A study of pre-treatments in the drying of regrowth *Eucalyptus obliqua* L'Herit

by

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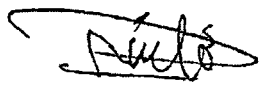

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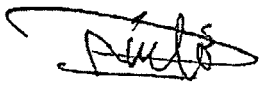

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Abstract

This study investigated the potential of pre-treatment techniques to produce high quality back-sawn boards from regrowth messmate stringybark (*Eucalyptus obliqua* L'Herit), which is very prone to collapse and checking. Saturated urea solution, one percent sodium hydroxide, four percent acetic acid, water, urea formaldehyde resin (UF), and polyvinyl acetate glue (PVA) were used.

In **Chapter 4**, the experiment of chemical soaking pre-treatments showed that soaking in sodium hydroxide solution for up to 15 days caused almost double increase of boards' drying rate. However, this technique and soaking in acetic acid solution caused more collapse and checks.

In **Chapter 5 and 6**, the surface coating experiment confirmed that coating with UF resin did not significantly improve the drying properties of the boards. In contrast, PVA coating prevented surface checking and considerably reduced edge checking and collapse. The check value of these P boards was only a quarter the check value of control boards.

In **Chapter 6,** the pre-treatments trial proved that significant reductions of shrinkage and collapse were achieved mainly by urea soaking for eight weeks (S8W boards). Both tangential and radial shrinkages of S8W boards were less than half the shrinkages of control boards. The collapse free boards of S8W were almost double amount of that in control boards. However, this pretreatment caused more surface checks.

One-day urea soaking followed by eight weeks close stacking (C treatment) reduced checking. The check free boards of C, W, and P were 38%, 25%, and 88%, while that of the control, S8W, and S2W boards were the same, 19%.

The average drying rates of W, S8W, and S2W boards were respectively 1.3 times, 0.4 times, and 0.6 times the drying rate of the control boards. The average drying rates of P and C boards were almost the same as that of control boards (1.7×10^{-2} %/hour, in a four month drying trial).

This study indicates the prominent benefit of PVA surface coating in improving the quality of dried back-sawn timber of regrowth messmate stringybark. Further research, combining PVA coating and different drying process, such as high temperature drying, is needed to produce high quality dried timber in a much shorter time. This study also recommends water soaking when collapse and check prone timbers cannot be kiln-dried immediately after sawing.

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Contents

Chapter 1

Introduction

Wood, as a forest product, has high economic value that can be used for very broad purposes, such as building construction, bridges, boats, furniture, crafts, sports facilities, education facilities, kitchen utensils, toys and paper.

National and international demands for timber products, particularly for furniture and housing or construction, are quite high. This has encouraged timber industries to develop more efficient processes and competitive products in the market. In addition, public perceptions on land use and resource management, and global economic changes have pushed timber industries to reduce waste, increase output, and maximise the value and usability of the raw material.

Wood is preferred for furniture and for building or engineering material because it is quite strong, aesthetically pleasing, economical, requires low processing energy and is renewable. However, wood has some weaknesses that challenge technologists to overcome them appropriately. Rowell (1983) stated some of the weaknesses of wood: dimensional instability with moisture changes, biodegradability, flammability, and degradability by UV light, acid and bases.

The polymers in wood cell walls have a lot of hydroxyl groups that bind water molecules with hydrogen bonds. When the wood dries, the water molecules are released and move to the timber's surfaces and evaporate to the air. As a consequence, the wood shrinks. Conversely, if a piece of dry wood is put in a place of high relative humidity, its cell walls will attract water molecules from the air, which causes the wood to swell.

Termites and other insects, beetles, fungi, bacteria and marine organisms attack wood as their food and / or as their dwelling place. Generally, cellulose and other polysaccharide compounds are their main food targets. The deterioration caused by these organisms may severely affect the mechanical properties and aesthetic

features of wood. Therefore, the attacked wood degrades technically and economically.

Because of the decrease in mature forests in Tasmania and Victoria, sawmill industries in both states face a technical and marketing challenge to fulfil the demand for high quality products from younger regrowth forests and plantations. Waugh and Rozsa (1991) noted that in Tasmania, regrowth forest is the forest that is less than 100 years of age. In Victoria, regrowth timber comes from regenerated forests after wild fires occurred during the years between the two world wars.

Timber from regrowth forests is usually cut from smaller diameter and younger trees, unlike timber from mature forests. As a consequence, natural defects, such as knots, growth stresses, brittle heart and end splitting, are more prominent in regrowth timber production. In addition, the regrowth timbers usually have a lower basic density, lower extractives content and higher green moisture content than mature timbers (Waugh and Rozsa, 1991). With these properties, they tend to be faster drying, but suffer more collapse and surface and internal checks, compared to mature timbers.

The application of a conventional kiln drying method on regrowth eucalypts timbers results in unacceptably severe surface and internal checking. Therefore, the drying of regrowth ash-type eucalypt timber is usually by air-drying, followed by a combination of steam reconditioning and final kiln drying (Waugh and Rozsa, 1991).

Saw-millers generally use two sawing strategies: back-sawing that produces boards with the face parallel to the growth rings and quarter sawing that produces boards with the face tangential to the growth rings (**Figure 1.1**).

According to Waugh and Rozsa (1991), back-sawn timbers from regrowth eucalypts usually have more kino veins, checking, warp, cupping and shrinkage than quarter-sawn timbers. Therefore, most saw-millers prefer to produce quarter-sawn timbers than back sawn timbers from regrowth eucalypts.

Although back-sawing strategies produce worse drying defects, the saw log yields and mill-door values are higher than those from traditional quarter-sawing strategies. Back sawn timbers (**Figure 1.2**) also have more attractive surface features and dry slightly faster than quarter-sawn timbers. High quality back-sawn timbers have a high price and demand, particularly for furniture (Schaffner, 1981). With back-sawing strategies, the mill-door log values could be improved by as much as $ 30 /m^3 (Waugh and Rozsa, 1991).

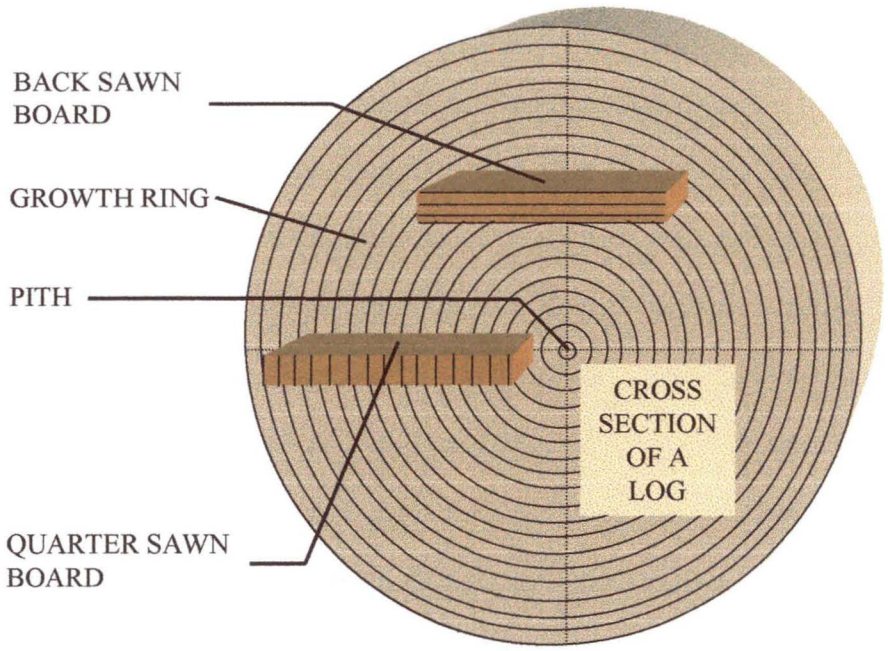


Figure 1.1 *Back sawn board and quarter sawn board taken from a log.*

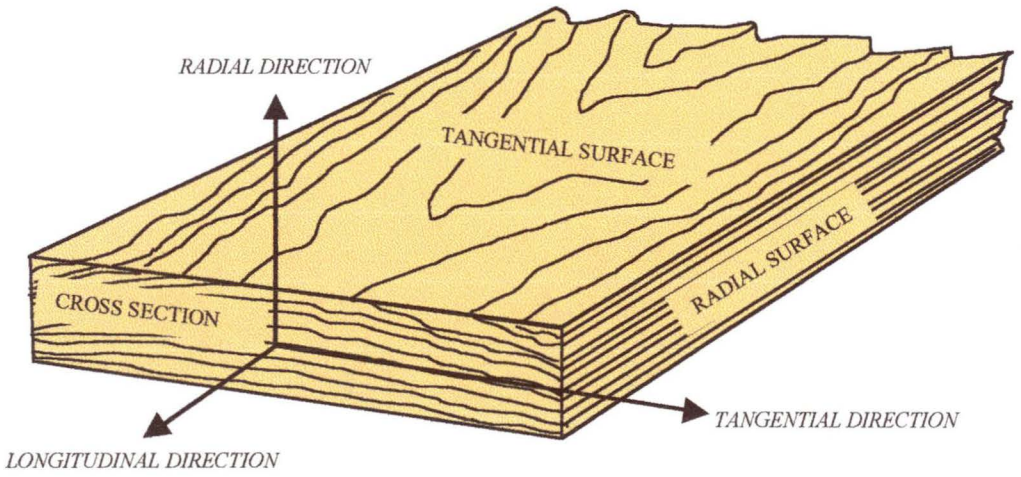


Figure 1.2 *A back sawn board and the three principal directions and surfaces with respect to fibre orientation and annual rings.*

Proper and complete drying can improve wood properties, such as dimensional stability and strength and reduce biodegradability by micro organisms (Rowell, 1983). The drying also results in high value added products, for example, according to Langrish et al. (1997), kiln dried timber for furniture was valued at up

to $ 2000.00 /ton, while low value products, such as wood chips were only worth $ 80.00 /ton.

A common drying technique for 25 mm quarter sawn timber of both mature and regrowth eucalypts in Tasmania is six month air drying to 20% moisture content, followed by 4 to 6 hours reconditioning and 4 to 5 days kiln drying. So, the total drying time is 26 weeks. If using a pre-dryer with low temperature kiln, the total kiln time can be reduced to 16 weeks.

The drying time of 25 mm, 38 mm and 50 mm boards for decorative purpose from green to marketable material takes 5 to 12 months, 12 to 15 month and 18 to 24 month respectively (Schaffner, 1981).

The current drying process still produces a quite high proportion of timber degradation. Langrish et al. (1997) reported that up to 50% of the processed timber could not be used for high value-added products because of drying defects. Such timber can only be used for wood chips or firewood.

There is a considerable economic incentive for improved timber drying in terms of product quality, reduced total drying time and lower wastage levels. Chadwick and Langrish (1996) said that the quality of dry wood includes the appearance, strength, durability, machining and finishing properties of wood.

The main requirement of wood for high value end use, such as furniture manufacture, is to be free of drying defects. Drying stresses are inherent phenomena in wood drying and become major problems in the drying industry (Kowalski and Rybicki, 1996). This forces the technologist to find an appropriate method to minimise the negative effects of the drying stresses.

The current study was done to investigate whether checks and collapse could be prevented or reduced by pre-treatment processes. The term 'pre-treatment' refers to any chemical, physical or mechanical treatment applied to timbers before the commencement of air-drying or kiln drying.

In this study, chemical soaking and surface coating were used as pre-treatments for the back-sawn timbers of regrowth *Eucalyptus obliqua* L'Herit. Sodium hydroxide,

acetic acid and urea solutions were used in the experiment of chemical soaking pre-treatments. Urea formaldehyde (UF) and polyvinyl acetate (PVA) were used in the surface coating trials. Water soaking was also done for comparison with other pre-treatments.

The effects of pre-treatments on physical properties were assessed. Then the effectiveness of pre-treatments in improving dry wood quality was compared. The objective of this study was to determine the most suitable pre-treatment to produce high quality dry back-sawn timber from regrowth *Eucalyptus obliqua* L'Herit.

Chapter 2

Basic properties of wood

2.1 Wood anatomy

2.1.1 Hardwood and softwood

The terms of 'hardwood' and 'softwood' originally came from the timber trade to indicate the hardness of timber. But, anatomically that classification bases on the presence or absence of vessels. Hardwoods have vessels, while softwood do not have vessel. Generally, hardwoods are from the broad-leaved trees that produce true flowers, whereas softwoods are from conifers that produce cones. According to the flora classification, the hardwoods and softwoods are members of *Angiospermae* and *Gymnospermae* respectively.

Compared to softwood, hardwood has a more complex microstructure with more cell types arranged in a greater variety of patterns (Butterfield, 1993).

2.1.2 The macroscopic features of hardwood

2.1.2.1 Heartwood and sapwood

Most wood species have darker and harder wood at the centre of the stem, named heartwood, while the outer part of the stem is called sapwood (see **Figure 2.1.2.1.1**). Wood cells in heartwood are dead and physiologically inactive. Generally, heartwood is formed after several years of stem growth, spreading outwards and upwards in the stem.

The formation of extractives in the walls and lumen of heartwood cells makes its character different from that of sapwood. Heartwood is more aromatic and more resistant to bio-deterioration (Butterfield, 1993).

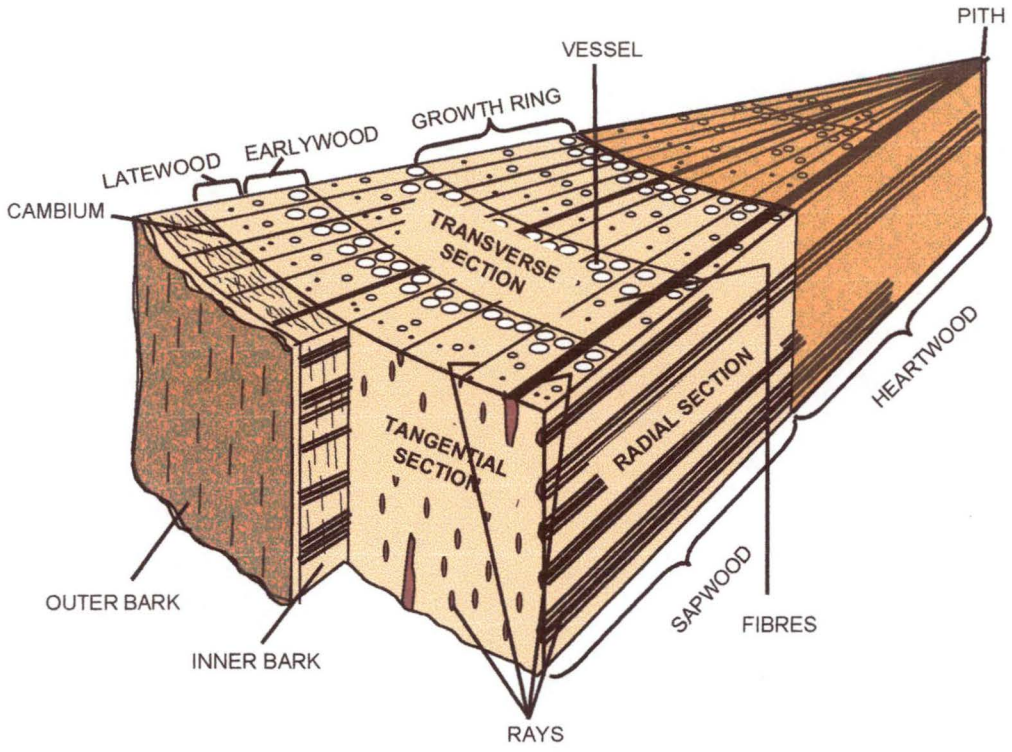


Figure 2.1.2.1.1 *The macroscopic feature of wood (Wilcox et al., 1991).*

2.1.2.2 Growth rings

The environment influences tree growth. In temperate regions, the seasons have a pronounced effect on the development of wood cells. In the growing season (spring and summer), the vascular cambium usually makes more conductive cells and wood cells with less density than in other seasons and is called early wood. The wood cells produced in autumn and winter are termed late wood. This makes a common feature on the cross section of a tree stem, namely a cylindrical ring pattern called growth rings or annual rings.

In temperate regions, one growth ring is usually produced in one year, but in tropical regions, more growth rings may be produced in one year. However, in some species the growth rings are not as distinct as in others (Butterfield, 1993).

2.1.3 The microstructure of hardwood

Based on the function, wood cells can be classified into three different groups: supporting cells, conducting cells and storage cells. Supporting cells and conducting cells are dead cells that contain cavities filled with water or air. Fibres and vessels represent supporting cells and conducting cells in hardwood respectively. The storage cells are parenchyma cells that have thin walls. They transport and store nutrients as long as they are in sapwood (Sjöström, 1993).

2.1.3.1 Fibre cells

Most hardwood has a high proportion of fibres. The greater proportion of fibres, the denser the wood. Fibres are imperforate, axially elongated cells with small lumens. The cells also taper into pointed tips. The length of fibres is between 0.25 mm and 1.5 mm (generally less than 1 mm), which are relatively shorter than tracheids that are the structural elements in softwood (Butterfield, 1993).

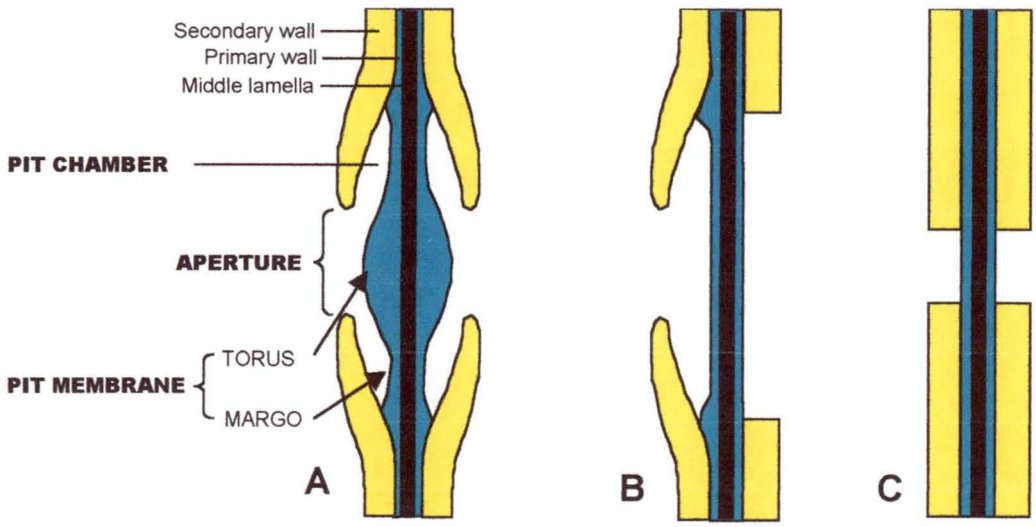


Figure 2.1.3.1.1 *Three types of pit pairs: A = bordered pit; B = half-bordered pit; C = simple pit (Sjöström, 1993).*

In wood cell walls there are pits, which are classified into three. Fibres and vessels have typical bordered pit pairs. Between fibres or vessels and ray parenchyma, there are half-bordered pits. Simple pits (without any border) connect parenchyma cells with one another (see **Figure 2.1.3.1.1**) (Sjöström, 1993).

