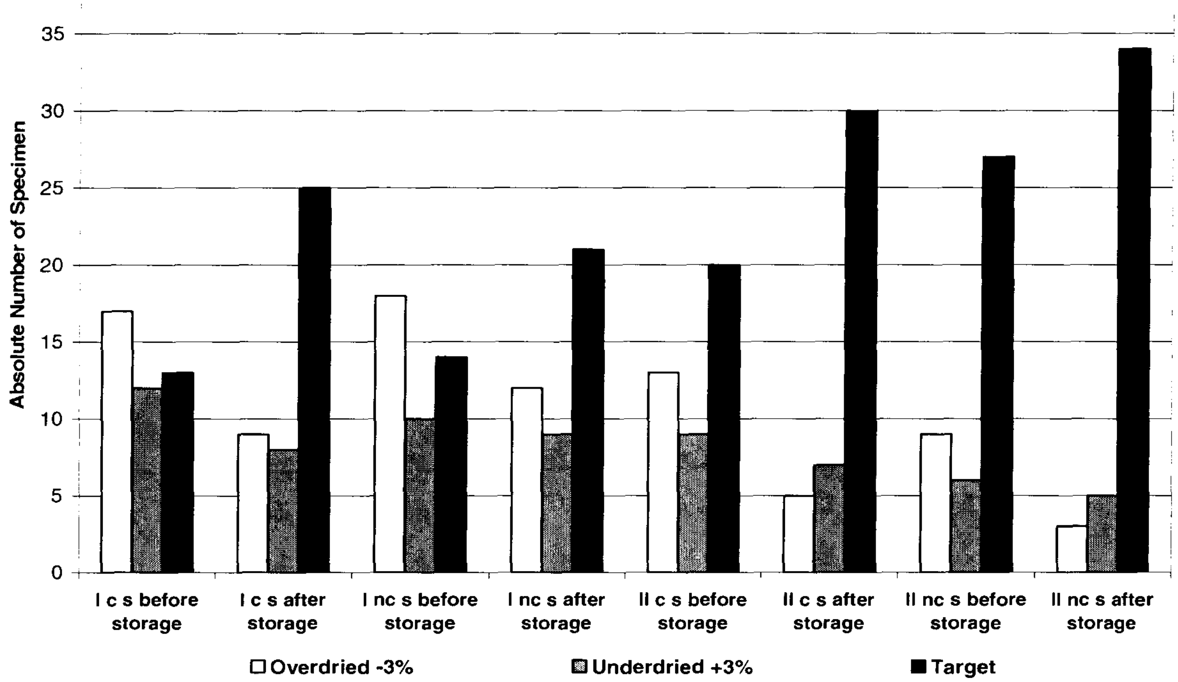

Figure 7.11: Absolute number of over and under-dried specimens per run, measured before and after storage, if over-dried is the mean of the run minus 3 percentage points, under-dried is the mean of the run plus 3 percentage points and target is the mean plus/minus 3 percentage points

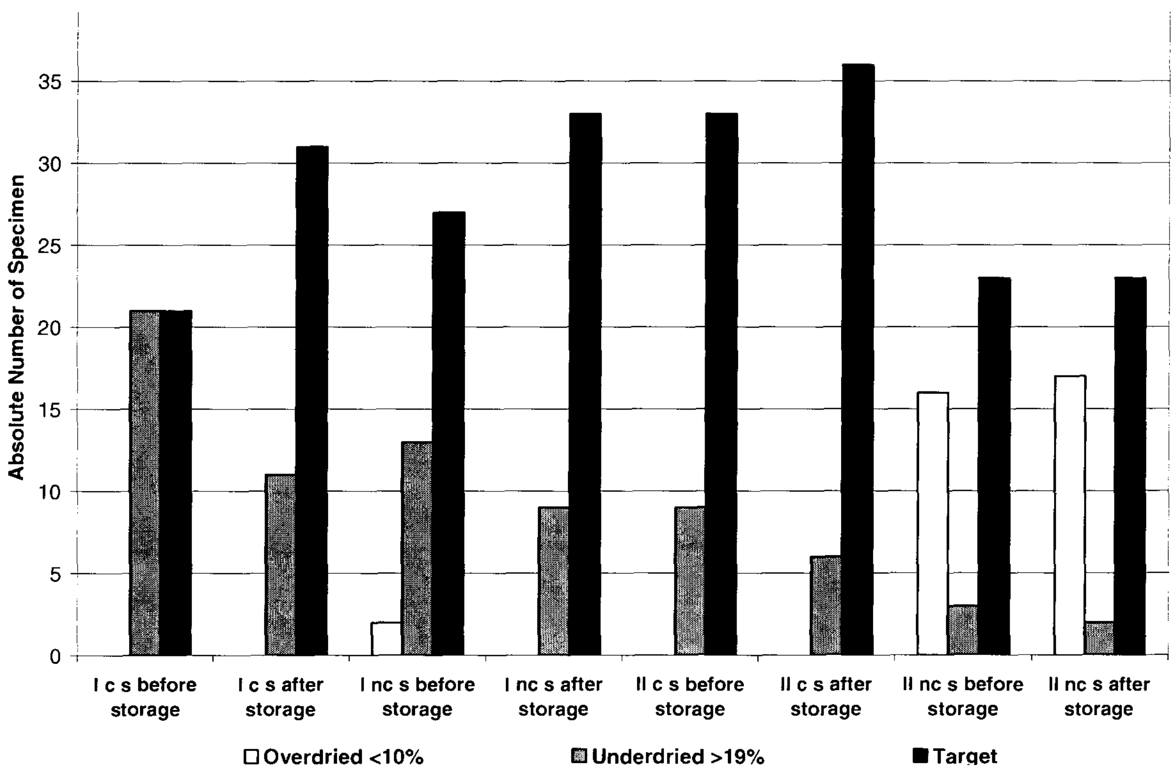

Figure 7.12: Absolute number of over and under-dried specimens per run, measured before and after storage, if over-dried is below 10%M, under-dried is above 19% M and target is between 10% and 19% M