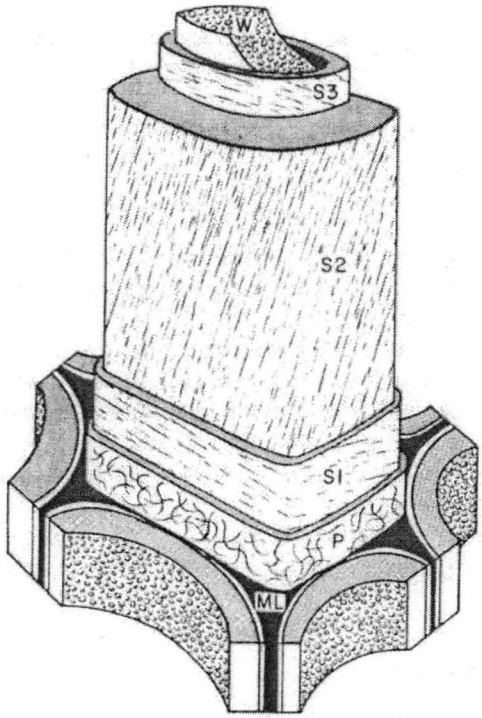


Figure 2.1.3.1.2 *Simplified structure of a fibre: ML = middle lamella; P = primary wall; S1, S2 and S3 = the outer, middle and inner of the secondary wall; W = warty layer (Cote, 1967 in Sjöström, 1993).*

A mature fibre cell is composed of two structures. The primary wall is the first formed structure that is developed during the cell growth and differentiates it from the cambium. This cell encloses the protoplasm growth. The other structure is the secondary wall that grows after the formation of the wall surface (see **Figure 2.1.3.1.2**).

The microfibril orientation in the primary wall is different between the inner and the outer part. On the inner surface, microfibrils are transverse, while on the outer surface, they seem to be interwoven.

The secondary wall is much thicker than the primary wall. There are three layers in the secondary wall: S1, S2 and S3 layers respectively from the outside to the inside of the cell. Every layer is composed of some lamellae, which consist of a number of microfibrils. The microfibril orientation of successive lamellae is different in the first (S1) and third (S3) layers, whereas in the second (S2) layer, all lamellae generally have similar microfibril orientation (Sarkanen and Ludwig, 1971).

Walker (1993a) said that in the S2 layer, microfibrils are orientated nearly parallel to the fibre axis. This is the most influencing factor in the anisotropic character of wood. For example, the mechanical properties in the fibre direction are stronger than in the transverse direction. To a less significant degree, the anisotropic properties of wood are influenced by the geometry of fibre cells (long, thin and hollow) as well.

2.1.3.2 Vessel cells

According to Butterfield (1993), vessels as conductive elements in hardwood consist of many vessel elements joined end to end. Between vessel elements, there are pores aggregated into a perforation plate. Most openings in the perforation are formed due to hydrolyses of non-cellulosic components and the loss of the remaining cellulosic web at the beginning of transpiration.

In deciduous trees, the vessels are usually arranged predominantly in the early wood and termed as ring porous. But, in evergreen species, they are mostly distributed throughout the growth ring and are called diffuse porous. Within both arrangements, the vessels may have a solitary pattern or multiple patterns.

Some hardwood species often contain tyloses in their vessels. These tyloses are formed in the neighboring paratracheal axial parenchyma cells and break through the pits expanding into the vessels. The presence of tyloses may obstruct the passage of preservative into the vessels.

2.1.3.3 Ray cells

Other distinct cells in wood are ray cells. These cells lay on radial direction in wood, from the pith to the end of sapwood tissue. According to Butterfield (1993), hardwoods usually have larger and more types of rays than softwood. The ray cells in hardwood are about 15% or up to 50% of wood volume in some species. Most hardwoods have multiseriate rays, while softwoods have uniseriate and sometimes biseriate rays.

2.1.3.4 Other microstructures

Parenchyma cells are storage units in wood. Parenchyma cells oriented in the longitudinal direction are called axial parenchyma. They have thin walls. So a high proportion of parenchyma may reduce the weight and hardness of wood. In addition, axial parenchyma may contain starch grains, crystals, and other extractives. In hardwoods, longitudinal parenchyma is unique and can be used for wood identification (Haygreen and Bowyer, 1989).

Illic (1987) also noted that some wood species have vertical canals that are usually filled with gum. In eucalyptus, they are called kino veins. The canals do not have a cell wall, except an epithelium of parenchyma cells. The feature of vertical canals can be used for wood identification as well.

2.1.4 Reaction wood

Reaction wood has an eccentric growth in stems. In hardwood, reaction wood is also called tension wood and forms on the upper side of the leaning stems and branches. Tension wood is harder and denser than normal wood. Sometimes the colour is darker with a woolly appearance on sawn timber. In tension wood, the vessels are fewer and smaller, and the fibres have an extra wall layer inside, a gelatinous layer, which is rich in cellulose. Tension wood has a higher longitudinal shrinkage than normal wood due to the higher microfibril angle of the outer walls of the cells (Butterfield, 1993).

Walker (1993b) said that the presence of reaction wood could be identified by the elliptical form of logs because of its increased growth. Tension wood has a silvery sheen (in temperate hardwood) or darker streaks (in tropical hardwood). Tension wood has more lignified fibres than normal wood. There is a gelatinous (G) layer in each cell that replaces the S3 layer or both S2 and S3 layers. The G layer is unlignified and is usually separated from other cell layers. The vessel in tension wood is smaller than in normal wood. Beside high longitudinal shrinkage, the main problem of tension wood is collapse and warp.

2.2 Wood chemistry

The components of wood fibre are mainly classified into three groups: the framework components that consist of cellulose; the matrix components that include hemicellulose, other polysaccharides and their derivatives; and the encrusting components called lignin (Sarkanen and Ludwig, 1971).

Cellulose provides good tensile strength to the wood, while lignin gives high compressive strength and prevents buckling in microfibrils. Cellulose and lignin are linked with hemicellulose, which allows the effective transverse of shear stresses.

Compared to softwood, hardwood generally has a lower proportion of lignin, but a higher proportion of cellulose, hemicellulose and extractives (Walker, 1993a).

2.2.1 Cellulose

Cellulose is a polymer derived from glucose: β-D-glucopyranose. Glucose is a monosacaride that has the hexose sugar chemical composition, $C_6H_{12}O_6$. There are five hydroxyl groups (-OH) in glucose, which is very soluble in water. Within the polymer molecule and between adjacent polymer molecules, there is hydrogen bonding. The hydrogen bonding is not available between cellulose chains that are packed on top of one another. There are only attractive forces holding these layers together (named Van der Waals forces). Both hydrogen bonds and van der Waals forces are not strong compared to the covalent bond occurring within glucose molecules. The comparison of strength between covalent bond, hydrogen bond and

Van der Waals forces are 200 to 800 kJ mol^{-1}, 10 to 40 kJ mol^{-1} and 1 to 10 kJ mol^{-1} respectively (Walker, 1993a).

Most of the cellulose framework is crystalline. The aggregation of cellulose forms an elementary fibril that is the basic structure of a microfibril. Every microfibril also has some paracrystalline phases surrounding the elementary fibrils (Sarkanen and Ludwig, 1971). In addition, Walker (1993a) reported that the cross section of a microfibril is 10 nm, while an elementary fibril is 3.5 nm x 3.5 nm, which contains 40 cellulose chains.

2.2.2 Hemicellulose

Hemicellulose is a polysaccharide comprising pentose sugars (L-arabinose and D-xylose) and hexose sugars (D-glucose, D-mannose and D-galactose). So, hemicellulose is mixed polymer, while cellulose is pure polymer. Hemicellulose has a low molecular weight with short side-chains, whereas cellulose is a very high degree polymer without branching. Therefore, the solubility and susceptibility of hemicellulose to hydrolysis is greater than cellulose (Walker, 1993a).

2.2.3 Lignin

Lignin can be defined as the encrusting material of the plant that is developed mainly of phenyl-propane building stones and constitutes most of the methoxyl content of the wood (Brauns, 1952). Lignin is also an aromatic substance produced by dehydrogenation of three p-hydroxynamyl alcohols. Lignin has a different structure from carbohydrates, but has some similar functions with silisilic acid, tannins, other phenols and polymeric condensation products in terms of heart wood formation (Freudenberg and Neish, 1968).

Lignin has no sharp melting point. When it is heated in aqueous suspension, it softens at temperatures from 80°C to 90°C; when heated in a dry condition, it softens at around 120°C and slowly melts at about 140°C to 150°C (Brauns, 1952). In addition, Walker (1993a) stated that the structure of lignin is totally amorphous (non-crystalline). Hardwood lignin has a lower molecular weight than that in softwood, and consists of guaiacylpropane and syringylpropane. The corners of

middle lamella and S2 layers of vessels are rich in guaiacyl (more than 80%), while the S2 layers of fibres are rich in syringyl (88%).

According to Sarkanen and Ludwig (1971), in the middle lamella the lignification level is greatest at the cell corners and greater in the radial than in the tangential walls. Based on UV spectroscopy of mature wood cells (Walker, 1993a), the middle lamella and primary layers have the highest proportion of lignin followed by hemicellulose and cellulose. In the S1 layers, the lignin content is still higher than hemicellulose and cellulose, but the proportion of hemicellulose and cellulose increases. In the S2 and S3 layers, the cellulose proportion is very much higher than the others. However the proportion of cellulose in S3 is lower than in S2. Even though the concentration of lignin decreases through to the S2 layer, about three-quarters of the total lignin is in the secondary wall, while in the middle lamella and cell corners it is only a quarter. This is because of the thicker layer of S2 in the cell wall.

The formation of lignin starts from the corners then spreads to the whole middle lamella. The lignification of a cell wall begins during S1 formation and continues until just before S3 formation (Walker, 1993a). Brauns (1952) stated that lignification causes the cell function to change. The cells die and serve as reinforcement to the wood and as a water piping system. The lignification results in cementing and anchoring the cellulose fibres together, and stiffening and protecting them from chemical and physical attacks. Sarkanen and Ludwig (1971) also said that the optical, staining and mechanical properties of cell walls are changed by lignification. In addition, it can increase the stability and compressive strength of the cell wall.

Brauns (1952) said that two or three hours boiling in water or extraction by alcohol could reduce the lignin content of wood. Lignin is also soluble in hot alkali (such as sodium hydroxide) and bisulfite, and easily condensable with phenols and thio compounds. But, lignin is insoluble in some organic solvents, such as ether and benzene and alcohol-benzene. Lignin is also resistant to hydrolyzation by strong mineral acids, while polysaccharides can be hydrolyzed by these acids to become water-soluble compounds. On the other hand, lignin is easily attacked by oxidizing agents and decomposed to water-soluble products, whereas cellulose is resistant.

2.2.4 *Extractives*

Technically, the term "extractives" refers to the numerous compounds, which can be extracted from wood with polar and non-polar solvents. An example of an extractive that can dissolve in water is carbohydrate, while those in dichloromethane are resin acids, fatty acid triglycerides, other esters and neutral compounds (sterols) (Uprichard, 1993). Dilute alkaline (such as sodium hydroxide) can extract gums and resins. Some organic solvents, such as ether and benzene and alcohol-benzene can also remove fats, wax and resins from wood (Brauns, 1952).

Furthermore, Uprichard (1993) said that the extractives vary from low molecular weight volatile monoterpenes to higher molecular weight substances such as triterpenes and sterols, and from hydrocarbons to complex polyphenolic structures.

The amount of extractives in wood is about 1% to 20%, depending on the species and the position in the tree. Generally, the extractive content decreases with the tree height and is more abundant in heartwood than in sapwood.

There are some effects of extractives on wood utilisation, for example, polyphenol compounds lead to high durability in wood from bio-deterioration. The presence of phenols and tannins can cause staining and corrosion in woodworking. A high extractives content may cause problems in papermaking.

Walker (1993a) stated that wood also contains inorganic elements, for example, calcium, magnesium and potassium. The amount of inorganic ash content is usually 0.1% to 0.3% of oven-dry wood weight. But, in tropical regions, this content may be more than 0.5% because of the silica content, which causes problems in wood machining.

2.3 *Wood physics*

2.3.1 *Density*

Wood density is the mass of wood per unit volume at a given moisture content (Siau, 1984). The density can be expressed as kilograms per cubic meter or grams

per cubic centimeter. In the units of grams per cubic centimeter, the density is numerically identical with specific gravity, the ratio of the particular density to the density of water (1.00 g/cm^3). The specific gravity of wood is defined as the ratio of the oven-dry weight of a wood sample to the weight of a volume of water equal to the volume of the sample, at a specified moisture content. Therefore the specific gravity is dimensionless. The specific gravity of cell walls is the same for all kinds of wood cells, for earlywood and latewood, in sapwood and heartwood and among various tree species. The value is always near 1.5 (Wilcox et al., 1991).

There is density variation within annual rings, within trees, between trees and between trees from different sites. The density variation within annual rings is caused by the formation of earlywood and latewood (Walker, 1993e).

2.3.2 Moisture content

Wood starts to dry immediately after a tree is cut. The water released initially from wood is called free water. Free water is located in the lumen. Further drying releases bound water that is located in cell walls (Kollman and Cote, 1984). Besides free water and bound water, there is also water vapor in wood (Haygreen and Bowyer, 1989). Mills (1991) said that the bound water is released after the free water because the bound water has an ionic bond with wood. Therefore, more energy is needed to release bound water than free water.

The amount of water in wood is usually expressed as moisture content, which is defined as the weight of water in a sample divided by its oven dried weight expressed as a percentage.

Kollman and Cote (1984) said that green wood moisture content varies in different species, trees, parts of tree and places. But the variation in different seasons is not significant. According to Mills (1991), in some species of hardwoods, the moisture content can be more than 100% and in other species is below 100%.

When wood cells contain only bound water, this condition is called fibre saturation point (FSP). The exact moisture content of FSP varies in different species. Walker (1993e) stated that usually the FSP of wood ranges from 25% to 35% or can be

assumed as 30%. At moisture contents below FSP, there are changes in the physical and mechanical properties of wood.

Timber continuously releases water until there is a balance between its moisture content and the atmospheric moisture (humidity). This level moisture content is called the equilibrium moisture content (EMC). Actually there is no exact level of EMC of timber, because the atmosphere always changes and the capability of timber to adjust with the environment is slightly different depending on species, thickness of boards and surface coatings. Changes in relative humidity or temperature can change the EMC of the wood.

For practical use, however, the long run average EMC should be determined for particular areas. Then this EMC is the target used for drying timber to minimise dimensional changes of the timber. In Australia, timber is usually dried to the range of 10% to 15% moisture content to correspond to the average EMC in Australia, except if there is agreement between the supplier and the purchaser, or for other specific purposes.

When a board dries, the moisture content in surface layers drops quickly because of evaporation, while inside the board it decreases more slowly. As a consequence, the moisture distribution varies from the highest moisture content at the center of board to the lowest moisture content at the surfaces. This uneven moisture distribution is called moisture gradient. A very steep moisture gradient, mainly in a thick board, indicates a severe drying condition. So, maintaining a small moisture gradient is very important to prevent high drying stress that can cause drying failure (Mills, 1991). The moisture gradient proportionally influences the drying rate of wood until the wood reaches the EMC (Kollman and Cote, 1984).

2.3.3 Shrinkage

Wood begins to shrink when bound water leaves the cell walls. Conversely, if dry cell walls absorb moisture, the wood will swell (Mills, 1991). However, slight shrinkage may occur above FSP (Kollman and Cote, 1984; Innes, 1995b).

Wood shrinkage or swelling is usually expressed as a percentage of the dimension before change. The dimensional change of wood is proportional to the change of moisture content (loss or gain moisture) below FSP (Mills, 1991).

The amount of shrinkage also depends on the wood's basic density. High-density woods have more cell walls, so they usually shrink or swell more than low-density woods. Since the surface of boards will reach FSP sooner than the inner part, the total volume will reduce although the average moisture content is still above FSP.

The presence of extractives in cell walls might reduce wood shrinkage and hygroscopicity at high humidity (Walker, 1993c). Chafe (1987) also found that volumetric shrinkage has a negative correlation with lignin and extractive content and a positive correlation with polysaccharide content.

Shrinkage and the internal stresses mostly relate to drying defects in wood. Wood shrinkage is different in different directions, parts of the stem and between normal wood and wood containing natural defects (Kollman and Cote, 1984).

Wood shrinks differently in three principal directions. In the tangential direction, shrinkage is usually 1.5 to 2.5 times that in the radial direction, especially when wood dries from green to oven dry condition. The shrinkage in the longitudinal direction is very small, and is often ignored.

The main cause of this anisotropic shrinkage is the microfibril orientation in the thickest layer, S2 of the cell wall, which is at 10° to 30° angle with the longitudinal axis. The shrinkage is restrained in the direction parallel to the microfibril axis and forced in an orthogonal direction to the microfibrils. However, reaction and juvenile wood have significant longitudinal shrinkage, which may exceed the tangential shrinkage. This is because the microfibril angle may be more than 40° (Barber and Meylan, 1964 in Walker, 1993).

Dimensional stabilisation can minimise the bad effects of anisotropic shrinkage. Coating with an oil-based paint or water-based emulsion (e.g. acrylic emulsion) can reduce vapor movement in and out of the wood. Moreover, using paraffin wax is more effective in reducing water absorption and wood movement, especially for a limited period of time (Rowell and Banks, 1985 in Walker, 1993).

Bulking cell walls with chemicals, such as salts, can slightly reduce wood shrinkage. However it causes a damp surface and corrodes fittings. Polyethylene glycol (PEG) is the most successful bulking agent in wood. It can be applied to green timber (Rowell and Konkol, 1987 in Walker, 1993).

Bulking cell walls can be done with thermosetting resins as well, such as phenol formaldehyde that is polymerised with heat and a catalyst. With a 35% resin content, 70% to 75% swelling can be resisted. Moreover, it improves resistance to decay and acid.

Reducing wood permeability can be achieved also by impregnating cell lumens with vinyl monomers polymerised with ionising radiation, such as gamma rays. This technique greatly improves hardness, wear resistance, resistance to chemical staining and stability. However, it requires high cost technology and is associated with some safety concerns (Meyer, 1984 in Walker, 1993).

Wood stabilisation, using cross-linking technique, is used more for preventing swelling than shrinkage. Principally, the neighboring polysaccharide chains are cross-linked with methylene bridges ($-CH_2-$). This technique can reduce 50% to 70% of wood swelling, while the weight increase is only 4%. Moreover, the wood becomes resistant to fungi attack, but its mechanical properties are reduced.

High dimensional stabilisation (about 75% to 80% reduction in swelling) can be achieved by acetylation that increases the weight by about 15% to 20%. The cell walls are bulked with acetyl groups that replace hydroxyls. As a result, the wood becomes less hygroscopic. This technique improves resistance to fungi, termites and marine organisms. In addition, the mechanical properties are not reduced (Walker, 1993c).

2.3.4 Permeability

The transport of moisture in wood can be divided into two main types. The first is moisture flow through the interconnected voids of wood structures under the influence of a static or capillary pressure gradient. The second is diffusion that consists of intergas diffusion and bound water diffusion. The intergas diffusion

occurs when water vapor transfers through the air in the lumens of cells. The bound water diffusion occurs within the cell walls of wood (Siau, 1984).

Moisture movement in wood depends on fluid, driving force (e.g. pressure, moisture gradient) and wood structure. The measure of the ease of fluid flow is named permeability. Permeability is different from porosity. Porosity is the proportion of free space in a material. Therefore, some timbers have the same porosity, but their permeability may be different.

Permeability in the longitudinal direction of sapwood is very high due to vessels. Their diameter is between 20 μm and 300 μm. However, the presence of tylosis may resist the flow in vessels.

The transverse flow through ray tissue and pits (diffusion) on the radial surface of fibres is very small compared to the flow in the longitudinal direction. In softwood, this transverse flow is slightly higher than that in hardwood (Langrish and Walker, 1993).

Spolek and Plumb (1981) studied free liquid capillary transport in the drying of softwood. They found the dependence of capillary pressure on saturation value: the less saturation, the higher the capillary pressure. The magnitude of capillary pressure was controlled by the menisci, which are formed between the liquid and gas in the tracheid lumen.

$$S = \frac{\text{liquid volume}}{\text{void lumen}} = \frac{M - FSP}{Mmax - FSP} \qquad \textbf{(2.3.4.1)}$$

where:

S = saturation value;

M = moisture content of sample (%); and

Mmax = maximum mositure content of sample (%).

When there is no pressure gradient in a permeable timber, water can migrate across swollen cell walls by diffusion processes from a high moisture content region to a low moisture content region. The rate of diffusion depends on the diffusion

coefficient and driving force, such as concentration gradient or chemical potential (Langrish and Walker, 1993).

Siau (1984) defines diffusion as a molecular mass flow controlled by a concentration gradient. Therefore, diffusion can occur without a static pressure difference. In addition, Schaffner (1981) explained the theory of Fick's law under a steady-state condition. According to this theory, the rate of water-vapor transport through a unit area of a wood section is proportional to the concentration gradient measured as normal to the section.

$$F = -D.\frac{\partial C}{\partial X} \qquad \textbf{(2.3.42)}$$

where:

F = rate of transfer per unit area ($kg/hr.m^2$);

D = water-vapor diffusion coefficient of wood (m^2/hr);

C = concentration of diffusing substance (kg/m^3); and

X = the length in flow direction (m).

Langrish and Walker (1993) said that the diffusion coefficient is sensitive to moisture content, which is greater in high moisture content. Diffusion within cell walls also depends on temperature. It might increase 37-fold when the temperature increases from 25°C to 100°C. Based on this theory, a high drying temperature was developed. Moreover, diffusion is very important in drying timbers that are impermeable or at too low moisture content for hydrodynamic flow of water in permeable timbers.

In addition, drying impermeable timbers from the fibre moisture content to the EMC will take the same time as that of permeable timbers having a similar basic density because the moisture transfer of both timbers in this stage depend on moisture diffusion. In drying from above FSP, free water can flow through the pits in permeable timbers causing faster drying than that in impermeable timbers, which still rely on diffusion.

Transverse diffusion is determined by the diffusion coefficient of cell walls, because it is much less than that of the water vapor in lumen, mainly at low moisture content. The presence of pits and their condition does not significantly influence transverse diffusion, except at very small moisture content and with very thick cell walls.

Furuyama and Kanagawa (1994) concluded that the vapor pressure gradient was more reasonable than the moisture gradient as the driving force of the moisture diffusion in wood. The moisture diffusion coefficient derived from the vapour pressure gradient decreased with decreasing moisture content.

2.4 Messmate stringybark

In the market, messmate stringybark (*Eucalyptus obliqua* L'Herit) is also called Australian oak or Tasmanian oak, which includes two other species, *Eucalyptus delegatensis* and *Eucalyptus regnans*. The geographic distribution of messmate stringybark in Australia extends from northern New South Wales, to southern Tasmania. This species is one of the more fire-resistant eucalypts and regenerates quickly after fire (Turnbull and Pryor, 1978). Messmate stringybark trees can reach 60 m to 90 m in height, with clear and straight boles. Their diameter is up to 2 m, but mostly 1.0 m to 1.2 m.

The colour of this timber is pale with a pinkish to a light brown tint. Its sapwood width is 25 mm to 38 mm. It is paler and indistinct from the heartwood. The grain is usually straight, but can sometimes be interlocked or wavy. The texture is coarse. Its density ranges from 670 to 990 kg/m^3 (in average about 780 kg/m^3) (Farmer, 1972).

Illic (1997) made a key determination of three species from the ash group (*E. regnans, E. delegatensis and E. obliqua*). There are some differences in basic density, growth rings, pore grouping, ray width, proportion of multiseriate rays, and the height of multiseriate rays. Roughly, *E. delegatensis* has distinct growth rings, while the other two do not. *E. obliqua* has a basic density of more than 605 kg/m^3, while *E. regnans* is less than 390 kg/m^3.

The main difference of *E. obliqua* is in the ray cells, which are more bulbous with a higher proportion of multiseriate cells than the other two species. The height of multiseriate rays is 1 to 9, mostly 5 cells in *E. obliqua*, while in the other two it is 1 to 5, mostly 1 to 2 (to 4) cells. The width of individual ray cells is 10 μm to 30 μm, usually 15 μm to 20 μm in *E. obliqua*, and 5 μm to 16 μm, mostly 8 μm to 12 μm in the others. Pockets or veins containing kino are more common in *E. obliqua* than in *E. regnans* and *E. delegatensis*.

Some species have some similarities with each of these eucalypts. *E. nitens* and *E. fastigata* are similar to *E. regnans*. *E nitens* and *E. delegatensis* have similarities too, but have less distinct growth rings. *E. viminalis, E. baxteri, E. muellerana* and *E. eugenioides* are similar to *E. obliqua*.

Farmer (1972) said that in green condition, the bending strength, modulus elasticity and compression parallel to grain of *Eucalyptus obliqua* L'Herit are 71 N/mm^2, 11,700 N/mm^2 and 34.8 N/mm^2 respectively. However, at 12% moisture content, they are 119 N/mm^2, 14,500 N/mm^2 and 64.7 N/mm^2 respectively.

Messmate stringybark timber dries quickly but it is very prone to collapse and internal checking. Some surface checks and distortion tend to occur in early drying. Therefore, preliminary air-drying is recommended and reconditioning is needed to relieve collapse. This wood shrinks from green to 12% moisture content (after reconditioning) about 6.5% - 10.0% tangentially and 4.0% - 5.0% radially.

Generally, the working properties of messmate stringybark are good. But in terms of durability, it is prone to powder-post beetle attack and is difficult to treat with preservative, especially the sapwood.

Messmate stringybark can be used for many purposes, such as pulp, joinery, furniture, flooring, paneling, and general construction (Turnbull and Pryor, 1978).

The drying behavior of eucalypts from plantations and young natural regrowth is quite different from mature eucalypts. Although young eucalypts can be dried more quickly, drying defects may be more severe than those in mature eucalypts. Some research results show that young eucalypts, which have lower density and are more permeable than the mature ones (500 - 800 kg/m^3, relatively impermeable),

have a higher risk in terms of collapse, shrinkage, growth stress, wrap, and check. The wood near the pith area is prone to check (Campbell and Hartley, 1978).

According to Walker (1993b), in mature hardwood the different properties between core wood and outer wood and between butt and top logs can be neglected. But, in young hardwood, the growth stress gradient is quite high. In addition, knot volume is usually more frequent in young trees. Large knots reduce wood strength and lead to low grade timber. Close spacing can reduce branches and knot size, reduce the core wood zone and lessen stem taper, but long rotation is needed to produce large log diameters.

Young hardwoods usually contain low extractives and minimum kino veins. The presence of extractives causes high chemical consumption in pulping and the weight increase of wood.

Chapter 3

Wood drying

Wood is a porous material that contains air and water, as well as wood substances. The moisture content of freshly cut wood varies largely from over 200% to as low as 40%. If allowed to dry, this moisture content will reduce towards a moisture content in equilibrium with the surrounding air, about 6% to 20 % (Walker, 1993d). Because the EMC is below FSP, wood shrinkage is inevitable. This shrinkage should be controlled during drying to minimise timber degradation.

Timber drying is also called timber seasoning and can be defined as drying timber to a moisture content suited to the condition and purpose of use. The drying aims to ensure the dimensional stability of timber before it is used in a structure or manufactured item (Mills, 1991). According to Kollman and Cote (1984), the objective of timber drying is to prevent and minimise drying defects in as short as possible drying time. Timber drying is very important for the economical utilization of wood. The advantages of timber drying are as follows:

1. increases wood resistance to fungal and some types of insect attack;
2. reduces wood warping, twisting, checking, splitting and honey combing;
3. reduces wood weight to reduce the cost of handling and transportation;
4. improves mechanical strength, stiffness, hardness and nail holding power;
5. improves painting quality; and
6. improves glueability and working properties.

In addition, Mills (1991) said that wood drying improves the heat and electrical insulating properties and preservative treatment of wood. Nevertheless, drying cannot improve the shock resisting ability.

Differential shrinkage due to moisture gradient is the most difficult problem in drying. Slow drying can minimise this effect, but it takes a long time and may be uneconomic. Therefore most drying kiln practices dry timber as fast as possible without causing excessive defects (Walker, 1993d).

3.1 Some common problems in wood drying

3.1.1 Drying stresses

In wood drying, stress can be defined as internal forces exerted by either of two adjacent parts of a wood upon the other across an imagined plane (McMillen, 1955). The deformation of a wood due to stress is named strain.

Usually the rate of moisture evaporation is faster than the rate of moisture movement in the wood. Therefore, the moisture content of surface layers becomes lower than that in the core. This moisture content difference is called moisture gradient.

Low permeability wood usually has a steep moisture gradient, particularly in high temperature or very low humidity drying. High moisture gradient leads to high drying stresses: tension stress in the surface layer and compression stress in the inner zone. If the tension stress exceeds the wood strength, surface checks will occur (Mills, 1991).

Walker (1993d) explained the phenomena of stress reversal that leads to case hardening. It usually occurs in the final stage of wood drying. When the tensile stress on the surface exceeds the elastic limit but is less than the failure strength of the wood, the fibres on the surface are stretched, because their shrinkage is restrained by the inner zone of the timber. So their shrinkage is less than is expected. As the drying continues, the interior fibres begin to dry below FSP and shrink. However, the outer fibres that are set in a stretched condition restrain the shrinkage. At this stage the drying stresses begin to reverse. The interior fibres experience tension stress, while the exterior fibres are in compression. Under these conditions, case hardening occurs.

If case hardening is not relieved after kiln drying, timber will distort (cupping) when ripped. The distortion is towards the saw cut because the board surface is in compression while the core is under tension. It will also press the saw during cutting. Furthermore, bowing may also occur when there is too much machining on

one surface of the case-hardened board. These are not desirable. The boards should be free of such stresses and have stable dimensions after kiln drying.

In many kiln practices, conditioning and equalising processes are applied in the final stage of drying to relive these drying stresses.

Drying stresses result in strain development in dried wood. So, in many research activities, strain behaviour is used for stress analysis in dried wood. Wu and Milota, (1994) described four components of inelastic strain that occur in wood during drying: instantaneous strain, creep strain, shrinkage strain and mechano-sorptive strain. The instantaneous strain is generated immediately after the development of stress. This strain varies with moisture content and stress at a given temperature. Creep strain is a time-dependent deformation under constant stress and moisture content. Wood creep is generally faster at higher temperature and moisture content. Shrinkage strain is the dimensional change caused by moisture loss without restraint. Mechano-sorptive strain is the deformation resulting from the interaction of stress and moisture change. It is different from creep. Mechano-sorptive strain does not directly depend on time, while creep depends on the duration of loading.

Wu and Milota (1994) demonstrated the significance of creep and mechano-sorptive strain in relieving the stresses during the drying of 50 mm by 190 mm Douglas fir (*Pseudotsuga menziesii*) heartwood lumber. In addition Martensson and Svensson, (1997) said that without mechano-sorptive behaviour, wood couldn't be dried properly.

Innes (1995b) developed a mathematical model that predicted stress and strain distribution within fibre walls as a function of temperature, moisture content and fibre wall strength and size in the early drying. This model showed that stress and strain were sensitive to temperature changes of about 5°C. Furthermore Kowalski and Rybicki (1996) reported that heterogenous moisture content and temperature distribution influenced the drying stresses. The intensive heating resulted in a fast drying of the boundary layer and led to checking.

The presence of transverse stress can be determined by the prong test. The test is done on a sample crosscut from a board. The sample, then, is cut into several even thickness strips (depending on the thickness of the board). The cutting begins from one end up to ± 15 mm from the other end of the sample, parallel to the original board surfaces.

The prong patterns immediately after cutting and after one-day air-drying are compared. In the early drying stage, the surface strips usually turn out immediately after cutting, indicating the presence of tensile stress in the surface of the board. In the later drying stage, the surface strips turn in immediately after cutting. This shows the presence of compression stress in the board surfaces. Straight or nearly straight prongs and deflection-free strips after cutting represent good stress relief (Mills, 1991).

Longitudinal stress is caused by longitudinal tension set in the surface of lumber or longitudinal shrinkage differentials due to reaction (tension) wood. The presence of this stress can be identify by longitudinal bandsaw cuts approximately every 1/8-¼ inch to about one-half the length of the sample board (Boone et al., 1988).

3.1.2 Collapse

Collapse is defined as abnormal and often irregular shrinkage occurring above FSP (Mills, 1991). It is indicated by rippled or 'wash-boarded' effects on the wood surface (Innes, 1997a).

Collapse has become an economic problem in the domestic and overseas timber market, because it causes appreciable waste and influences acceptance in timber markets. This problem is most known in the ash group of eucalypts (Greenhill, 1938). According to Walker (1993d), there are some other timbers which are also prone to collapse, such as oak (*Quercus spp*), black walnut (*Juglans nigra*), western red cedar (*Thuja plicata*) and redwood (*Sequoia sempervirens*).

Collapse is a seasoning defect that occurs in wood when high temperature is applied in the early drying period. Because of this temperature, the wood becomes plastic,

has less compressive strength that allows internal crushing including high stress (Kollman and Cote, 1984).

However, some species might collapse at ambient temperatures. Innes (1997a) showed that Tasmanian *Eucalyptus regnans* timber collapses at 28°C. Lee and Redman (1998) found that the collapse threshold temperature for *E. obliqua* was very low, 7°C and was independent of the sawing orientation of the boards.

The effects of collapse on the cells are flattening, buckling and closing. These defects lead to a reduced cross section dimension, corrugated wood surfaces and deformations (Campbell and Hartley, 1978). Collapse is also highly correlated with internal checking (Illic and Chafe, 1986). Moreover, Kollman and Cote (1984), Oliver (1991) and Innes (1996) explained that severe collapse could cause high differential shrinkage that can induce surface and internal checks (honey combing) in boards.

Collapse is different from normal shrinkage in which the fibres remain nearly cylindrical, although volume and wall thickness are reduced (Mills, 1991). Collapse occurs when the free water inside cell cavities of green wood moves. On the other hand, normal shrinkage is caused by the release of moisture from the cell wall. Therefore, wood mainly collapses when its moisture content is above FSP, while normal shrinkage occurs below FSP (Greenhill, 1938; Oliver, 1991). Chafe and Illic (1992) also reported that a large portion of wood collapse occurs in drying from green to 17% EMC. Below 17% EMC, there is still some small collapse which is apparently caused by drying stresses. Furthermore, Walker (1993d) said that collapse can be relieved by reconditioning with steam at 100°C and 100% relative humidity for four to eight hours.

Theoretically, there are two main causes of wood collapse. Kollman and Cote (1984) said that wood collapse could be caused by the tension produced by capillary forces in partially water-filled wood cells and the drying stresses due to moisture gradient across lumber during seasoning.

Bisset and Ellwood (1950) believed that collapse was caused by the development of internal tension. By using a photomicrograph, they showed that earlywood

collapsed more than latewood, while normal shrinkage was greater in the latewood than in the earlywood. It was unlikely that this collapse phenomenon was caused by the compressive drying stress. The samples were very small and taken from different single growth rings of *Eucalypus regnans* F.v.M. and *E. gigantea* Hook F.

Similarly, Wilkins and Wilkes (1986), by using scanning electron microscopy, found that collapse mostly occurred at the periphery of wood where fibres were undamaged. When the periphery cells are damaged, collapse occurred in the adjacent cells. So, it seemed to be that the true collapse event was caused by internal tension.

According to the boiling or vapour bubble formation theory, there is a minimum size of bubble to form against surface tension. A bubble that is smaller than this size will collapse and disappear. Similarly, some wood species have wood cells with a lumen diameter less than the minimum size to form a bubble. So, when water is removed from the cells, the free water inside these cell lumens goes into tension and causes a compression effect in the cell wall. If the cell walls are not thick and strong enough, the cells will collapse. This collapse leads to extra shrinkage above the normal shrinkage (Mills, 1991).

Booker (1994) also explained that water tension causes compression forces in the fibre walls, which are proportional to the cell lumen's width at right angles to the wall divided by the wall's thickness. Therefore, the wider the lumen and the thinner the cell wall, the greater the compression stress on the cell wall.

When water evaporates from the surface of a board, water tension in the water-filled cells increases until the fibre wall is damaged or the water tension reaches a maximum. This tension can be limited by air bubble entry from other cells through the pits or other openings between the cells or by spontaneous cavitation of air bubble when water stress is large enough. However, in collapse-prone species, water tension is usually not relieved until the cell wall ruptures. According to Booker (1994), there are various types of collapse in wood:

1. Radial collapse, which can occur in the earlywood of softwood, because it has thinner cell walls, and many latewood tracheids are air-filled. In addition,

tracheid cells are arranged in radial direction that leads them to be more resistant to deformation. So thin earlywood bands may collapse, although without any internal checking.

2. Tangential collapse might occur in both early and latewood of softwood if fibres in both early and latewood have large, water-filled lumens and quite thin walls.
3. Diagonal collapse may occur in both early and latewood by the bending of the lumen corners.
4. Deformation in multiple directions can occur in water-filled fibres of hardwood such as eucalypts. The presence of stress risers, such as large vessels, may cause internal checks and collapse.
5. Radial checking and tangential collapse. This collapse occurs after radial checking in middle lamella between adjacent tracheids or between tracheid and rays when the tension in the earlywood is large enough. This checking can not extend to the latewood because it is under compression. This compression is caused by more collapse in earlywood than in latewood.

In addition, Innes (1995a) suggested that collapse in fibres was likely to be precipitated by failure in the S3 layer that was a temperature independent mechanism. This collapse might be started mainly from the fibres near vessels or rays.

Compression stress seems to be the only supplementary force in collapse occurrence (Innes, 1996). The stress causing collapse must be greater than the cross-grain tension strength but less than longitudinal compression strength of the wet wood (Bariska, 1992).

An experiment by Kauman (1958) concluded that drying stress significantly influenced wood collapse. He found that in any structural direction of samples, the greatest total shrinkage and collapse was in the thickness at the central position of the samples, while the least was in the width. Even in longer samples, the total shrinkage was somewhat greater. It was much clearer when the samples were end-sealed or during higher temperature drying. These cases resulted from the restraint effect by the surface zone that experienced tension set. The restraint in a particular

direction led to the increase in total shrinkage at right angles to that direction. This fits with the Poisson effect in elasticity.

Kauman (1960) also found that the influence of tension stress in the surface zone of collapsed wood was seen when there was more collapse in the core of samples, mainly in end-sealed samples. Moreover, collapse on the width of rectangular cross section samples was more than that in cube-shaped samples.

Clarke (1972 in Bariska, 1992) said that when the moisture content of board's surface goes below FSP, there is a large moisture gradient in the board: the compression stress occurs in the inner zone, while the outer zone experiences tension stress. In addition, wet wood fibres usually have less strength, so the fibres under compression stress may collapse.

In terms of collapse susceptibility, there is some variation among different species, different trees, and even in different positions and directions in a stem. The variation of wood properties influences its sensitivity to collapse.

Bariska (1992) observed collapse occurrence at the bottom end of five eucalypt species directly after felling (in the field) and in a laboratory by using a scanning electron microscope. He showed the rank of collapse susceptibility, starting from the higher risk species, E. *macarthurii, E. elata, E. nitens, E. fastigata*, and *E. grandis.*

Generally, wood from young or regrowth trees tends to collapse more than that from mature trees. Hillis and Brown (1978) said that most wood from young trees had more shrinkage before reconditioning than that from mature tress of the same species. But after reconditioning, the shrinkage of the young and mature materials was not much different. Moreover, Oliver (1991) showed that in over-mature heartwood, collapse was rarely seen; because the cell walls were stiffened by lignin and the internal tensile could be restrained.