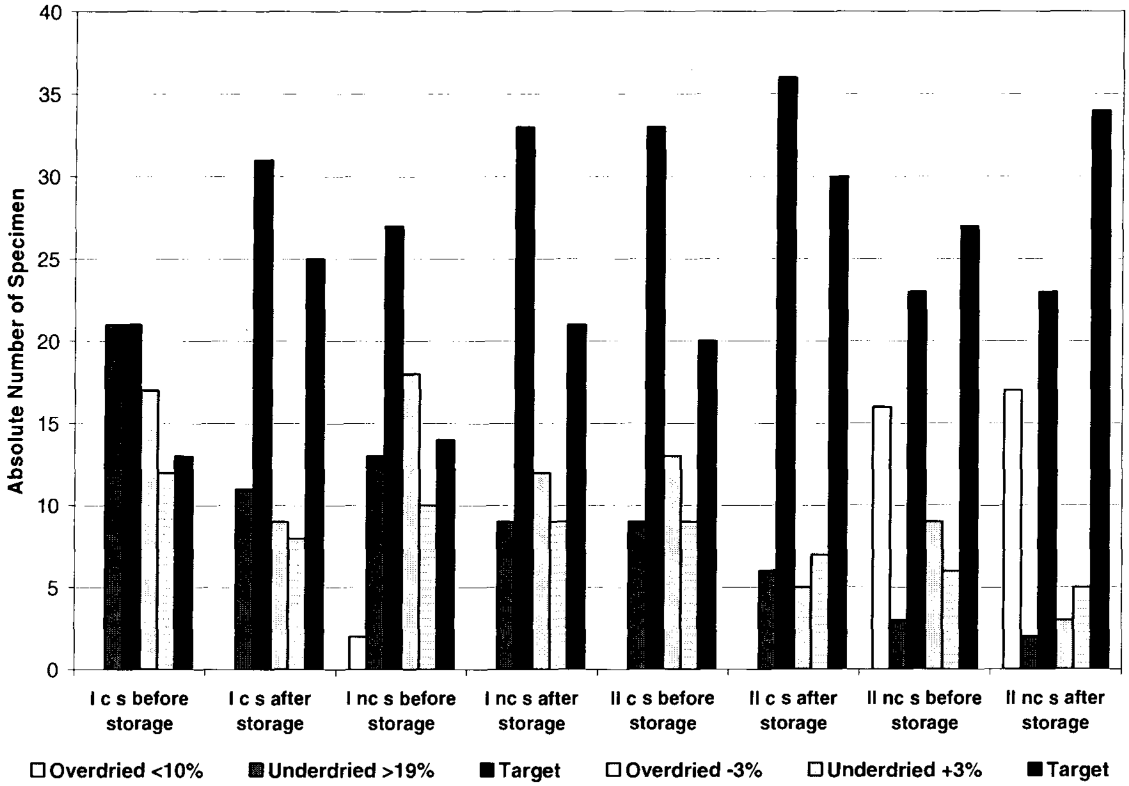

Figure 7.13: Absolute number of over and under-dried specimens per run, measured before and after storage, comparison of both methods of counting over and under-dried specimens. In the first method over-dried is the mean of the run minus 3 percentage points, under-dried is the mean of the run plus 3 percentage points and target is the mean plus/minus 3 percentage points. In the second method over-dried is below 10%M, under-dried is above 19% M and target is between 10% and 19% M.

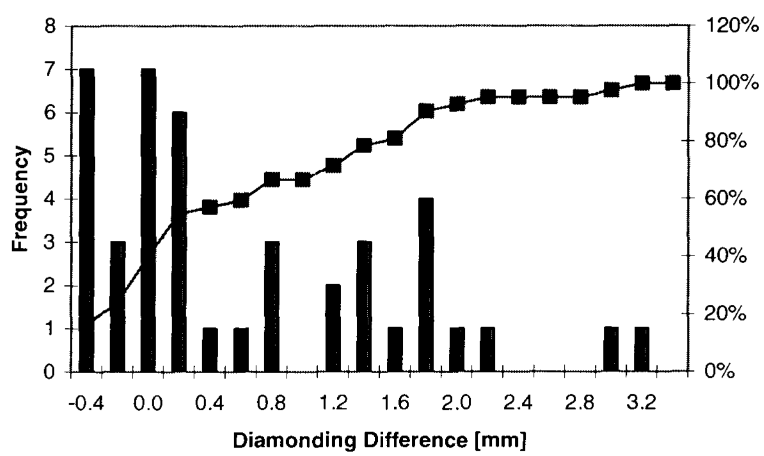

Figure 7.14: Difference (Kiln dry – Green) diamonding for "Control"

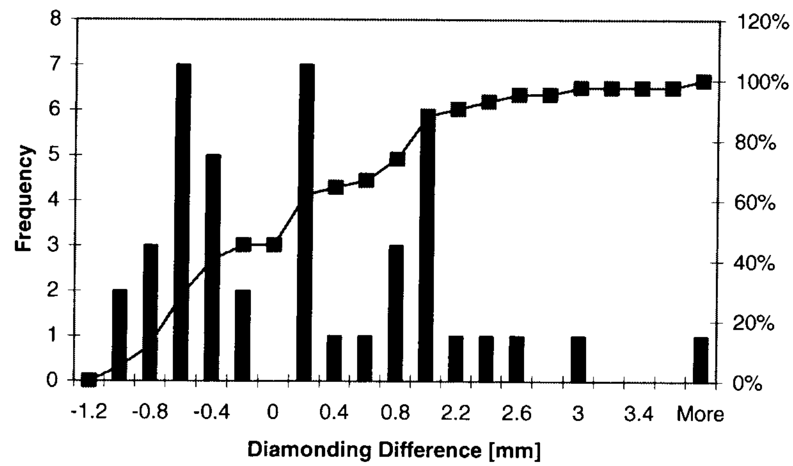

Figure 7.15: Difference (Kiln dry – Green) diamonding for "I c ns"