In terms of position in a tree, Kauman (1960) noted that wood from the butt end of a log collapsed more than that from the top of the log. A similar finding was from Pankevicius (1961) who revealed that the increase of collapse caused by the

increase of drying temperature was much greater in the butt logs. In other words, collapse intensity was less in wood from a higher position of the tree.

Some comparisons of collapse occurrence in sapwood and heartwood have been done.' The results vary with respect to species and other possible factors. Pankevicius (1961) found that in 50 year old *Eucalyptus regnans* and 300 year old *Eucalyptus gigantea* there was no appreciable difference in collapse intensity between heartwood and sapwood, except in wood at a higher position in the tree which had less recoverable collapse in the sapwood. However, Chafe (1985) showed that, in *E. regnans,* sapwood collapses more than heartwood.

In many cases of collapse, the signs of collapse initially appear in the earlywood because the fibre walls in this part are thin and cannot resist the internal tension effect (Oliver, 1991). Likewise, Illic's (1982) experiment showed a general tendency that collapse-prone wood had less latewood fibres than other woods.

The chemical composition and anatomical features, such as lack of lignin and different micro-fibril orientation respectively were responsible in the collapse severity of hardwood containing reaction (tension) wood (Wardrop and Dadswell, 1955 in Bariska, 1992).

Wilkins and Wilkes (1986), using the SEM examination, were unable to clearly determine the influence of extractive deposition during heartwood formation on reducing pore size and the increase of hydrostatic tension and collapse susceptibility. Although the FWPRDC research (n.d.) reported that lignin and extractive concentrations have a negative correlation with collapse, Chafe (1987) suggested that collapse was positively correlated with lignin and extractive content and negatively correlated with polysaccharide content.

Temperature has a very significant influence on wood collapse. This was proved by Greenhill (1938) who found that a higher temperature and longer period of drying caused a much greater collapse and less recoverable collapse in wood. High temperature could permanently weaken the cell walls. However, the volume of cell lumen that was about 60% of green volume of *E. regnans* limited the amount of

collapse. Correspondingly, Pankevicius (1961) came to a similar conclusion about the effect of temperature on high collapse intensity.

Kauman (1960) also showed that total collapse was a linear function of wood temperature. This function depended only on the surface tension, and structural and rheological properties of wood. He found that in temperatures of more than 88°C or in very low humidity, collapse depended significantly on time.

In high temperature drying, Kauman (1960) found that below FSP, wood collapse was still increasing. He believed that the weakening of cell walls as a result of hydrolysis or other chemical changes caused this.

Kauman (1961) reported that in the drying of the heartwood of *E. regnans* (mountain ash) from Victoria and Tasmania, *E. diversicolor* (karri) and *Flindersia pubescens* (silver ash), exceeding one to two days at temperature 82°C, six hours at 110°C, or two hours at 137°C caused the increase of wood collapse and the decrease of its recovery attainable in reconditioning. But, at 20°C, 38°C, and 54°C the effect of thermal degradation on collapse and shrinkage was negligible.

In thermal degradation, the acidity of wood increased to the maximum that was proportional to the additional shrinkage. There was no further change in shrinkage and collapse recovery after acidity decreased. This acid could be produced from the hydrolysis reaction of the O-acetyl groups in wood during the thermal treatment.

Illic (1982) used a Digital Image Processor (DIP) to analyse wood anatomy and its correlation with collapse occurrence. He compared some anatomical properties, such as proportional vessel area, vessel frequency, basic density, area proportion of rays, parenchyma and fibre, and TWLARF (Transverse Wall to Lumen Area of the Fibres) in terms of their correlation with collapse in wood. He concluded that TWLARF value has the best correlation with collapse phenomena in wood.

Illic and Chafe (1986) reported that collapse was highly correlated with initial moisture content and basic density. The FWPRDC research (n.d.) also revealed that collapse intensity had a good correlation with specific gravity and moisture

content, while wood permeability had a positive relationship with the diffusion coefficient and was negatively related to collapse.

Chafe (1985) found that in *E. regnans* volumetric shrinkage could confidently be used for predicting collapse severity. Moisture content was also an independent and indirect indicator of collapse, while basic density, P, Q and green density could be used for indicatory values. Collapse and volumetric shrinkage had positive correlations with moisture content, the percent of theoretical saturation and the percent of cell cavity containing water (P). But they were negatively correlated with basic density. Moreover, Chafe (1986b) reported that the best collapse determinant in latewood is percent saturation, while in earlywood it is density.

$$P = \left(\frac{M}{Mmax} \right) \times 100 \qquad \textbf{(3.1.2.1)}$$

$$Q = \frac{(M - 28)\,BD}{1000 - 0.93\,BD} \qquad \textbf{(3.1.2.2)}$$

where:

P = percent of cell cavity containing water;

M = moisture content;

Mmax = maximum moisture content; and

BD = basic density (Brown et al., 1952).

Illic and Chafe (1986b) reported that the depth of pin penetration (6 Joule Pilodyn with 2 mm diameter pin) and the electrical pulse resistance using a Shigometer were significantly related to collapse and could be used as guides to classify collapse-susceptible wood. The measurements were taken with these devices at the middle and 15 cm from the end of the sample. The shrinkage measurement was done using an image processor and expressed as the percent of the green cross sectional area. However, these devices had a less accurate prediction for collapse susceptibility in high-density wood.

A rapid collapse prediction was made by Illic and Hillis (1986) by measuring collapse factor (CF) and volume shrinkage (Sv) in small samples of *Eucalyptus regnans*. The samples were dried at 100°C for 6 hours and 7 hours (the best period for drying for CF and Sv measurements respectively). An image processor was used to measure changes in shape and area.

CF had a more comprehensive correlation with internal checking and collapse than Sv, however both CF and Sv had significant correlations with the percentage of collapse. Both CF and Sv were significantly correlated with initial moisture content (Mi). Although Mi was less accurate than CF and Sv in predicting collapse, Mi was quicker in predicting collapse (Illic and Hillis, 1986).

The collapse factor (CF) is a shape factor that is determined in dry samples (Wechsler, 1981) as:

$$CF = \frac{(\text{the perimeter of the cross-section board})^2}{\text{cross-section area of board}} \qquad \textbf{(3.1.2.3)}$$

The perimeter is the length of outside boundary and that of internal checks, while the cross-sectional area does not include the area of the checks.

$$Sv = 1 - \left[\frac{Ad}{Ag}\right] \qquad \textbf{(3.1.2.4)}$$

where:

Sv = volume shrinkage;

Ad = dry cross section area (does not include checks area); and

Ag = green cross section area.

3.1.3 Checking

Checking is the cracking of wood that occurs during drying when stresses exceed ultimate tension levels. Checking is a serious problem in timber drying. It can

reduce the strength and quality of wood. Therefore drying recovery is very low and causes economic loss. According to the position in the board, checks can be classified into three types, i.e. end checks, surface checks, and internal checks.

End checking usually results from the more rapid loss of moisture from the end part rather than from the inner part of a board. When the end part has a moisture content below FSP, it starts to shrink before the inner part of the board. This results in tension stresses around the ends of lumber and compression stresses in the inner part. Because wood is weaker in tension than compression in the direction perpendicular to the grain, end checks develop. When all parts of the wood dries, some stresses release and some checks tend to close again (Kollmann and Cote, 1984). Furthermore, Walker (1993d) stated that end checking can be minimised by proper end-sealing and wide stickers.

Kollman and Cote (1984) defined surface checks as longitudinal openings at weak points in the wood occasioned by the stresses produced in differential shrinkage. Previously Campbell (1959) said that checking was caused by high drying stress due to severe moisture gradient. In worst conditions, it can lead to splits and honey combing.

Checking also may occur where compression wood is located adjacent to or between the normal woods because the normal wood restrains the high longitudinal shrinkage of the compression wood (Kollmann and Cote, 1984).

Walker (1993d) explained that in drying with a severe schedule, surface checks might occur in the early stage due to steep moisture gradients. Checking is usually formed at the weakest point, for example, along wood rays. Therefore, surface-checks usually occur in back sawn boards, while edge-checks occur in quarter sawn boards. To avoid surface checking high humidity and low dry bulb temperature could be applied in wood drying, which can maintain wood strength.

In the later stage of drying, when the surface is in compression, the interior timber might check because the tension stress exceeds its tensile strength. This internal check is called honeycombing, which mostly occurs in the radial direction

following the rays. Generally, honeycombing can be prevented by avoiding large stresses in the early drying and a too high temperature in the final stage of drying.

Oliver (1991) said that internal checking could also be caused by differential collapse. The worst internal checking tended to occur in the wide growth rings of earlywood. Booker (1994) suggested that according to analysis based on geometrical and engineering principles, collapse and internal checking are competing phenomena caused by water tension. These internal checks and collapse will not occur if water stress is too small or the wood is very strong. Besides that, internal checks initially can be caused by collapse due to water tension. According to Mills (1991), these internal checks mostly closes in the middle of drying, but reopens during reconditioning and becomes a serious problem in moulding or furniture application.

Yang (1998) affirmed that internal check could be caused by severe collapse in the early stages of drying and enlarged by drying stress. In this case, the initial small checks acted as the stress raiser for the larger checks. Chafe and Carr (1998a) also found that the number of internal checks was related to shrinkage from green to 12% EMC, while the area of checking was related to the shrinkage from 12% moisture content to oven-dry.

When there is a large differential stress among adjacent fibres, internal checks may occur. This differential stress results from different cell wall contraction due to the different strength of adjacent fibre walls or by air-filled fibres adjacent to water-filled fibres. This internal checking will lead to collapse if the cell walls are not strong enough (Booker, 1994).

In addition, Innes (1995) said that internal checking is caused by differential shrinkage. It possibly occurs without any collapse, and vice versa. Collapse in adjacent earlywood may reduce differential shrinkage (contraction) and so reduce checking.

Temperature is an important factor in wood checking. McMillen (1955) reported that in the drying of northern red oak (*Quercus rubra* L.), raising drying temperature (from 27°C to 60°C) increased the maximum surface tensile stress at

the beginning of drying and maximum internal tensile stress after stress reversal. As a consequence, the surface checking and honeycombing tended to be more pronounced than at the lower drying temperature. Maintaining low temperature pre-drying until the wettest point in the board was below FSP then followed by the drying at higher temperatures might prevent excessive internal set and honey combing. The high final drying temperatures slightly relieved both tension and compressive set.

Internal checking may also occur due to severe collapse at a low drying temperature. Innes (1996) showed that drying at temperatures between collapse threshold temperatures of late and earlywood (between 20°C and 28°C) caused initial internal checking in the latewood. Drying above the collapse threshold temperature of earlywood caused initial internal checking in both early and latewood. According to this analysis, the internal checks would occur even when drying slowly to prevent surface checks (Innes, 1995b).

Board dimension influences the occurrence of internal checking. It was shown by Chafe and Carr (1998a) that internal checking in 50 mm x 100 mm cross sections of Eucalyptus *regnans* was more severe than that in 50 mm x 50 mm or 25 mm x 100 mm cross sections. This was because more drying stresses in association with collapse occurred in 50 mm x 100 mm samples.

Checking area was positively related to shrinkage in thickness, but negatively related to shrinkage in width. In addition, checking had a strong negative correlation with permeability and density, but a positive correlation with moisture content (Chafe and Carr, 1998a).

Booker and Doe (1995) reported that in wood drying when localised irreversible stress was released, acoustic emission (AE) was generated and the strain energy reduced. The strain energy on a board surface could be calculated by using surface stress and instantaneous strain data.

The peak AE value was closely related to the surface instantaneous strain and indicated the nearness to failure, but a cumulative count could not be used for measuring the tendency of surface checking. The AE rate represents the acoustic

energy generated on a board surface over a short period of time, while the cumulative count represents the total acoustic energy on the surface board during drying.

AE is directly related to Young's modulus that changes with moisture content and temperature. The cumulative count (total ring down counts) of AE was related more to unrecoverable strain energy than to elastic strain energy.

3.1.4 End split

Split in logs can occur between the pith and cambium very early, about two days after felling (Bariska, 1992). Material from 50 mm of the pith is usually prone to surface check and end split (Hillis and Brown, 1978). During green sawing, there was a 23% loss of sawn product because of end-split, which was higher than that which occurred in the drying process (Lee, 1998).

Most end splits are not drying defects, but come originally from growth stress release. During drying, the splits may extend and become a serious problem for timber quality (Hillis and Brown, 1978). Overhang board or unsupported board ends are mainly the cause this end-split extension (Lee and Redman, 1998). Severe collapse can also extend the split primarily to the heart region after five days. This split is called collapse split. If the split extends to the periphery of the log, it is classified as growth stress split (Bariska, 1992).

Growth stresses develop during the formation of wood cells. Wind and growth competition among trees influence the development this stress. With the formation of new cells at the cambium, longitudinal compressive stress and radial tensile stress occur and increase in the wood near the pith, while the wood near the cambium experiences longitudinal tensile stress and tangential compression stress.

Growth stresses are more severe in hardwood than in softwood and heavier in high competition stands. The transverse growth stresses are about a tenth of longitudinal growth stresses, but they can cause internal splitting (star shake or ring shake) after felling and crosscutting due to the weaker wood strength in these directions and the

relief of longitudinal growth stresses. Moreover, during drying, distortion and splitting may increase. In small stems, growth stress is less likely to cause end-split or heart check, but more likely to cause warp (Kubler, 1987 in Walker, 1993b).

Growth stresses can be reduced by thinning trees, long term (3 to 6 months) wet storage of logs and by heating logs to 100°C (Walker, 1993d). However, Walker does not mention the heating period.

Bariska (1992) said that there are some possible factors that reduce end split and collapse in sapwood, such as:

1. The net effects of the combined collapse and growth stresses slightly reduce the stem diameter. The growth stress causes tension stresses in the tangential direction and compression stresses in the radial one.
2. It has been mathematically proven that small radial deformation is followed by tangential deformation, so the tangential stresses possibly reduce and prevent split.
3. Sapwood has a higher moisture content than heartwood.
4. Heartwood has more juvenile character than sapwood.
5. Split formation in heartwood reduces the residual stresses in sapwood.

Besides that, in cold and rainy seasons, the split growth stopped and some of them seemed to close again.

3.1.5 Warping

Warping is caused by anisotropic shrinkage. Spiral grain, cross grain, reaction wood and juvenile wood contribute to this deformation. There are different types of warping, such as diamonding, cupping, bowing, crook or spring and twisting. Diamonding is found in square cross-section with growth rings running diagonally. Cupping is the concave curvature across the face of a flat sawn board. Bowing is the longitudinal curvature on the board face. Crook is a longitudinal curvature on the board edge. Bowing and crook are influenced by the presence of juvenile wood. Twist is the spiral distortion along the length of timber. It is caused by spiral grain (Walker, 1993d).

Warping can be minimised by restraint (Walker, 1993d). However, restraint may cause severer surface checking. Furthermore, Sharma et al. (!988) found that the incident of warp and crook could be reduced by the balance tangential sawing (BTS) technique (see **Figure 3.1.5.1**), which was better than that by conventional back sawing and quarter sawing.

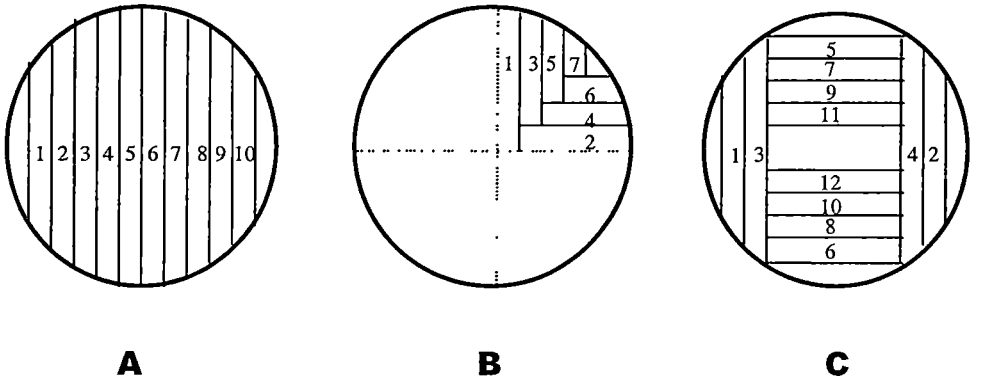


Figure 3.1.5.1 *Sawing strategies of logs: A = conventional back sawing, B = quarter sawing, C = balanced tangential sawing; The numbers represent the sequence of sawing.*

3.1.6 Staining

The problem of staining can be minimized by quick handling between felling, milling and drying, allowing the boards to reach a low moisture content as soon as possible. Dipping timber in a prophylactic anti sapstain immediately after milling can prevent staining for a few months (Walker, 1993d).

3.2 Variable factors in drying control

There are three important factors or elements affecting the drying conditions of wood, temperature, relative humidity (RH) and air circulation or velocity.

Mills (1991) stated that when the air temperature is raised, the rate of moisture evaporation from the surface of timber increases due to the increase in the rate of heat transfer to supply the latent heat for vaporisation. Besides that, the relative humidity decreases so the moisture holding capacity of the air increases.

In addition the temperature rise is required to accelerate the moisture transfer (diffusion) from the inside to the outside of timber, which is caused by the increase of vapour pressure (driving force) of the moisture in the wood.

Humidity is the amount of invisible water vapour in air. It can be expressed as absolute humidity or relative humidity. Absolute humidity is the weight of water vapour in a unit weight of dry air, for example as grams per kilogram of dry-air. Relative humidity is the amount of water vapour in air revealed as a percentage of maximum vapour that can be held by the air at the same temperature. Therefore, the relative humidity is 0% in completely dry air, whereas in saturated air it is 100%.

Relative humidity is usually measured by using a dry bulb thermometer and a wet bulb thermometer that is wrapped in a wet cloth wick. The end of the wick is dipped into clean water. When the water in the wick evaporates, the temperature of the wet bulb thermometer reduces. The temperatures from both thermometers are used for determining relative humidity, referred to in a table. The difference between the dry bulb temperature (DBT) and the wet bulb temperature (WBT) is called wet bulb depression (WBD).

Water evaporation from the wick depends on air humidity and temperature. If air humidity increases or air temperature decreases, the evaporation rate decreases. Consequently WBD reduces. So WBD indicates the drying potential of the air.

There is a psychrometric chart showing the relation between dry bulb temperature (DBT) and relative humidity (RH) or wet bulb depression (WBD). The corresponding value of EMC is also available (**Figure 3.2.1**). According to this chart, the effect of RH or WBD on EMC is more significant than that of DBT. It shows that in constant WBD, the changes of DBT cause only little change RH and EMC. But, in constant DBT, the changes of WBD cause significant changes to EMC.

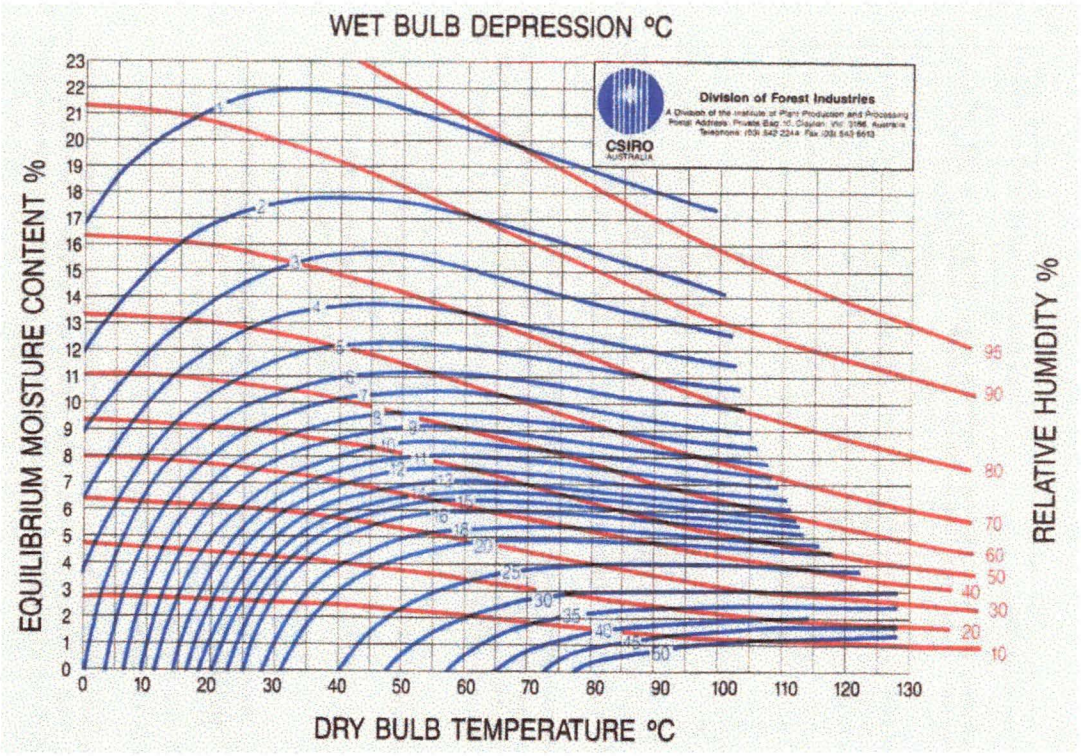


Figure 3.2.1 *Equilibrium moisture content (EMC) of wood as a function of dry bulb temperature (DBT), wet bulb temperature (WBT) and relative humidity (RH) (CSIRO in Mills, 1991).*

The function of air circulation in timber drying is as a transfer medium that takes hot dry air to the timber and removes cooler moist air from its surface. The speed of air circulation controls the drying on the wood's surface as well. The faster the air is circulated, the more moisture is removed (Mills, 1991).

The velocity and uniformity of airflow determines the rate of drying and wood quality. High velocity air (3 m/s or more) is beneficial in the initial drying of green permeable timber, because it causes more moisture evaporation from the timber surface. But in slow drying of impermeable species an air speed of 1.5 to 2.0 m/s is sufficient (Walker, 1993d).

The moisture variation of the boards in a kiln was caused by progressive air humidification and airflow mal-distribution. Airflow reversal was more effective in reducing moisture variation due to air humidification, while airflow-rate increase was more effective in reducing moisture variation due to airflow mal-distribution.

The airflow reversal was more effective in the early stage of drying, when there were large moisture content differences across the kiln. Commercially, the frequency of reversal varied from at least once during drying to once every two hours. However, in the drying of *Pinus radiata,* one reversal was adequate to achieve a relatively uniform moisture content in a minimum time (Nijdam and Keey, 1996).

3.3. Drying process in wood

Basically, there are two processes of moisture movement in timber drying, the moisture evaporation from the timber surface to the moving air, and moisture movement from the interior to the timber surface. Those processes should be in balance by controlling the drying elements. If the evaporation is too fast, checking may occur due to the steep moisture gradient, which is accompanied by high drying stresses exceeding the wood's tensile strength (Walker, 1993d).

In the early drying of permeable wood, the moisture movement is dominated by mass flow. This mass flow can maintain the surface moisture above FSP for some time. In this stage, the drying rate is proportional to the heat transfer, which is controlled by air velocity and the wet bulb depression. The heat transfer and the evaporation rate increase with the increase of air velocity and are proportional to the wet bulb depression. Density and thickness of timber do not influence the drying rate. However, drying time depends on the drying rate and the amount of water to be transported, which is proportional to the wood density and thickness (Hart, 1975 in Walker, 1993d).

When the moisture content is near FSP (40-50%), the transfer of molecules from the wet line to the surface is by diffusion, because mass flow becomes ineffective. This diffusion is proportional to the cross product of the moisture gradient and the diffusion coefficient. In addition, temperature increase causes increase of vapour pressure and diffusion rate.

When the moisture content at the timber surface drops below FSP, its temperature rises. So, the temperature difference between timber surface and air lessens and the

heat transfer to the surface reduces. The drying rate becomes slower until zero when the timber is approaching its EMC (Walker, 1993d).

In the drying of highly impermeable timber, there is no mass flow. All the water molecules migrate by diffusion that is quite slow. So the drying rate is inversely proportional to wood density and thickness, and proportional to the saturation vapour pressure, which is closely related to the diffusion coefficient. The drying time is proportional to the square of thickness, to the square of density and to the saturation vapour pressure of water.

The drying rate from FSP to the EMC of permeable and impermeable timbers is about same when their densities are the same (Hart, 1975 in Walker, 1993d).

3.4. Drying technique

There are some general suggestions to successfully dry timber. Campbell and Hartley (1978) said that timber needed to be handled rapidly to allow it to dry under control. In addition, Kollmann and Cote (1984) said that end coating with a moisture-impermeable material is very useful to prevent end checking.

Proper stacking is very important in timber drying to minimise defects and accelerate the drying rate. Kollman and Cote (1984) said that boards are usually piled in a flat system and lengthwise to prevent drying defects.

Timber stacking needs weighting or restraining systems, mainly on the end parts of timber (Campbell and Hartley, 1978). Although loading in a board stack can prevent cupping, it caused an increase of surface checks, which was five times more severe in the lower rack than in the upper rack (Lee, 1998).

Timber layers should be separated with stickers to let air pass over the timber surface equally. Kollman and Cote (1984) suggested that stickers should be placed in a vertical column in the boards' pile. The ends of each board should be on stickers.

Stickers should be made from a similar kind of timber and be uniform in thickness. In USA, the common sticker thickness is 22 mm. In Germany, it depends on board thickness; for example, boards up to 30 mm in thickness need 15 mm thick stickers. Thicker boards usually need thicker stickers.

The space between stickers depends on the thickness and condition of the timber. Thin boards (up to 25 mm) and rather fresh wood (thickness up to 75 mm) need sticker spaces of 0.45 m to 0.50 m. Thicker timber (50 mm and up) in air-drying needs spaces between stickers of 0.60 m to 0.75 m. Other types of board usually use 0.90 m to 1.20 m sticker spaces.

Boards should be of a similar thickness and species, because wood dimension can affect the drying rate. For example, wood veneer quickly adjusts to a new EMC, while a thick lumber needs a longer time to reach EMC. If there are more than one species in different layers, the lowest drying schedule that is suitable for the timber should be used (Kollman and Cote, 1984).

Generally, wood drying can be divided into two categories: air-drying or natural drying and kiln drying or artificial drying. In fact, these two methods are often used as a continued process. Many people or companies use air-drying as a pre-drying process before kiln drying

3.4.1 Air-drying

The success of air-drying really depends on climate and geographical conditions (Kollman and Cote, 1984). Therefore, it may take a quite long time, 50 to 200 days for 25 mm thick hardwood and 30 to 150 days for softwood of the same thickness. The drying rate also depends on the stacking system (Walker, 1993d).

Air-drying is relatively simple and cheap which is why many people use it, mainly for preliminary drying to remove free moisture from the wood. However, in particular species, air-drying causes some problems, such as surface checks in ash wood. Air-drying becomes very slow when the timber moisture content is below FSP and timber cannot be dried to below the local EMC (Mills, 1991). Moreover,

boards on the top of stacks are more prone to degrade because of exposure to the sun's heat and rain, and there is less weight to resist distortion.

Air-drying is done by stacking timber outside with or without shelter. It is suitable for impermeable or collapse prone timber, large size timber and the timber for exterior uses which do not need to have a low final moisture content. Air-drying can also be used as pre-drying before kiln drying.

The area of air-drying should be sealed and have good drainage. The yard should be clean of wood waste that can be a fire hazard and a breeding host of fungi and insects. The timber stacks are usually placed at 0.5 m above ground level supported by a firm foundation. Their width should not more than 2 m and the height is no more than three times of the width (Walker, 1993d).

Timber stacks should have ample air circulation. Usually they are placed parallel to the direction of the prevailing wind. There should be enough space between stacks and the wind should not be blocked by buildings or trees near the stacks (Mills, 1991).

3.4.2 Kiln drying

Kiln drying is usually used after air-drying, except for some species that are only dried by kiln, such as radiata pine. In kiln drying, temperature and humidity are strictly controlled to achieve minimum defects and time of drying (Mills, 1991).

Compared to air-drying, kiln drying needs more technical skill and capital investment. However, it has advantages. For example, kiln drying is much faster and more timber can be dried in the same period. The final moisture content can be much lower than with air-drying, with lower drying defects. Moreover, it does not depend on weather (Walker, 1993d). According to Kollman and Cote (1984), kiln drying can also prevent wood staining and decaying fungi or insects, which may have been present inside the wood.

Compared to air seasoning with or without a shed, kiln drying usually results in fewer surface checks. Lee and Redman (1998) reported that the average surface

check-free lumber product in fully controlled kiln drying (with KilnSched program), under shed and open air seasoning were about 50%, 38% and 33% respectively. They were 25 mm thickness lumber, while the values of 19 mm thickness lumber were 58%, 43% and 40% respectively.

In kiln drying, the timber is stacked without gaps within each layer and the free area in the end or over the stack should be minimised or baffled off to force the air to pass through the stacks (Walker, 1993d).

3.4.3 Drying schedule

To achieve maximum drying recovery and minimum drying time, drying schedules are required. Millis (1991) stated that because green wood is weaker than dry wood, a drying schedule is usually not constant.

Walker (1993d) suggested that initially timber in the kiln should be warmed up to enhance moisture transfer to the surface, which may reduce the stresses due to previous air-drying. The kiln should be maintained at a low wet bulb depression, no more than 2°C for about an hour per 10 mm timber thickness. Furthermore, temperature and humidity in the kiln should be adjusted according to an appropriate drying schedule by manipulating heating coils, spray valves, and the inlet and outlet vents. Generally the initial drying condition is low temperature and high humidity to prevent checking and case hardening. The schedule for permeable timber is usually more severe than that for impermeable timber. However, permeable timber treated with a preservative may need a lighter drying schedule than untreated timber.

Boone et al. (1988) said that there are two major groups of drying systems in U.S or Canadian woods, i.e. drying with conventional temperature schedules (maximum DBT $\leq$ 82°C) or elevated temperature (maximum DBT 82-104°C) and drying with high-temperature schedules (maximum DBT > 100°C). Softwood can be dried with conventional or elevated temperature in two alternative ways, with moisture content-controlled schedules and time-controlled schedules. All high-temperature schedules are time-controlled schedules.

In kiln drying, the airflow should be uniform and adequate through all parts of the stacks. The higher the drying temperature or the higher volume of the stacks, the greater volume of air is necessary, so a faster air speed is essential to prevent a high moisture gradient across the stacks. The recommended air speed in different drying systems, is as follows:

a. high temperature drying from green 5 to 10 m/s;
b. high temperature final drying 3 m/s;
c. conventional final drying (< 100°C) 2 m/s;
d. solar and dehumidifier drying 1 m/s;
e. pre-driers and progressive kilns 0.5 m/s; and
f. curing sheds 0.2 m/s;

For eucalypts wood, Campbell and Hartley (1978) suggested a moderate drying schedule because it is quite prone to drying defects.

Moreover, Langrish et al. (1997) optimised a continuous drying schedule for Australian ironbark timber by keeping strain below 0.02 mm/mm and the surface moisture content above seven percent. The schedule had milder conditions in the starting stage, but harder conditions towards the end unlike that in a conventional schedule. Mechanical properties data in cross grain direction were required to establish this schedule.

3.4.4 Equalising

Equalising treatment is a common practice at the end of the drying process to reduce the moisture content difference within boards and between boards in a kiln. This treatment is applied when the driest sample is three percent below the final target moisture content and the moisture content difference between the wettest and driest of the kiln samples exceeds three percent in the final stage of drying (Boone et al., 1988).

In equalising, air humidity is increased by increasing WBT at the same DBT as the last schedule. The EMC of equalising is the same as the driest timber. Therefore, the driest timber will not continue drying, while the wet timber is still drying. The

equalising is terminated when the wettest timber reaches the target moisture content (Walker, 1993d).

3.4.5 Conditioning and high humidity treatment

Conditioning is practiced to relieve the drying stresses and tension set (case hardening) in the final stage of timber drying after equalising treatment. Failure in conditioning usually causes some defects during the machining of lumbers, such as cupping, crooking, bowing or twisting (Boone et al., 1988). According to Walker (1993d), however, conditioning is applied before equalising moisture content, therefore some compression stress on the board surface and tension stresses in the boards after conditioning can be relived by equalising.

Some other benefits of conditioning are recovering collapse (Campbell and Hartley, 1978) and board cupping (Lee, 1998).

Mills (1991) used high humidity treatment (HHT), which is different from conditioning in terms of process, to relieve residual stresses. The conditioning always uses high temperature, while in high humidity treatment, high temperature is only sometimes used. The temperature of HHT is 85°C DBT and 3°C WBD. Timber with 25 mm thickness usually needs three hours HHT, and longer for thicker timbers. This treatment softens the out layers and reduces the moisture gradient, because moisture diffusion is increased, while moisture evaporation is reduced.

Walker (1993d) explained that timber becomes more plastic under high temperature and humidity. In conditioning, the fibres on the board surface absorb moisture and want to swell again, but the inner zone restrains them. The compression stress on the board surface increases. When the compression stress exceeds the elastic limit of the fibres, the compression set is generated. This compression set will be the counterbalance of the initial tension set on the board surface. Campbell and Hartley (1978) said that extending the holding period before conditioning could be useful for wood with difficult drying properties.

Alexiau et al. (1990) said that the temperature of conditioning is 82°C or higher. Boone et al. (1988) added that conditioning is applied by raising 1°C from recommended WBT and extending the time for four hours per inch of thickness. But, for thinner boards and species with less density, the conditioning period can be shorter. According to Walker (1993d) the humidity in conditioning is increased with the EMC about 3% to 4% above target moisture content. The DBT may be higher than that at equalising.

Haslett and Bates (1997) reported that pressurized steaming was more rapid and more effective in relieving drying stress than standard atmospheric pressure steaming. This was caused by more complete softening by the pressure steaming on wood. However, the application of pressurized steaming should not be too long because it might cause thermal degradation of the wood. One hour pressurized streaming on 40 mm thick radiata pine boards with 2.8 bars pressure, 130°C DBT and 130°C WBT caused stress relief that was at least as good as three hours of standard steaming technique using 100°C DBT and 100°C WBT.

The conditioning process should not be too long so as to avoid too much water being absorbed by the board surface. This can cause excessive compression set on the surface zone that usually results in more shrinkage than in normal wood when it reaches the EMC. Tension occurs again on the board surface, while compression is generated in the core, and the board experiences reverse case hardening that cannot be cured.

Before unloading, dried timbers should be cooled to prevent continuous drying by the air warmed by the timbers. The heat is turned off, so the timbers cool under constant wet bulb depression (± 5°C). The timbers can be safely removed from the kiln when their temperature is within 15°C to 20°C. Then the timber should be block stacked without stickers and wrapped with plastic.

3.4.6 Kiln types

There are various types of kiln drying, such as conventional heated kilns, solar kilns, and dehumidifier kilns. A solar kiln works by increasing air temperature to

reduce relative humidity and to improve moisture transfer in the wood, while a dehumidifier kiln reduces air relative humidity by condensing air moisture on the coils of a refrigeration unit. The condensed water is then drained to the outside (Mills, 1991).

There are many users of the solar dryer because of the low drying cost and it is faster than natural drying processes. This dryer is more efficient in low humidity regions than in tropical regions (Ong, 1997). However, the solar dryer produces a slower drying rate than the electric resistance kiln and the dehumidifier kiln (Ong, 1999).

In the United States and Canada, most people use steam-heated kilns for timber drying. Direct-fired kilns, dehumidification kilns and vacuum dryers are used as well. Humidity control in the direct-fired kiln is limited and the temperature is usually more than 100°C. These kilns are used mainly in drying softwood for construction. Dehumidification kilns are commonly used for hardwood, with lower temperatures than steam-heated kilns. Vacuum dryers use various methods in transferring energy into wood, for example, by radio frequency (RF), hot air, heated platens or electric blankets. These three kiln types cannot use the schedule of steam-heated drying, because it needs precise control of temperature and relative humidity (Boone et al., 1988).

Drying with a microwave applicator caused uneven temperature and moisture distribution in wood. This problem might be solved by moving load or by alternating the position of the microwave applicator (Antti and Perré, 1999).

3.5 Some modifications in drying techniques.

3.5.1 Stack cover

Finighan and Liversidge (1964) reported that stack covers could protect timber from defects such as checking and warping which are usually serious in the upper layers of stacks in natural drying. The cover should exceed the ends and sides of the stacks by about 0.30 m. It works well because the covers can improve the drying rate and uniformity, and can prevent re-wetting of the timber as well. They found that fibreen, corrugated galvanized iron and two thicknesses of black polythene film were the selected materials for this function. However, only galvanized iron can be used for more than 18 months.

3.5.2 Pre-drying

Before kiln drying, timber may be subjected to pre-drying which includes two steps. The first step uses a forced air dryer under a roof with 1-2 m/s air speed. The fan can be turned off when the relative humidity is 85% to 90 % or below 40% to save power and prevent checking respectively. The next step is pre-heating at 10°C to 20°C above ambient temperature.

This pre-drying is useful for drying green or preservative treated timber as it takes less time and causes fewer defects than air drying (Walker, 1993d).

3.5.3 Low temperature pre-drying

Low temperature kiln drying or partial air-drying can prevent collapse (Walker, 1993d). Innes (1996) said that using very mild drying can avoid surface checks, but internal checks may still occur initially in collapsed latewood near the surface. It seems that to prevent internal checks in drying, collapse should be completely avoided.

Collapse is a temperature dependant process, so it can be avoided by seasoning under the collapse threshold temperature (CTT) until timber moisture content is below FSP. Drying at a temperature between the CTT of latewood and earlywood still results in checking, even with very slow drying. Innes (1995a) defined the

collapse threshold temperature as the highest temperature of drying which causes no collapse in a certain wood.

3.5.4 High temperature drying

High temperature drying is effective for permeable timber. It uses 120 ± 10 °C DBT, 75 ± 5 °C WBT and a high-speed fan (5-10 m/s). The stickers should be wider (up to 45 mm) and thicker (25mm to 32 mm). Therefore, the timber will not be indented and have enough airflow. With this technique, 50 mm permeable softwood timber can be dried within 24 hours, while with a conventional kiln it takes 5-7 days.

Chen et al. (1997a) suggested that the first stage of high temperature drying is controlled by an evaporative front receding into the board, while in the later stage, the diffusion of bound water and vapour prevail. Cavitation may occur randomly in tracheids when experiencing water tension, particularly in the beginning period of drying. This leads to rapid moisture loss from wood.

Walker (1993d) said that there are three processes that contribute to high temperature drying: in the drying stage I (evaporation) is very fast, because of the high fan speed and WBD. In stages II and III, vapour flows through the pits and diffusion acts in parallel. The vapour pressure gradient is maintained by heat flow into the timber. Therefore, the drying time is independent of density, proportional to the square of board thickness and inversely proportional to WBD. With this high temperature drying, FSP of timber will be lower than that at conventional drying temperature.