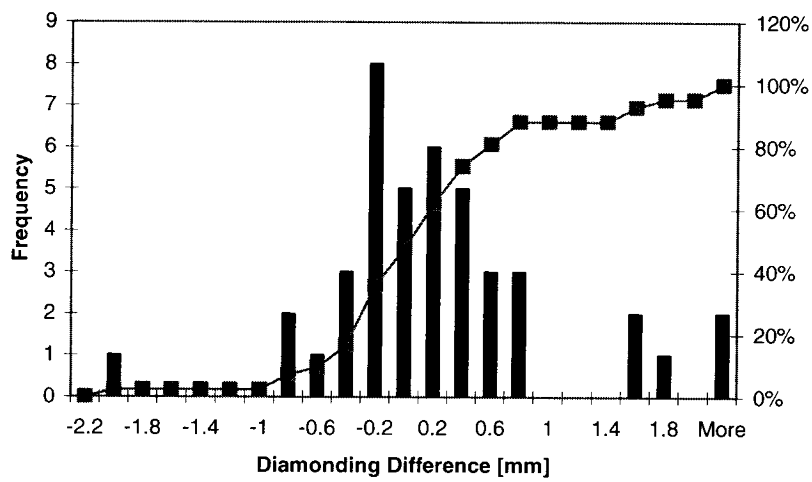

Figure 7.16: Difference in diamonding for "I nc ns"

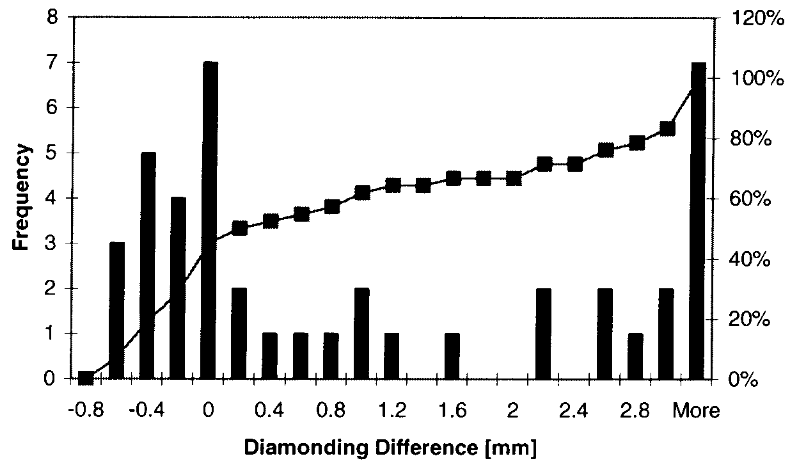

Figure 7.17: Difference in diamonding for “II nc ns”

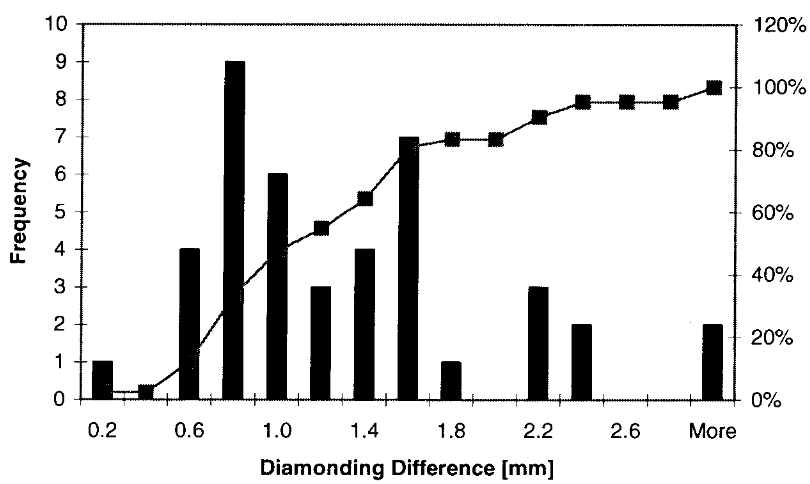

Figure 7.18: Difference of diamonding for “I c s”

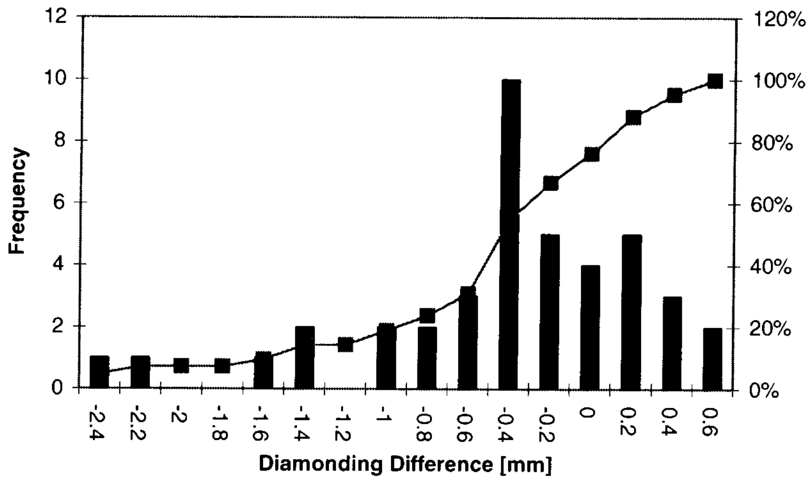

Figure 7.19: Difference of diamonding for "I nc s"

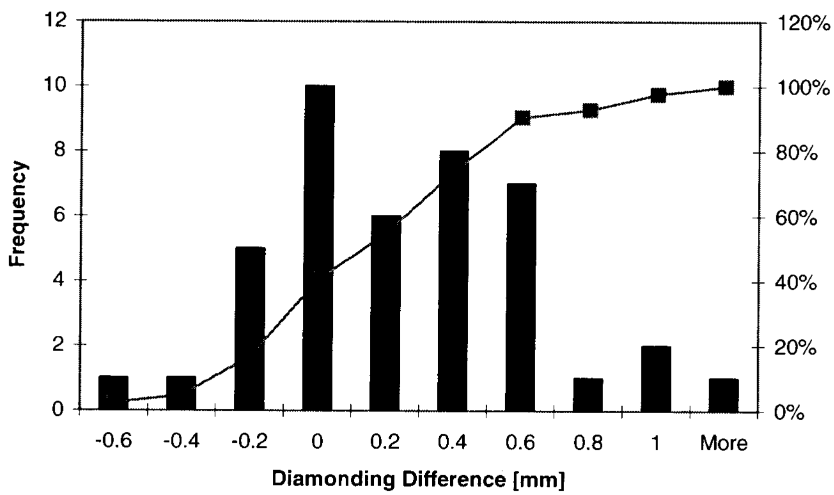

Figure 7.20: Difference of diamonding for "II c s"

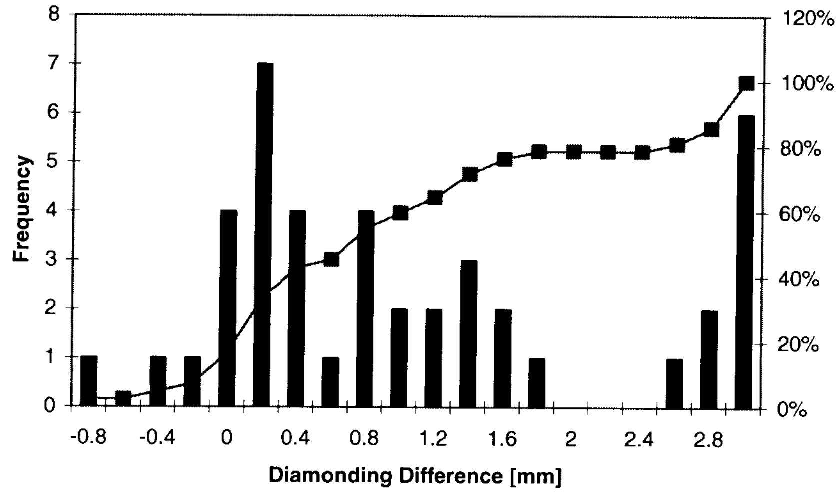

Figure 7.21: Difference of diamonding for “II nc s”

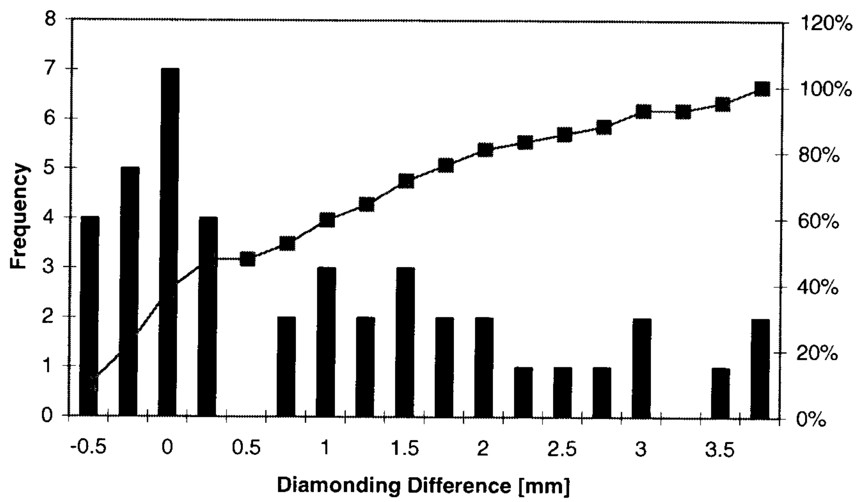

Figure 7.22: Difference of diamonding for “II c ns”

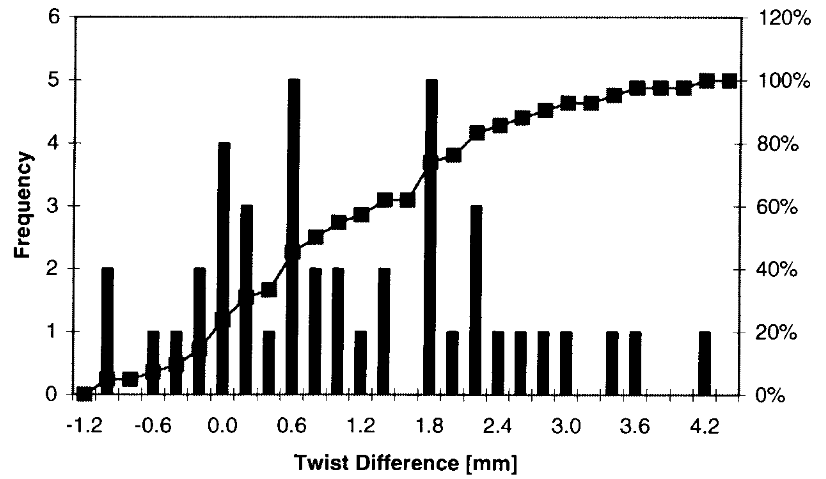

Figure 7.23: Difference (Kiln dry – Green) twist for “Control”