In high temperature drying, there is slight steam pressure within timber that causes a mass flow of water vapour to the surface. This drying technique is suitable for permeable timber where water vapour can flow through the pits. According to Campbell and Hartley (1978), high temperature drying can be applied to young eucalypt with 30% moisture content.

There is a good prospect in high temperature drying, as explained by Innes (1997a), that it can reduce differential shrinkage and the wood could be better at resisting differential shrinkage, because at higher temperatures, the wood is softer. However, there are some disadvantages of high temperature drying, such as total shrinkage may be more than that of near ambient temperature drying. Besides that, irreversible collapse could be more, because the high temperature exceeds wood softening temperature or fibres delamination at the S2-S3 interface.

Simpson et al. (1998) reported that using a severe schedule in drying hardwood for structural function is more efficient than using an ordinary mild schedule, because the wood performance can be neglected as long as there is no structural grade loss.

Chen et al. (1997a, 1997b) reported that in the first stage of high temperature drying, mechano-sorptive strain significantly influenced the magnitude of stress. Creep caused the large tensile stress falling after its peak value. Because of the enhanced creep and softened material behaviour, high temperature drying might not cause severe defects. Moreover, the mitigation effects of mechano-sorptive and creep-strain caused smaller total shrinkage than that of a pure elasto-plastic model.

The mechanical properties of wood vary at different temperatures and moisture content. Under high-temperature conditions, wood may sustain plastic strain after passing the yield point. Checking occurs only when the ultimate strain is exceeded.

There are some other potential problems in high temperature drying. The moisture content of the timber stack is not even. The timber usually has a darker colour, and slightly reduced mechanical properties. Besides that, the timber becomes more prone to collapse, honeycombing and warping. Therefore, some timber should be pre-dried to below FSP to reduce some degradation. However, some other timber cannot be dried with high temperature drying at all (Walker, 1993d).

3.5.5 *Freeze-drying*

Choong et al. (1973) observed the effect of freeze-drying on collapse and moisture flow in *Eucalyptus delegatensis*. Freeze-drying is wood drying by sublimation at temperatures from 0°C to -20°C by using a vacuum of a few microns. They used a very cold temperature, -42 °C and 0.05 torr vacuum. They concluded that freeze drying can prevent wood collapse, because it can eliminate hydrostatic tension. However, because of the high moisture content at the time of freezing and the volume expansion of water to ice, this freezing tends to cause checks and splits.

In terms of drying rate, freeze-drying is much faster than drying by kiln, because the external gas pressure is lower than the vapour pressure of the ice in the wood. So the vapour can flow from the cell lumina to the outside through the pits of the cell walls. It is much greater than diffusion flow even in kiln drying at normal temperatures (Choong et al., 1973).

3.5.6 *Intermittent or cyclic drying*

Intermittent drying produced less internal checking than continuous drying (Chafe, 1995a). However, the rate of intermittent drying was slower than that of continuous drying. Intermittent drying also caused more width shrinkage (tangential direction), while continuous drying produced more thickness shrinkage (radial direction). Higher tangential shrinkage in intermittent drying was caused by less permanent set in the shell due to lower drying stresses. High permanent set in continuous drying resisted tangential shrinkage and increased radial shrinkage (Chafe, 1995b).

Chadwick and Langrish (1996) compared continuous drying and two cyclic drying techniques on Australian turpentine timber. The first cyclic method used high humidity relaxation, while the second cyclic method used ambient temperature relaxation.

The first cyclic method had a similar drying time to continuous drying, whereas the drying time of the second cyclic-drying method was 20% less than the continuous

drying time. The levels of bow, spring, shrinkage and surface check were similar among those drying methods. However, twist was greater in the first cyclic drying method. Collapse was eliminated in both cyclic-drying methods. The internal check in the first-cyclic drying method was 80% greater than in the continuous drying method, while internal check of the second cyclic drying was 10% less than in the continuous drying method.

3.5.7 Radio-frequency/vacuum drying

Avramidis and Zwick (1996) revealed that radio-frequency/vacuum (RF/V) kiln drying of western cedar (*Thuja plicata* Donn), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), amabilis fir (*Abies amabilis* (Dougl.) Forbes), mix (hem-fir), and Douglas-fir (*Pseudotduga menziesii* (Mirb.) Franco) with proper schedules resulted in no lumber staining and internal stress, reduced surface checking, a more uniform final moisture content and less shrinkage than conventional kiln drying. The RF/V kiln drying could dry lumber sizes that could not be dried with a conventional kiln because of excessive drying time and defects.

3.6 Modifying wood drying properties

The variety of wood properties leads to different drying properties. Therefore classifying wood based on its seasonability is an important step to achieving a good drying result.

Innes (2000) created a technique of measuring seasonability to improve the recovery and time of drying. Core samples with 12 mm diameter and 230 mm length were taken by drilling longitudinally from the logs. The samples were dried at constant temperature, humidity and air speed for 24 hours, then oven-dried. Their weight and length were measured before and after first drying and after oven drying. Visual assessment was done on the surface of samples. These data were processed to classify the timbers' seasonability.

Some treatment before drying could be applied on timbers that have difficult drying properties to improve their seasonability. A lot of research has been done on this, but the results differ, depending on wood variety.

3.6.1 Compression

Pre-compression to improve wood properties and to reduce wood collapse has been studied. But according to Hart (1984), pre-compression had no effect on collapse, except at extreme magnitudes. Yang (1998) also reported that cell-wall deformation due to longitudinal compression did not reduce drying defects (collapse and internal checking).

3.6.2 Pre-steaming

Two steaming methods can be applied before wood drying, direct system and indirect system. In direct system, steam is sprayed directly onto board piles. It is difficult to control local over-heating with this method. On the other hand, indirect steaming uses steam to heat coils that are arranged on a basin. The water in the basin evaporates slowly towards board piles. In this case, thermal control is better. However, the steam may contain oil (Kollman and Cote, 1984).

Steaming can be done when timber is in green condition or at an interrupted stage of drying when the moisture content is around 50%. But the total period of steaming should not be more than six hours or it can induce irreversible collapse. In addition, periodic steaming during drying can not increase the drying rate beyond that obtained with one initial steaming treatment, and can result in irreversible collapse (Campbell, 1960).

Kollman and Cote (1984) also stated that long term and high pressure wood steaming can cause hydrolysis of cellulose and hemicellulose, reducing wood density and mechanical properties. This was supported by Hart (1984), who found that a long period steaming (four days) caused some thermal degradation and caused more collapse.

The benefit of pre-steaming on improving wood drying properties is not consistent over trials. Previously, preliminary steaming in kiln drying was intended to reduce drying time, to kill fungi and insects in wood, and to darken some woods. Based on reports from some seasoning plants, steaming could improve collapse recovery and machining qualities, and reduce defects. British investigations in 1940 also showed that steaming did not significantly degrade the quality of drying properties, workability and dimensional stability.

The result of the FWPRDC Project (n.d.) showed that pre-steaming could increase the drying rate. Campbell (1960) also reported that steaming for about two hours on 25 mm thick stocks at 100°C could cut about 20% to 25% of the drying period of ash eucalypts, myrtle beech *(Nothofagus cunninghamii)*, *E. gigantea* and *E. regnans,* but not *E. gigantea.*

Wang et al. (1994) revealed that pre-steaming red oak (*Quercus* sp.) reduced the drying time by 23%. But, because of faster moisture loss, maximum drying stress in pre-steamed samples occurred before that in the control samples.

According to Kollman and Cote (1984), steaming in 95% relative humidity (RH) can relieve any stress that is caused by case hardening during air seasoning. Mills (1991) also said that pre-steaming reduces some growth and sawing stresses due to plasticisation and creep after high temperature.

Moreover, preliminary steaming (in 80% to 100% RH) for a few hours can be applied to heat the kiln and boards, and to release stresses, which are set up by case hardening during air drying. In this process, fans are used to equalise airflow, and dampers should be closed. Fresh stock releases some moisture, while air dry stock adsorbs about 5% to 8% moisture. After pre-steaming, wood collapse can also be reduced due to the increase of permeability and low moisture gradient (Mills, 1991).

Hukka (1998) found that humidifying kiln air with low pressure steam during the warm-up period can save warm-up time by about 50% to 80% and decrease checking by up to 50%.

Choong et al. (1999) compared five pre-treatments of wood drying. They were: steaming in a saturated condition for one and five hours respectively; steaming at a moisture content near FSP for one hour; steaming at 100°C and near 95% RH at an EMC slightly below FSP for one hour; and soaking in hot water for ten hours. The results showed that moisture diffusivity of wood above and below the FSP was increased by hot water soaking and prolonged steaming. In addition, during drying wood extractives moved with water due to moisture gradient. The changes of extractive distribution caused variations of the diffusion coefficient.

According to Campbell and Hartley (1978), steaming before drying can reduce drying period, moisture gradient, and surface checks, and gives better collapse recovery, except in eucalypts. Lee (1998) also reported that pre-steaming of green sawn regrowth eucalypt timber did not have any significant effect on total drying time and shrinkage behaviour.

Alexiau et al. (1990) found that surface checks occurred during pre-steaming of *Eucalyptus piluraris* Sm at 100°C for three hours, although total surface checks and moisture gradient were reduced.

The results of the FWPRDC Project (n.d.) showed that pre-steaming *Eucalyptus delegatensis* timber at 100°C for one hour or two hours did not reduce internal and surface checking. However, pre-steaming for 0.5 hour caused a slight decrease of degrade. Chafe (1990b), however, reported that brief pre-steaming (30 minutes at 100°C) of green *Eucalyptus regnans* caused greater total volumetric shrinkage and recoverable collapse, whereas initial moisture content and percent saturation were smaller than without pre-steaming.

Another finding of the undesirable effects of pre-steaming was found by Wang et al. (1994), that after pre-steaming of red oak, drying stresses increased by up to 36% when it was dried from 80% to 16% average moisture content at 44°C and 75% RH.

3.6.3 Preheating / pre-boiling

The effect of preheating on drying properties is still not clear, and has some different results. Chafe (1990a) said that collapse increased after hot water extraction. The relation of shrinkage after reconditioning and basic density became more significant and more relevant with Stamm formula ($Sv = f\rho$) mainly in heartwood.

Chafe (1993) reported that a pre-boiling treatment resulted in a significant increase of shrinkage before reconditioning in heartwood, while in sapwood the shrinkage reduced after pre-boiling treatment. This was because of permeability increase after extractive modification. The thermal degradation of cell walls during the pre-boiling treatment was responsible for the collapse increase in heartwood, whereas sapwood could overcome this degradation. The increase of recoverable collapse occurred mainly after eight minutes boiling time. After 16 minutes pre-boiling, shrinkage after reconditioning showed an overall decrease.

Moisture content after reconditioning of pre-boiled samples increased and reached the highest point after two minutes pre-boiling, then the moisture content decreased and was less than the control after 16 minutes boiling time.

The intersection point, unit shrinkage, R-ratio, collapse-free shrinkage, total collapse and residual collapse had a cubic relationship with the logarithm of pre-boiling time. In addition, they generally reached minimum value after eight or 16 minutes boiling times, except the estimated total collapse that had a maximum value after 16 minutes of the treatment.

Glossop (1994) found moderate surface checking in the drying of regrowth jarrah boards (*Eucalyptus marginata* Donn ex Sm.) that were pre-soaked in hot water. However, their drying rate was faster than the control boards.

Shrinkage and internal checking reduced due to preheating green boards of mountain ash in water (Chafe, 1994a). Preheating resulted in a greater reduction of

internal checking in low-density wood compared to that in high-density wood (Chafe, 1994b).

According to Chafe and Carr (1998b), preheating had little effect on the checking of *Eucalyptus regnans* boards with 50 mm x 50 mm and 25 mm x 100 mm cross section size. In boards with 50 mm x 100 mm cross-section size, preheating significantly reduced the internal checking area and the number of checks after drying. At 90°C preheating, the reduction of checking area and the number of checks were 89.8% and 53.3% respectively for tangential grain, 62.7% and 62.2% for intermediate grain and 69.1% and 53.9% for radial grain.

Preheating treatment increased the shrinkage of board width and reduced shrinkage in board thickness. It is possibly associated with check reduction. But the main cause of this reduction was the increase of moisture loss rate or permeability.

Gradual heating caused less shrinkage than sudden heating and extended gradual heating. The optimum temperature to reduce internal checking were 50°C, 70°C and 80°C for gradual heating, 50°C for sudden heating and 80°C for gradual heating extended. However, external shrinkage and surface checking tended to increase with preheating treatment (Chafe, 1994a).

Chafe (1995a) reported that the number of internal checks in *Eucalyptus regnans* reduced with the increase of temperature (between 50°C to 90°C) of gradual preheating in water. Preheating at 90°C caused a 45% reduction of internal checking. The increase of shrinkage might contribute to the decrease of internal checking.

3.6.4 Pre-freezing

Illic (1995) reported that in general, the practical temperature for pre-freezing was -20°C, while the duration needed less than 24 hours. Before drying, frozen wood needed a holding period for a few days to let the ice melt. The effectiveness of pre-freezing in reducing shrinkage might be better at a lower initial moisture content

Hart (1984) found that pre-freezing at -20°C for 24 hours moderately reduced collapse. In this pre-freezing, there was a swelling effect that was caused by extractive entering cell walls during free water movement. This extractive altered the creep behaviour of cells and reduced collapse. In addition, Glossop (1994) reported that pre-freezing increased the drying rate of regrowth karri boards (*E. diversicolor* F. Muell.), but their surface checking was severer than the control boards.

Illic (1995) suggested that pre-freezing had some benefits in reducing drying time, shrinkage, collapse and other drying defects in the heartwood of many hardwoods and softwoods, however some other wood species did not give clear positive responses to this treatment. In eucalypts, pre-freezing caused only some reduction of collapse and little improvement in internal checking.

3.6.5 Chemical treatments

Campbell (1959) reported that there are some water-soluble chemicals that can be used to control checking during wood drying, for example, sodium chloride, urea, invert sugar and ammonium phosphate. Their penetration into the surface layers of wood can reduce the surface vapour pressure and keep the surface moist. As a result, the moisture gradient can be kept at a safe level and shrinkage in the surface zone can be reduced. If more soluble chemical is impregnated, it can have an anti-shrink effect on the wood. Therefore, radial split in dried round timbers can be prevented.

Campbell (1959) also said that in collapse-susceptible species, however, the presence of the chemical in the outer zone could cause larger case hardening of wood and increased core tension stress. The internal checking is therefore likely to occur when the core dries and shrinks. The most suitable chemical for hardwood should have small anti-shrink effects and suitable vapour pressure characteristics. Besides that, the timber should be still in green condition.

There are several techniques of chemical treatment in drying control, such as dry spreading (sandwich method), dipping, spraying, brushing or soaking. The period of soaking is usually about one or two days per inch thickness of boards.

Salt soaking treatment is a more promising technique because of its small anti-shrink effect. However, it has disadvantages in use, for example corrosive action and sweating, mainly in humid circumstances, except if the salt-treated surface zone is finally removed.

Kauman (1960) said that the influence of tension stress on collapse could be reduced by sodium chloride treatment, even though it was still insignificant. This treatment could reduce collapse-free shrinkage and moisture gradient resulting from a declined evaporation rate.

Sharma et al. (1988) reported that soaking *E. tereticornis* logs in 40% (w/w) urea solution at 45°C for 48 hours did not reduce drying degrade of back sawn boards, such as surface checking, collapse in the centre heart portion and cupping.

Bariska (1975) showed that anhydrous ammonia (NH_3)-impregnation could not increase the dimensional stability of beechwood. When NH_3 was removed by further drying, more collapse and shrinkage occurred. This collapse resulted from the reduction of the lumen and perforation of wood cells.

When the treated wood was in contact with water, the swelling was about twice as much as that before treatment. This was as a consequence of additional polar groups being active which reduced the anti-swelling effect of lignin. In addition, there were more water-active hemicellulose and loosening of the wood substance after anhydrous ammonia treatment (Bariska, 1975).

Chafe (1990a) extracted *Eucalyptus regnans* with cold water (20°C, for eight days), hot water (70°C, for four days), hot methanol (55°C, for 21 hours) and one percent hot NaOH (75°C, two hours). The slope of regression relating collapse to the distance from periphery was successive reversals from positive (unextracted) to negative (hot water extracted) to positive (methanol extracted) to negative (NaOH extracted). However, the percentage of removed extractive negatively correlated to

collapse but positively correlated to shrinkage after reconditioning, except in NaOH extraction. After NaOH extraction, collapse increased significantly, mainly in heartwood.

Collapse decreased after cold-water extraction, except in radial direction, which showed an increase of collapse after cold extraction. After cold extraction, the relation of shrinkage after reconditioning and basic density was more significant and more relevant with Stamm formula ($Sv = f\rho$), mainly in heartwood.

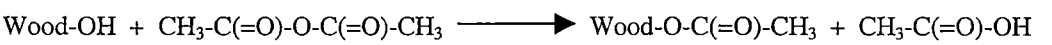
Chapter 4

Pre-treatments with sodium hydroxide and acetic acid

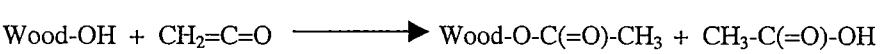
Various methods can be used to reduce the effect of moisture change on the dimensional stability of wood. One of the most satisfying methods to do so is by acetylation. According to Rowell (1983), acetylation is a chemical modification on wood by substituting its active hydroxyl groups with acetyl groups with or without a catalyst. The acetyl groups form covalent bond on cellulose, hemicellulose, and lignin.

Acetylation reduces wood hygroscopicity, improves dimensional stability and resistance to bio-deterioration (by termites, fungi and marine organisms). In addition, acetylated wood also has a higher density and generally has better mechanical properties than untreated wood.

Acetylation can be done by liquid or vapour phase reaction. The reaction of liquid-phase acetylation with acetic anhydride and pyridine as the catalyst is as follow:



Vapour-phase acetylation is only suitable for thin veneers because the diffusion rate varies inversely as the square of the thickness. This acetylation usually occurs at 55 – 60 °C for about six or eight hours. The reaction of this acetylation is as follow:



Gaseous acetic acid is often used in acetylation. The effects of liquid acetic acid treatment on wood, mainly on drying properties, are not clearly known.

There are some variables that relate to checking and other drying properties, such as lignin and extractives content, specific gravity and moisture content. The extractives may increase wood impermeability, internal checking and surface

checking. Wood with a low lignin content usually has more internal checks and surface checks (FWPRDC Project, n.d.).

Wood with a high extractive content usually has slow moisture movement and high moisture gradient during drying. Therefore checking is likely to occur due to high drying stresses exceeding the wood's tensile strength. Removing some extractives from the wood with water or cold sodium hydroxide in one percent concentration might increase moisture movement and reduce moisture gradient in dried wood. Therefore a reduction of drying stresses may be expected.

Surfaces coating with polyvinyl acetate glue (PVA) after water soaking were aimed at increasing internal moisture transport and slowing down moisture evaporation from the board surface. Therefore, a lessening moisture gradient and drying stresses in the surface zones of boards for a period of time in the early drying was expected.

The main objective of this experiment was to explore the effect of soaking in acetic acid, sodium hydroxide and water and PVA coating on some drying properties of *Eucalyptus obliqua* L'Herit back sawn boards.

4.1 Methodology

4.1.1 Sample preparation

Back sawn timbers of messmate stringybark (*Eucalyptus oblique* L'Herit) were bought from Clennett Timber, a timber company in Moonah, Tasmania. They were cut from regrowth stands about 70 years old in Hoptown, in the Dover area of Southern Tasmania. In this trial, five back-sawn timbers were randomly taken. Every timber was cut into 13 boards for 13 groups of trials. The boards' size was 30 mm x 110 mm x 300 mm (thickness x width x length). The boards were coded according to the treatments, as shown in **Table 4.1.1.1**.