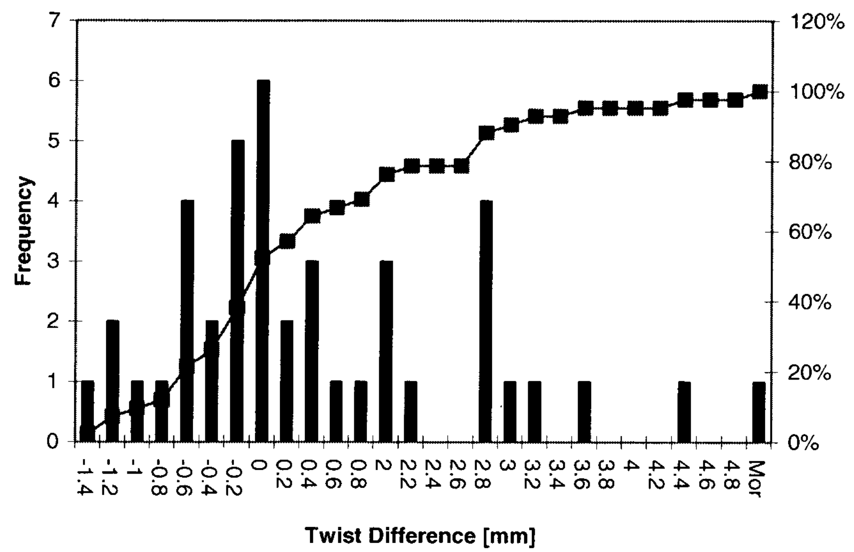

Figure 7.24: Difference (Kiln dry – Green) twist for “I c ns”

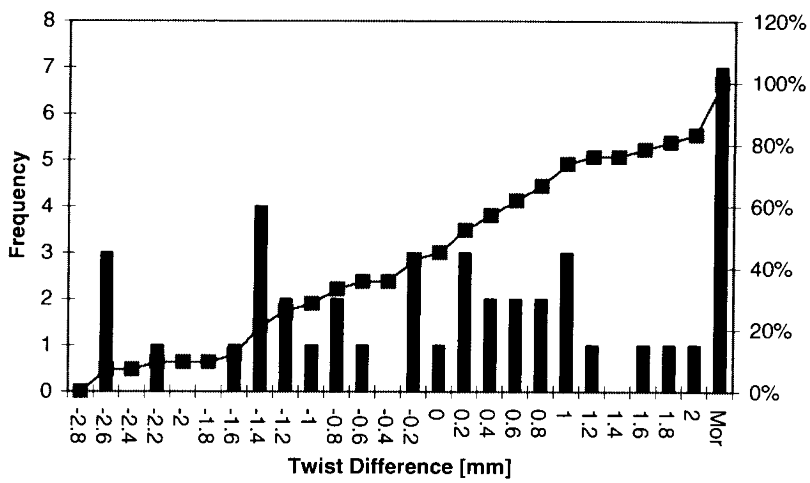

Figure 7.25: Difference in twist for “I nc ns”

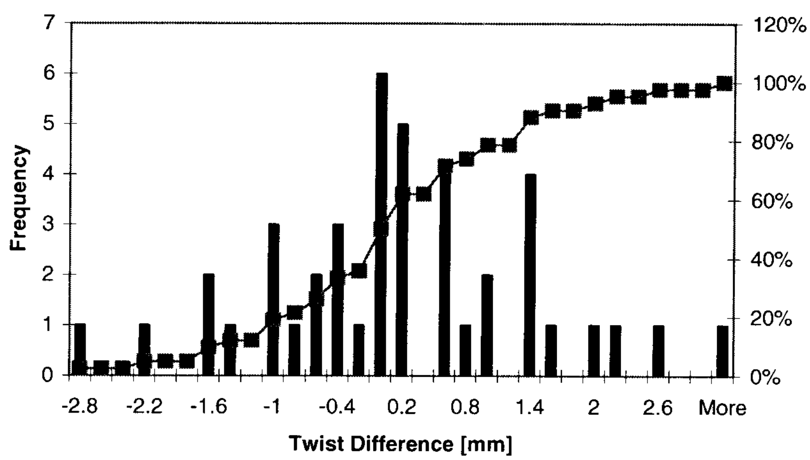

Figure 7.26: Difference in twist for “II nc ns”

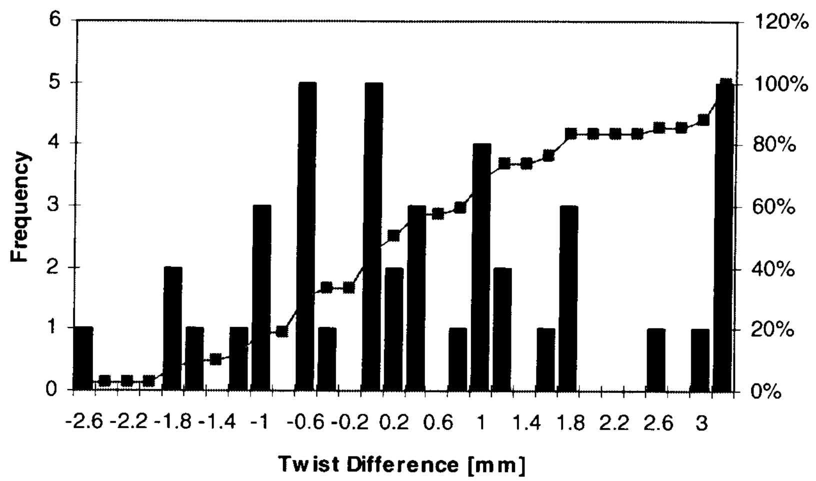

Figure 7.27: Difference of twist for "I c s"

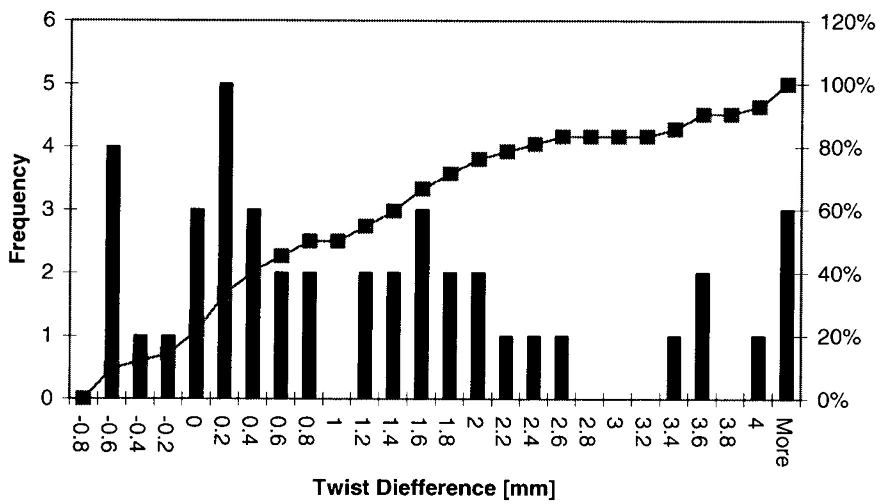

Figure 7.28: Difference of twist for "I nc s"