Table 4.1.1.1 *Codes of boards.*

Code	Treatment	Code	Treatment
A1	Soaking in CH_3COOH for 1 day	N1	Soaking in NaOH for 1 day
A3	Soaking in CH_3COOH for 3 days	N3	Soaking in NaOH for 3 days
A7	Soaking in CH_3COOH for 7 days	N7	Soaking in NaOH for 7 days
A15	Soaking in CH_3COOH for 15 days	N15	Soaking in NaOH for 15 days
W7	Soaking in water for 7 days	C	Control sample (without treatment)
W15	Soaking in water for 15 days	W7C	Soaking in water for 7 days
DW1	Soaking in circulated water for 15 days		followed by coating with PVA

CH3COOH = 4% acetic acid solution; NaOH = 1% sodium hydroxide solutiuon.

4.1.2 Board treatments

Fifteen days soaking treatments in one percent sodium hydroxide (1% NaOH), four per cent acetic acid (4% CH_3COOH) and water were done earlier, while other boards were wrapped with plastic as soon as possible after cutting to prevent moisture loss. The other soaking treatments were done on different days, so that all treatments were completed on the same day. Surface coating on W7C boards was done immediately after soaking.

Two 25 mm long grain pieces were cut from every board after discarding its 30 mm end. One piece was used for measuring initial moisture content and basic density, while the other was used for measuring normal shrinkage, collapse and the fibre saturation point (FSP). The procedures of these measurements are described in **Appendix B**. The boards were then immediately end coated with Selleys All Clear copolymer sealant and aluminium foil to prevent moisture evaporation from their ends (longitudinal direction) during the drying trial. Before commencing the drying trial, the boards were kept in plastic wrap to maintain their moisture content.

4.1.3 Drying trial

Before loading the boards into a kiln, two reference marks on every board surface and edge were made with a permanent marker (see **Figure 4.1.3.1**). Then the thickness (radial dimension), and width (tangential dimension) of the boards were

measured at the reference marks using a digital calliper with 0.01 mm accuracy. The boards were also weighed on a digital top loading scale with 0.01 g accuracy.

The boards were dried in a kiln with a constant condition at 22°C DBT, 20°C WBT and 0.5 m/s airflow. The specifications of the kiln are described at **Appendix D**. The boards were removed from kiln for evaluation at the eighth and 29th days of drying. Their mass and dimensions were measured again to determine their moisture content and shrinkage respectively. Drying defects (checks and collapse) on the surface and edges of each board were also visually evaluated at every evaluation time using the criteria listed in **Table 4.1.3.1**.

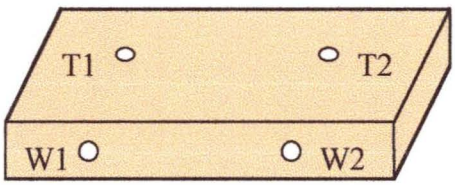


Figure 4.1.3.1 *Reference marks on a board for dimensional measurements: T1 and T2 = reference marks for thickness measurement at two positions of board; W1 and W2 = reference marks for width measurement at two positions of boards.*

Table 4.1.3.1 *Visual grading of drying defects on the edges and surfaces of boards.*

Grade of defects	Collapse	Checking
0	No collapse	No check
f	Less collapse = the depth of collapse < 3 mm	Less checking = the width of check < 0.5 mm
s	Worse collapse = the depth of collapse ≥ 3 mm	Worse checking = the width of check ≥ 0.5 mm

The moisture content was calculated by the following formula:

$$MC_t = \frac{m_t - \left(\frac{(100 \times m_i)}{(MC_i + 100)} \right)}{\left(\frac{(100 \times m_i)}{(MC_i + 100)} \right)} \qquad \textbf{(4.1.3.1)}$$

where:

MC_t = moisture content of a board at the time of measurement (%);

m_t = mass of the board at the time of measurement (g);

m_i = initial mass of the board (g); and

MC_i = initial moisture content of the board (%).

The shrinkage was calculated by using the following formula:

$$S_t = \left(\frac{(l_i - l_t)}{l_i} \right) \times 100 \qquad \textbf{(4.1.3.2)}$$

where:

S_t = board shrinkage at the time of measurement (%);

l_i = initial dimension of the board (thickness or width at the reference marks) (cm); and

l_t = board dimension at the time of measurement (cm).

Data of moisture content were used for drying rate evaluation. Drying rate was calculated by using the following equation:

$$DR = \frac{\Delta M}{\Delta t} \qquad \textbf{(4.1.3.3)}$$

where:

DR = drying rate (%/hours);

ΔM = the difference of moisture content between two measurements (%); and

Δt = the interval of drying time between two measurements (hours).

4.1.4 Data analysis

Data obtained in this trial were statistically analysed using Analysis ToolPak in Microsoft Excel. Analysis of variance (ANOVA) with a single factor or two factors was used to test the hypothesis that means from two or more samples were equal. If the result of this test showed a significant difference of means, the analysis was continued with paired t-tests to determine which sample had a mean distinct from the others.

4.2 Results and discussion

The practices of chemical pre-treatment using sodium hydroxide and acetic acid should be careful, because these chemicals might pollute soil and water. The smell of vinegar might be a problem during the soaking process. So, the soaking container needed to be cover properly. After soaking in acetic acid solution, the boards could be rather corrosive when they are in contact with metal, such as nails. But, this required further investigation. In general, the soaking process was simple and the cost was not expensive. Low concentration acetic acid and sodium hydroxide were like vinegar and caustic soda, which could be found in supermarkets for family/ public uses.

4.2.1 Physical properties of woods

Regrowth *Eucalyptus obliqua* wood used in this trial had a relatively low basic density compared to that of mature *E. obliqua.* Based on the oven dry technique, its basic density was 594 ± 32 kg/m^3, while mature *E. Obliqua* had 670 to 990 kg/m^3 basic density (Farmer, 1972) or more than 605 kg/m^3 (Illic, 1997). This indicated that the mass of the cell walls of regrowth *E. obliqua* was less than that of mature *E. Obliqua.*

Low basic density wood usually has thin cell walls and large diameter cell lumens. As a consequence, such wood cells are mechanically not strong enough to withstand

high compression stress. In addition, with a typical occluded pit structure of cell walls, this wood species becomes prone to collapse when it dries. This wood is also prone to surface checking because of high stresses during drying. These high stresses are induced by slow moisture movement in the wood and a high moisture gradient.

Table 4.2.1.1 shows that most boards soaked in one percent sodium hydroxide (1% NaOH) had lower basic densities than the control boards, whereas most boards soaked in four percent acetic acid (4% CH_3COOH) or in water had higher basic densities than the control boards. However, these differences were not statistically significant at 95% confidence level (**Table E.1** in **Appendix E**). The average basic density for all control and treated boards was 596 ± 28 kg/m^3.

Table 4.2.1.1 *Average basic density and initial moisture content of the boards after soaking in sodium hydroxide, acetic acid and water.*

Sample	BD (kg/mm^3)	M (%)
N1	590	76
N3	594	76
N7	589	82
N15	587	92
A1	592	74
A3	597	76
A7	604	77
A15	603	77
W7	602	79
W15	601	83
D15	600	85
W7C	596	78
C	594	70

BD = basic density; and M = initial moisture content. The replication number of samples in the treated and control boards was five.

A lower basic density of the boards soaked in sodium hydroxide solution compared to the control boards seemed to be caused by some extractives removal from the wood during soaking process. In contrast, a higher basic density of acetic acid treated boards was probably caused by the formation of acetyl groups replacing some active hydroxyl groups of wood cellulose, hemicellulose and lignin particularly in the zones near the surfaces. In water soaking, some microorganisms,

such as molds might have grown in the wood substance. Therefore, the measured mass of wood was a bit larger and so was its measured basic density.

After soaking treatments, all boards were wrapped with plastic and stored for a few days awaiting kiln drying. There was only a little moisture loss from boards during this storage time. Statistical analysis (**Table E.2** in **Appendix E**) showed that the moisture content of the boards before and after storage were not significantly different.

Table 4.2.1.1 indicates that all treated boards had a higher initial moisture content than control boards. Correspondingly, statistical analysis (**Table E.3** in **Appendix E**) showed that the initial moisture content of boards (before the drying trial) appreciably varied with treatments, particularly between C and N1, N7, N15, A1, A15, W15 and DW15 samples. In addition, the initial moisture content of N15 boards was significantly higher than that of N1and N3 boards.

The control boards had a relatively lower initial moisture content than the treated boards because all treated boards experienced wetting /soaking for certain periods, while the control boards were stored in plastic wrap for about 15 days. Therefore, a little or some moisture loss from the control boards was inevitable. The average value of initial moisture content of the control boards was 70 ± 7 %. This moisture content was still much higher than FSP. In addition, there was no visible collapse in those boards.

The initial moisture content of the treated boards tended to be higher with the longer period of soaking. The penetration process of chemicals into this particular wood was mainly by diffusion. Therefore, it would take a very long time (several weeks) for the solution to reach the core of such fresh (green) boards. In the short soaking treatments (maximum 15 days), the longer the soaking period, the more chemical diffused into the boards and the more solution replaced the extractives of the wood. Consequently, the moisture content of boards soaked for a longer period was higher than that of boards soaked for a short soaking period.

4.2.2 Moisture content and drying rate of boards

Drying rate evaluation was done in two parts of the kiln drying trial. The first drying period was seven days (168 hours), while the second period was 21 days (504 hours). The conditions of both drying periods were similar, 22°C DBT, 20°C WBT and 0.5 m/s air speed.

The charts in **Figure 4.2.2.1, Figure 4.2.2.2** and **Figure 4.2.2.3** show that the first drying period of all boards had steeper curves/ lines than the second drying period. This means that all boards had faster drying rates in the first period than those in the second period of drying. Statistical analysis (**Table E.4** in **Appendix E**) also revealed that the drying rates in the first period were significantly higher than those in the second period.

In the early drying, free water went out from the surface zones of boards. This drying was quite fast. Then the drying slowed down when the moisture content of surface fibres decreased to below FSP, because the bound water was more difficult to be released from the cell walls.

The moisture loss from the board surfaces was faster than the moisture movement from the inside to the surface of the boards. Therefore the moisture content of the fibres on board surfaces quickly dropped and became lower than that in the inner boards. The moisture movement from the inner zones to the surfaces of boards would continue as long as there was moisture gradient between the dry surface zones and the wet inner zones of the boards. The moisture content of the fibres inside the board reduced over the time of drying, which led to the reduction of drying rate.

This drying was discontinued when the average moisture content of the boards was still above 30%, because a lot of surface checks had developed in the control and treated boards except in the W7C boards.

The statistical analysis also showed that the effect of soaking treatments on drying rate was significant at 95% confident level, especially between C boards and N15,

DW15, W15, A15, and N1 boards. Moreover, N15 boards dried significantly faster than N1 boards.

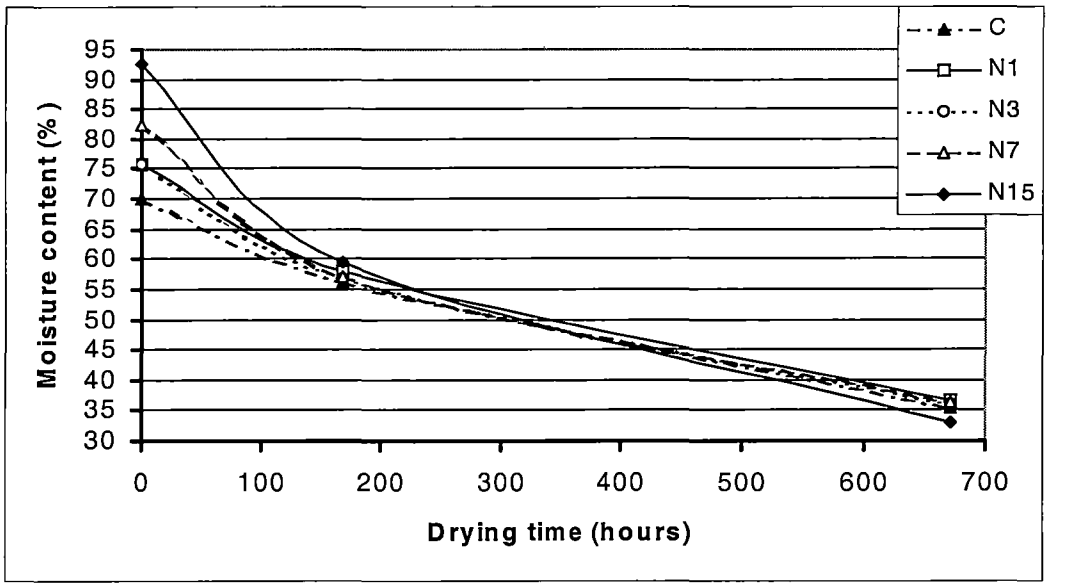


Figure 4.2.2.1 *Average moisture content of the boards treated with one per cent sodium hydroxide: C = control boards; N1 = boards soaked for one day; N3 = boards soaked for three days; N7 = boards soaked for seven days; N15 = boards soaked for 15 days.*

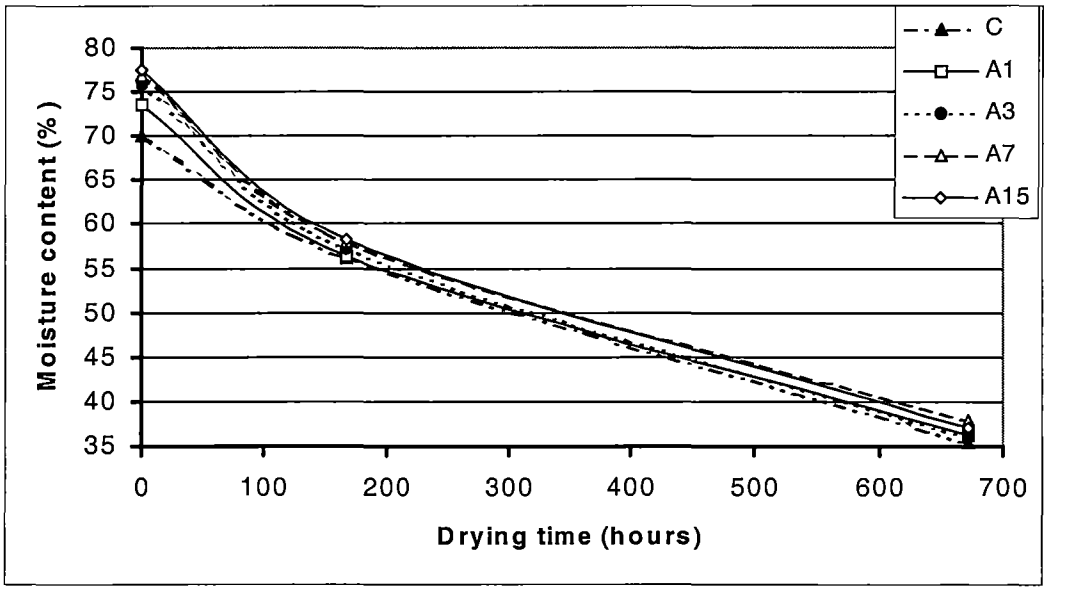


Figure 4.2.2.2 *Average moisture content of the boards soaked in four per cent acetic acid: C = control boards; A1 = boards soaked for one day; A3 = boards soaked for three days; A7 = boards soaked for seven days; A15 = boards soaked for 15 day.*

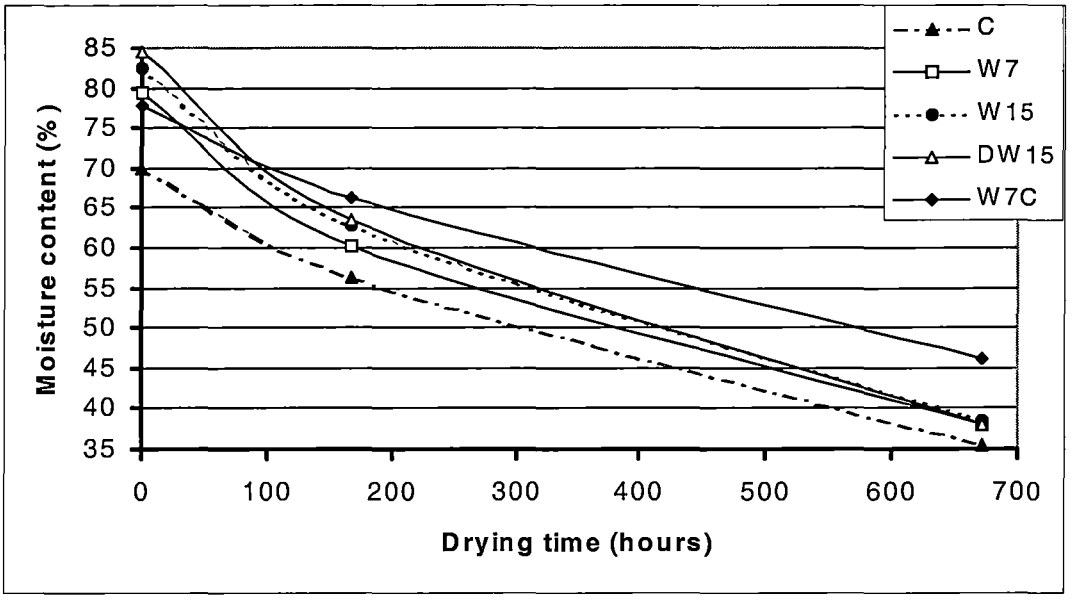


Figure 4.2.2.3 *Average moisture content of the boards soaked in water: C = control boards; W7 = boards soaked for one day; W15 = boards soaked for 15 days; DW15 = boards soaked for 15 days in circulated water; W7C = boards soaked for seven days then coated with polyvinyl acetate adhesive.*

The average drying rate of control boards in a month drying period was 0.05 %/ hour. N15 boards had the fastest drying rate in this trial. Their drying rate was 1.7 times faster than the control boards. The drying rates of DW15 and W15 were the same, about 1.3 times faster than the control boards. The drying rates of other treated boards were not much different from that of C boards.

Generally, the faster drying rate of the treated boards compared to the control boards was caused by more free water in the treated boards after soaking. The above three figures show that the initial moisture contents of the treated boards were higher than that of the control boards. In the second drying period, the drying rates of treated boards declined, possibly because their surface had dried to below FSP.

The N15 boards had higher initial moisture content and lower final moisture content than the control boards. It meant that N15 boards dried faster than the control boards. This was likely caused by the removal of some extractives due to soaking in sodium hydroxide solution for 15 days. After soaking N15 boards, the

colour of the sodium hydroxide solution became dark brown, which was darker than other solution and water used for soaking other boards.

4.2.3 Normal shrinkage and collapse of woods

Theoretically, wood shrinkage occurs when there is moisture loss below FSP. However, in certain conditions, wood dimension can contract when the moisture content is reduced above FSP due to the deformation of wood cells called collapse.

Table 4.2.3.1 showed that all treated woods had higher FSP than the control woods. There was also a tendency of higher FSP with the increase of soaking period in sodium hydroxide solution and in water. The soaking in circulated water also resulted in a slightly higher FSP than that in stagnant water soaking.

The difference of FSP was probably related to the removal of some extractives from the wood by water or chemical solution. When extractives were still in cell walls, they could physically restrain some contraction of cell walls caused by moisture loss. Without the bulking effect of extractives in cell walls, the fibres shrank more freely and earlier (in higher average moisture content of the fibres). The more extractives leached from cell walls, the less bulking effect restraining the contraction of fibre walls and the FSP tended to be higher.