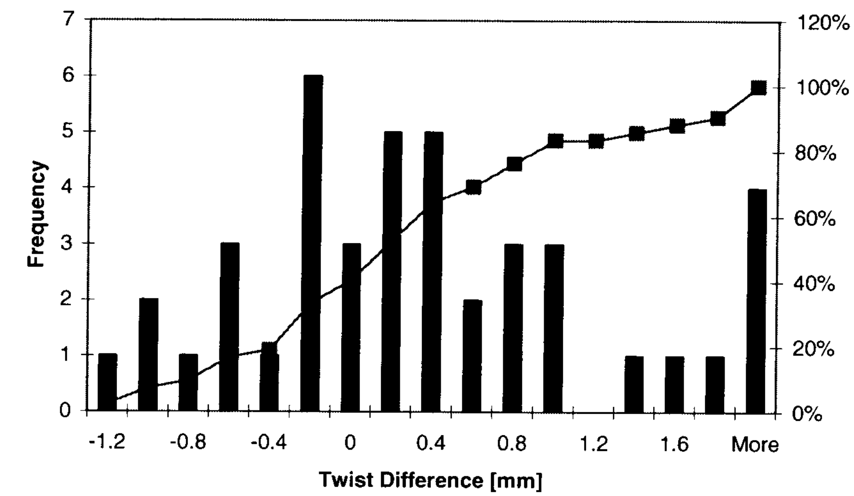

Figure 7.29: Difference of twist for "II c s"

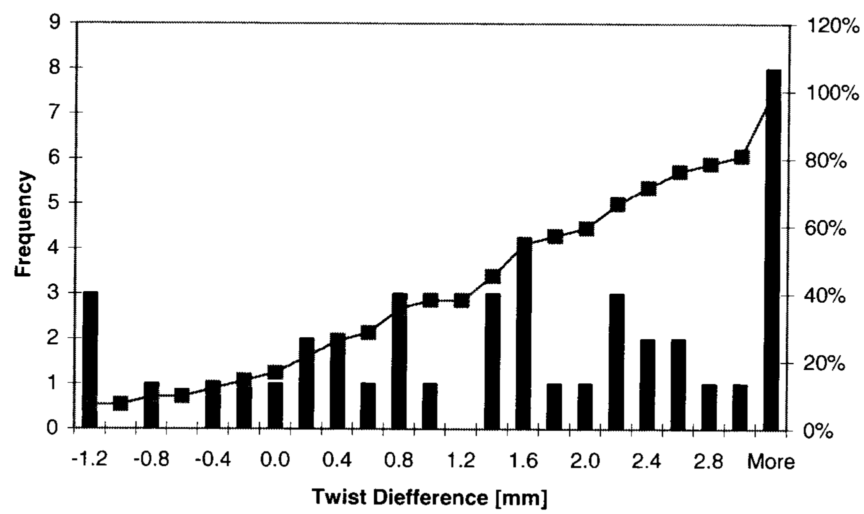

Figure 7.30: Difference of twist for "II nc s"

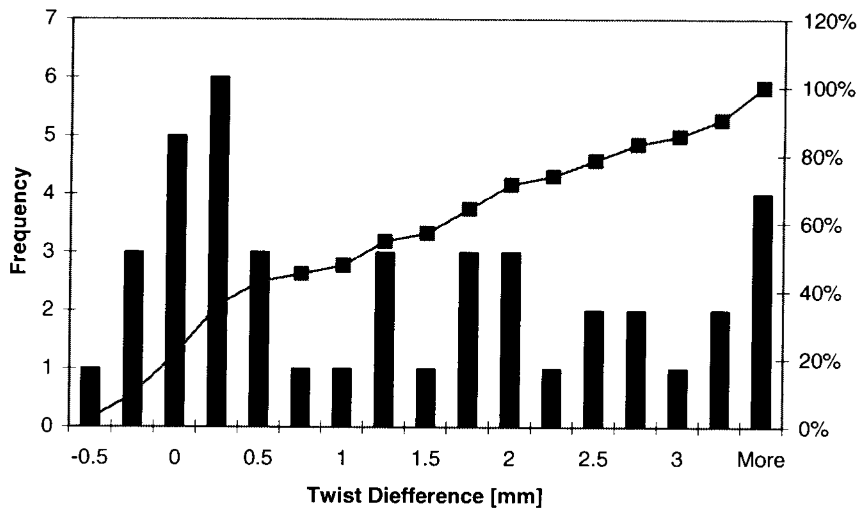

Figure 7.31: Difference of twist for "II c ns"

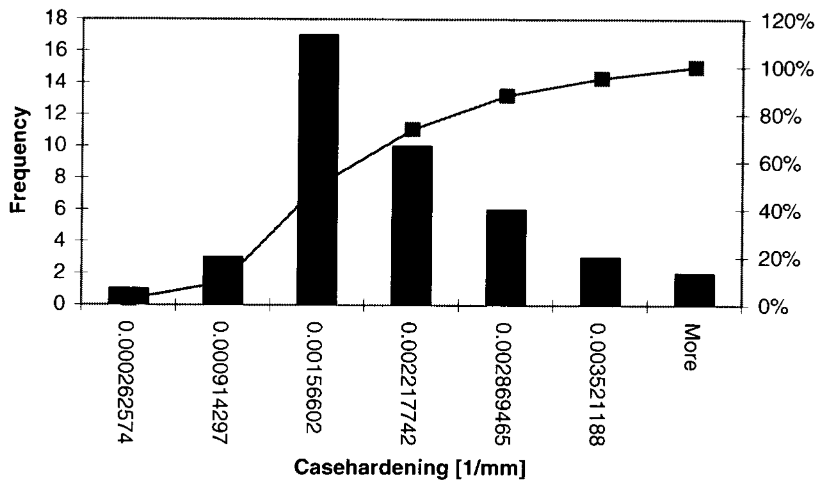

Figure 7.32: Casehardening for "Control"

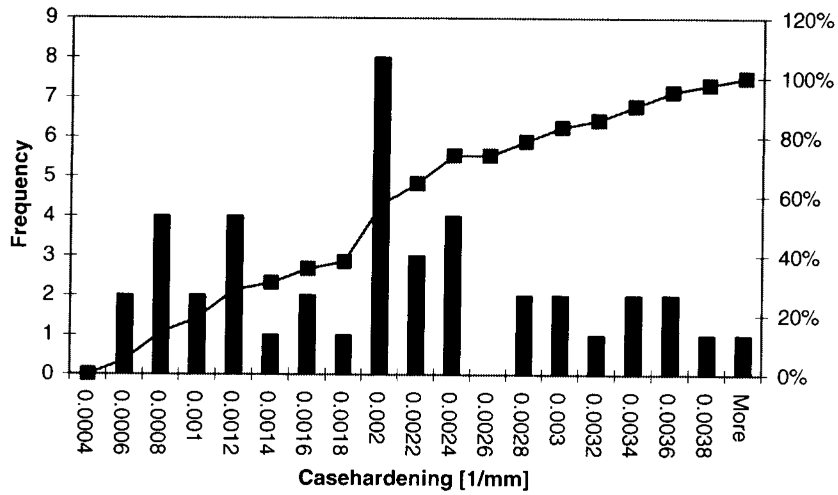

Figure 7.33: Casehardening for “I c ns”

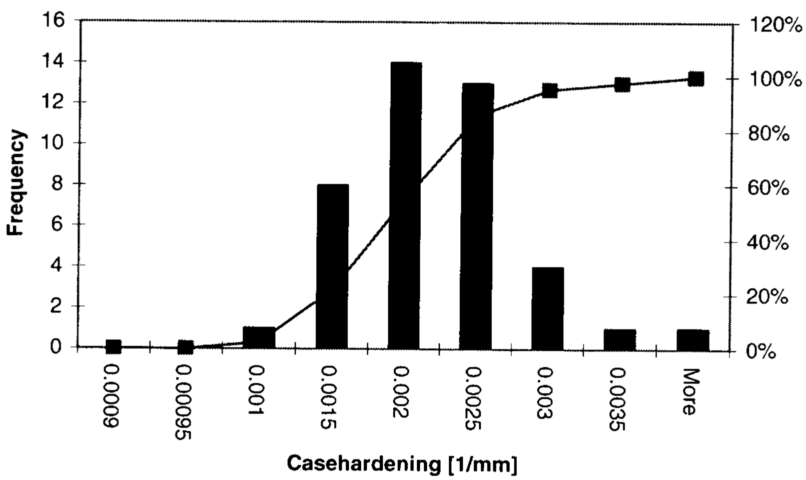

Figure 7.34: Casehardening for “I nc ns”

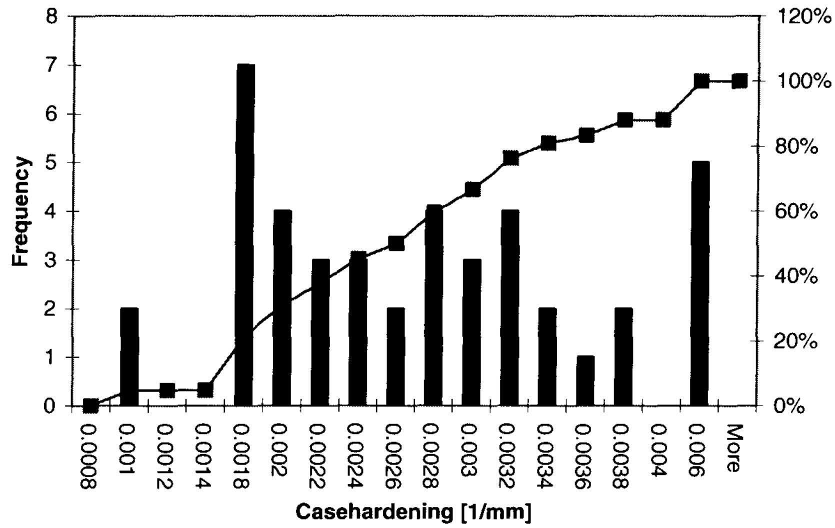

Figure 7.35: Casehardening for “II nc ns”

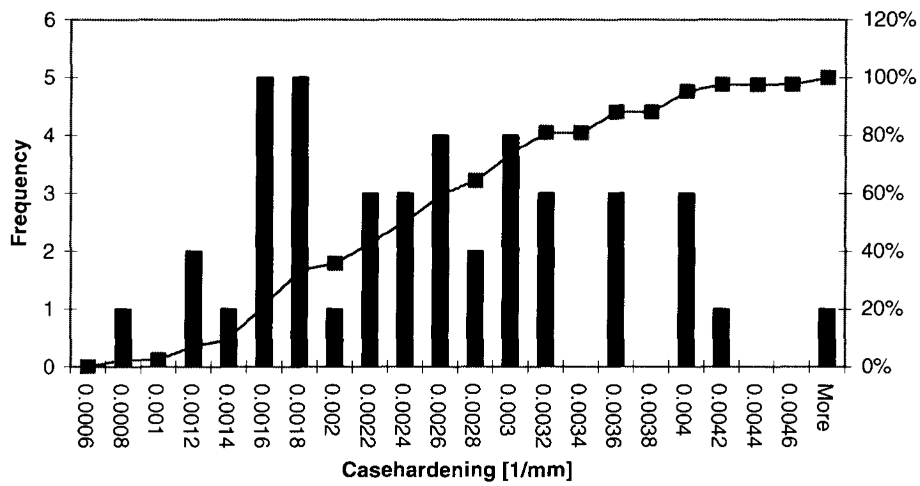

Figure 7.36: Casehardening for “I c s”

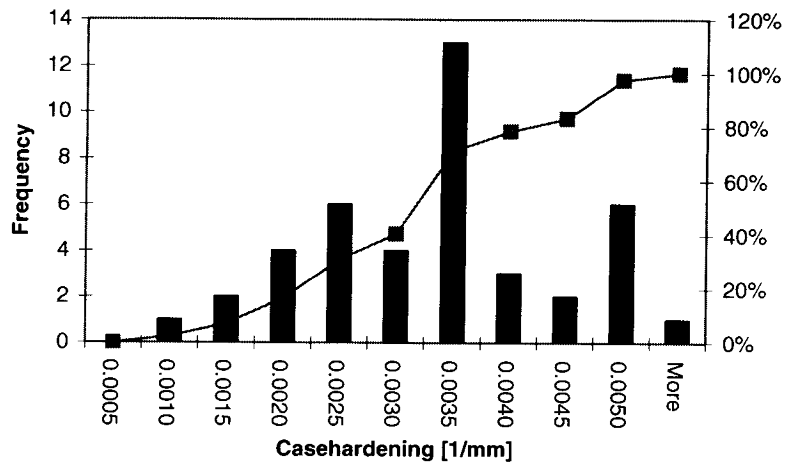

Figure 7.37: Casehardening for “I nc s”

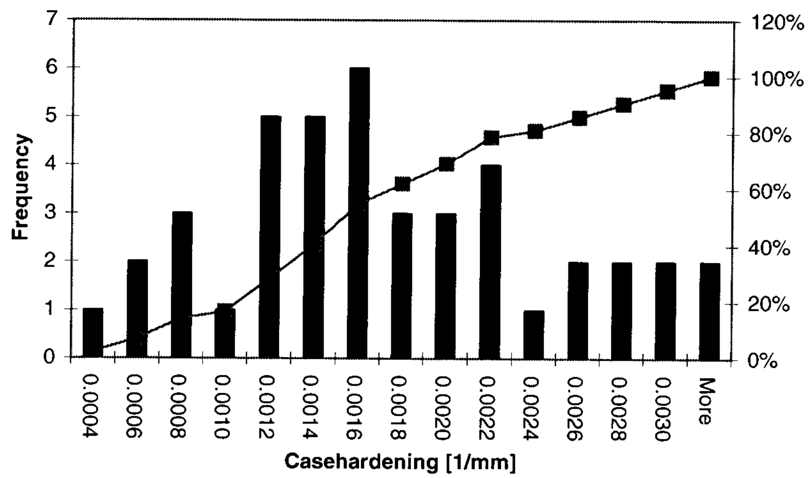

Figure 7.38: Casehardening for “II c s”

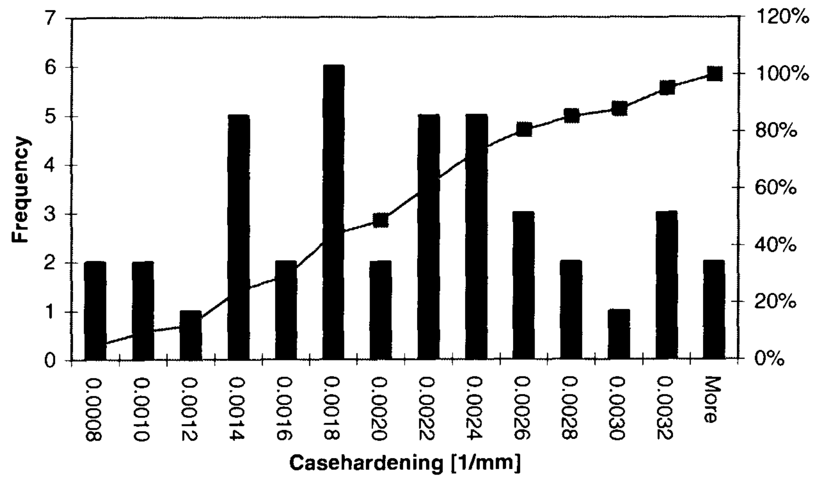

Figure 7.39: Casehardening for “II nc s”

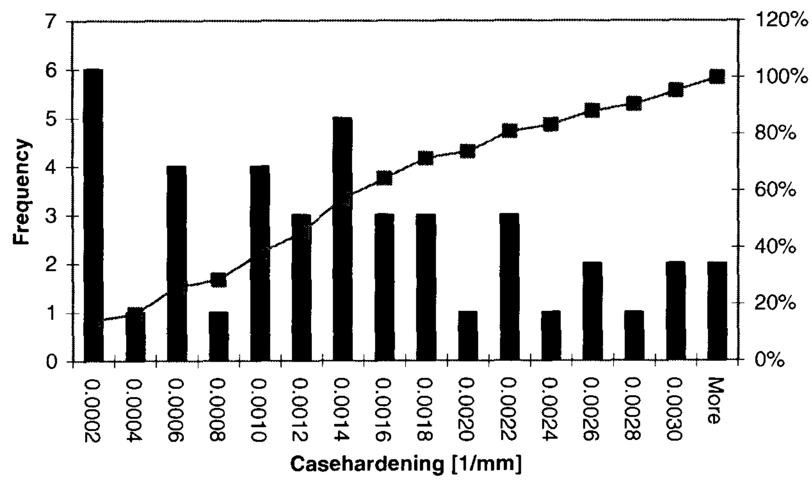

Figure 7.40: Casehardening for “II c ns”