Table 4.2.3.1 *FSP of wood samples after soaking treatments.*

Sample	t (%)	r (%)	Average (%)
C	27.7	31.4	29.6
N1	31.3	37.6	34.4
N3	29.3	46.6	37.9
N7	39.2	41.4	40.3
N15	48.9	81.4	65.2
A1	27.6	39.4	33.5
A3	27.8	37.1	32.4
A7	30.9	36.0	33.4
A15	34.8	56.4	45.6
W7	31.0	31.0	31.0
W15	29.3	35.6	32.4
DW15	33.7	35.6	34.7
W7C	32.5	34.3	33.4
Average (%)	32.6	41.8	37.2

t = FSP based on dimensional measurement in tangential direction; and r = FSP based on dimensional measurement in radial direction. Other symbols represent

treated and control boards, which have been explained in the methodology. The replication numbers of samples in the treatments and control were five.

The soaking period in acetic acid did not show a clear trend of FSP value. The formation acetyl groups in wood substances (cellulose and hemicellulose) possibly affected it.

The statistical analysis also showed that FSP obtained from radial measurements was significantly higher than that from tangential measurements. This is still not clearly understood. Considering wood ray orientation in radial direction, logically the rays could restrain or delay some radial contraction until a lower moisture content. But in contrast, the radial contraction occurred earlier or at a higher moisture content than that in the tangential direction. The formation and distribution of extractives in cell walls might affect this difference of FSP value. Possibly, the tangential walls had a higher extractive content than the radial walls, so the radial measurement resulted in a higher FSP value than that from tangential measurement.

Soaking in water and 1% sodium hydroxide tended to increase normal shrinkage because some extractives were removed from the wood. After these treatments, collapse seemed to increase as well. But the significant increase of collapse occurred only after 15 days soaking in sodium hydroxide solution (see **Table E.5, Table E.6**, **Table E.7** and **Table E.8** in **Appendix E**). Some particular lignin could be dissolved by this long period of soaking in 1% NaOH solution. Lignin is encrusting material for wood cells. It cements, anchors and stiffens the cellulose of fibres. Therefore, when some lignin is dissolved, the fibres' strength is reduced and they become more prone to collapse.

The chart in **Figure 4.2.3.1, Figure 4.2.3.2** and **Figure 4.2.3.3** indicates that tangential shrinkage and collapse seemed to increase with the increase of soaking period in sodium hydroxide, although it was statistically insignificant.

The effects of soaking in 4% acetic acid solution on collapse and normal shrinkage were not significant at 95% confidence limit. A slight reduction in normal shrinkage occurred after one and three days soaking in acetic acid, but after seven

and 15 days soaking, the normal shrinkage of wood were a bit more than that of the control samples. Moreover, there was a small increase of collapse after the wood soaked in acetic acid.

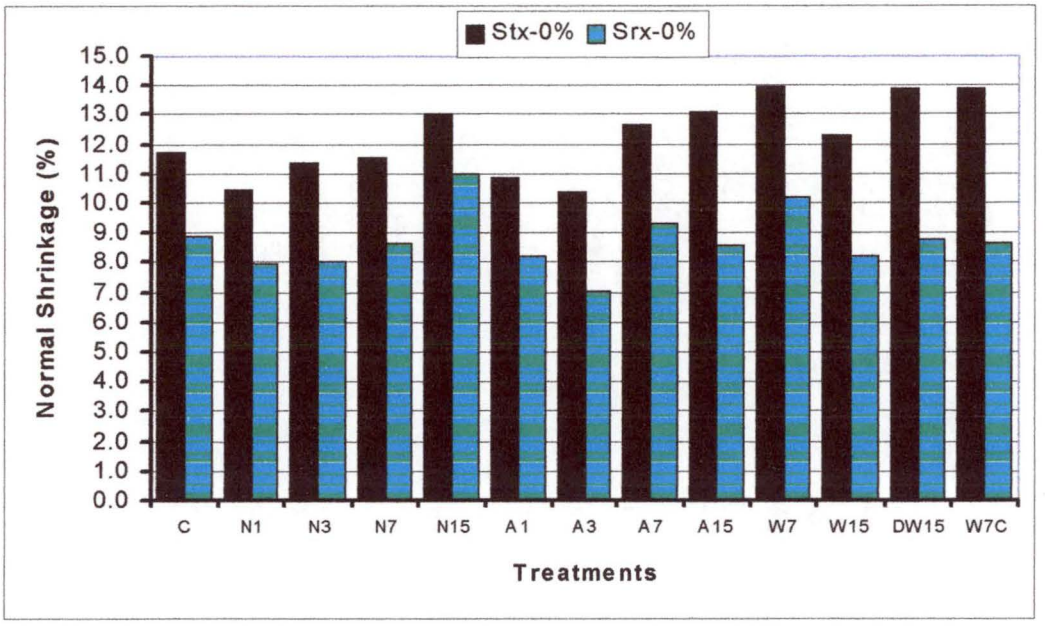


Figure 4.2.3.1 *Normal shrinkage in tangential and radial direction of slices from green condition to oven dry condition: Stx = normal shrinkage in tangential direction; Srx = normal shrinkage in radial direction.*

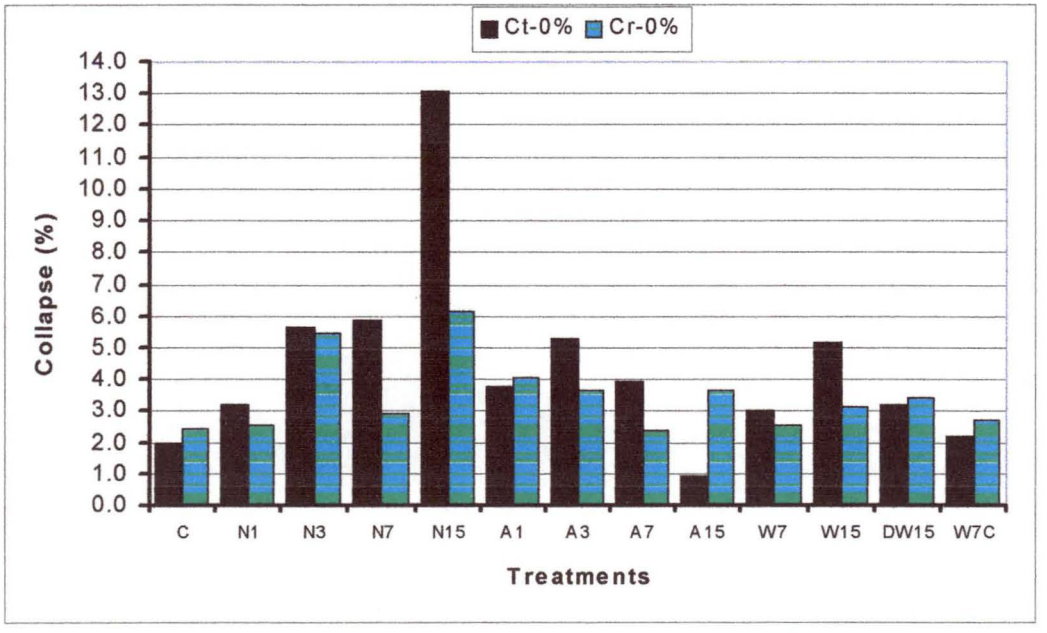


Figure 4.2.3.2 *Tangential and radial collapse of slices from green condition to oven dry condition: Ct = tangential collapse; Cr = radial collapse.*

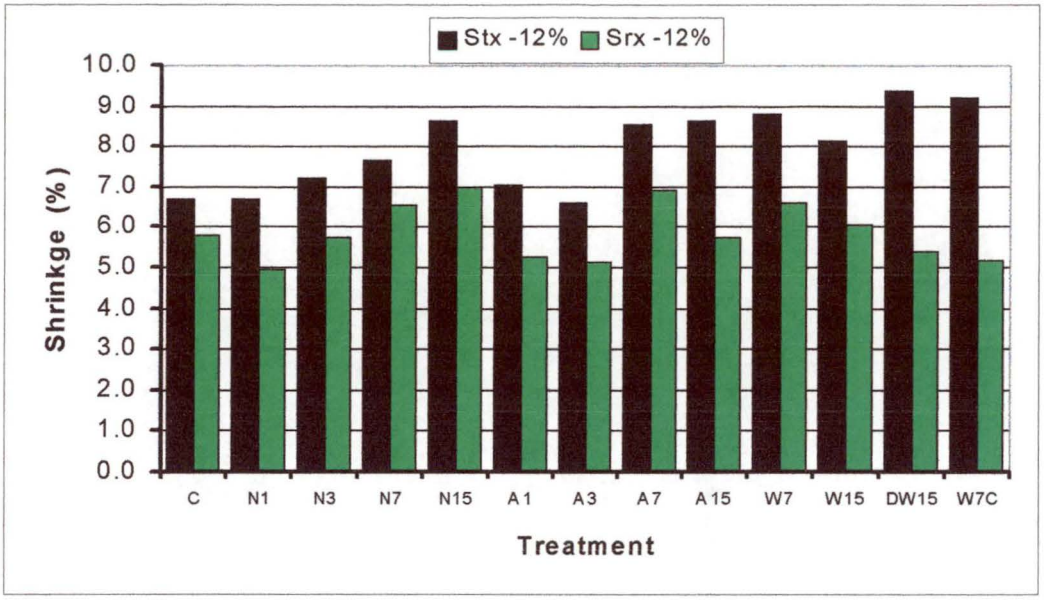


Figure 4.2.3.3 *Normal shrinkage in tangential and radial direction of slices from green condition to 12% moisture content: Stx = normal shrinkage in tangential direction; Srx = normal shrinkage in radial direction.*

The shrinkage reduction of samples, which occurred after one and three days soaking in acetic acid, was less than expected. These treatments possibly did not result in a complete substitution reaction in the hydroxyl groups of wood polymers (cellulose, hemicellulose and lignin). The slight shrinkage reduction after these treatments may also be caused by the cross-link between hydroxyl groups of adjacent polymers in wood that slightly reduced the places of water in cell wood. However in longer soaking periods (seven and 15 days) in acetic acid some degradation seemed to occur in wood cellulose.

Normal shrinkage in tangential direction of all samples was more than that in radial direction, whereas tangential collapse was not significantly different from radial collapse. The interaction between early wood and late wood affected this shrinkage difference in tangential and radial directions as explained by Pentoney (1953 in Walker, 1993c). Late wood shrank more than early wood because of the higher density of late wood. In tangential direction the total shrinkage was dominated by the high shrinkage of latewood. The high shrinkage of late wood was slightly restrained due to less shrinkage of early wood, while the early wood was forced to shrink more. In the radial direction, both late wood and early wood could shrink

independently. So the total radial shrinkage was the mean shrinkage of both the late wood and early wood.

The ray orientation also contributed to restraining radial shrinkage in wood. The longitudinal shrinkage of rays was assumed to be small due to their microfibril orientation in the longitudinal direction. This radial strain effect occurred particularly in the wood whose broad-rays occupy about 17% - 22% volume of wood tissue (Walker, 1993c).

The charts in **Figure E.1, E.2** and **E.3** in **Appendix E** show the relation between normal shrinkage and moisture content of the treated and control samples. From these charts, the normal shrinkage values of wood from fresh condition to 12% moisture content were determined by interpolation.

On average, the normal shrinkage of control samples from fresh to oven dry condition were 11.7% and 8.9% for tangential and radial direction respectively, while their collapse were 2.0% and 2.4% respectively. The shrinkage from fresh to 12% moisture content were 6.7% (tangential direction) and 5.8% (radial direction). The normal shrinkage of regrowth *E. obliqua* was not much different from that of mature *E. obliqua.* Farmer (1972) reported that *E. obliqua* shrank from green to 12% moisture content (after reconditioning) between 6.5%-10.0% in tangential direction and 4.0%-5.0% in radial direction.

4.2.4 The shrinkage of boards

After 28 days kiln drying, the boards' moisture content and shrinkage were determined and demonstarted in **Figure 4.2.4.1**. The magnitude of boards' shrinkage could not be compared, because the treated boards and the control boards did not reach the same moisture content. The chart shows that generally the shrinkage in thickness of boards (radial direction) was more that that in the width (tangential direction), except in W7C boards.

The moisture content of the boards' surfaces might quickly drop to bellow the fibre saturation point, while the inner zones were still wet. This was because the moisture

evaporation was faster than the moisture movement from the inner zones to the surfaces of the boards. This particularly occurred in the boards whose low permeability like messmate stringybark. This differential moisture content (between the surfaces and the inner zones) led to the differential shrinkage. The wet inner zones restrained some shrinkage of the surface fibres. This resulted in stresses in the boards. The boards' surfaces experienced tension stress, while the compression stress occurred in the inner zones. These drying stresses were mainly occurred in the width of the boards.

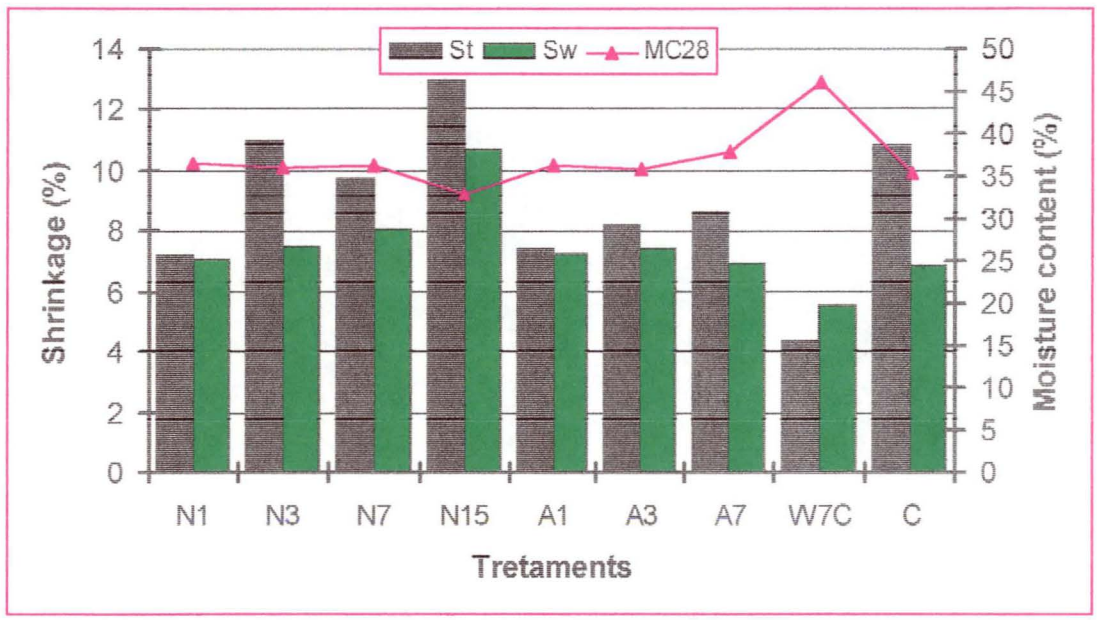


Figure 4.2.4.1 *Shrinkage and moisture content of the boards after 28 days kiln drying: St shrinkage in thickness; Sw shrinkage in width; and MC28 moisture content.*

Following the Poisson's effect theory, the restriction of shrinkage in the width led to the increase of the shrinkage in the thickness of boards. In addition, most shrinkage in the thickness was not restrained. Therefore the shrinkage in thickness was more than that in the width of boards.

If the drying trial is continued until the moisture contents of all parts of the boards were nearly the same (below FSP), the shrinkage of the width will possibly be larger than the shrinkage in the thickness, because tangential shrinkage is normally larger than radial shrinkage.

Although W7C boards and other treated and control boards were cut from the same long boards, W7C boards had a different shrinkage property from the others. W7C boards had more shrinkage in their width than in their thickness. The moisture content of the surfaces of W7C boards was maintained relatively higher compared to that of the other boards, because the coating material slowed down the moisture evaporation from the boards' surfaces. Therefore, the moisture gradients and drying stresses in W7C boards were less than that in other boards. As a consequence, shrinkage phenomena in W7C boards were relatively normal, where tangential shrinkage was more than radial shrinkage.

Figure 4.2.4.1 also shows that the shrinkage difference (between high shrinkage in thickness and low shrinkage in width) was less in the treated boards than that in control boards. This indicated that drying stresses occurring in the treated boards was less than that in the control boards. This might be caused by the removal of some extractives by water or chemical solutions in the treated boards, which led to an increase of moisture movement from the inside to the surface of the boards. As a result, the moisture gradient and drying stresses in soaked boards could be less than those in the control boards.

4.2.5 Collapse and checks in boards

Table 4.2.5.1 demonstrates the average grading values of collapse and checks on boards with five replication samples based on the visual grading criteria in **Table 4.1.3.1**. Data of visual collapse grading was statistically processed in **Table E.9** in **Appendix E**. The results show that the edges of boards collapsed more than their surfaces. The severity of collapse seemed to be influenced by compression stress during drying. When the board surfaces started to shrink due to moisture loss, the inner zone of boards experienced tangential compression stress that was much higher than the radial compression stress. In addition, the wet fibres inside the boards had less mechanical strength than the dry fibres. Therefore, the occurrence of collapse in the tangential direction (on the edges of boards) was more than that in the radial direction (on the surfaces of boards). In addition, the ray cells may have resisted board collapse in radial direction (thickness).

The soaking treatments generally resulted in a slight increase of collapse compared to the control boards. However, the significant increases of collapse were found only after fifteen days soaking in sodium hydroxide and circulated water (N15 and DW15). The collapse values of these boards were about five times more than that of the control boards. In addition, the longer the soaking period in sodium hydroxide, the tangential collapse (on the edges of boards) tended to be more. This visual assessment of collapse showed an agreement with the result of collapse measurement on slices made previously.

Table 4.2.5.1 *The average grading value of collapse and checks on the boards.*

Boards	Collapse value (after 28 days drying)		Check value (after 7 days drying)	
	Surface	Edge	Surface	Edge
N1	0	0	2.6	2
N3	0.4	0.6	3.4	2.2
N7	0	1	3	2
N15	0.4	1.8	2.8	2
A1	0	1	3	2.2
A3	0.2	0.2	2.2	1.6
A7	0.4	0.6	2.2	1.8
A15	0.2	0.6	3	2
W7	0.4	0.4	2	1.6
W15	0.4	0.8	2.2	1
DW15	0.6	1.4	2.2	1.8
W7C	0	0.6	0	0.4
C	0	0	2	1

Soaking treatments considerably affected check formation on boards. A significant difference of checking occurred between C and W7C, N1, N3, N7, N15 and A15. This is shown by statistical analysis in **Table E.10** in **Appendix E**. The average check values of the control boards were five times more than that of W7C boards.

On the other hand, the average check values of N1, N3, N7, N15 and A15 boards were twice as much as that of the control boards.

W7C boards had the least checking in this trial. The coating successfully reduced checking on these dried boards. Principally, surface coating with PVA maintained a relative high moisture content on the surface layers of boards, at least during several days of the initial period of drying when most checks usually occur. So the moisture gradient and drying stresses were less than in other boards.

There were more checks on the boards soaked in sodium hydroxide than on the control boards. This chemical might attack some lignin in middle lamella and in primary cell walls. The middle lamella has an important role in the bond between wood cells. The highest proportion of any substance in these middle lamella and primary cell wall is lignin. So, as the consequence of this chemical deterioration, the bond between fibres became weak and prone to fibre separation (checking).

Soaking in 4% acetic acid tended to increase surface checking. The significant increase of checking was found on the boards after 15 days soaking in the acetic acid solution. In that period of soaking, the acetic acid possibly degraded polysaccharide, particularly hemicellulose in the middle lamella and primary wall of wood cells. This caused the bond between fibres to weaken. Therefore, the wood had less strength to withstand the surface tensile stress, which occurred in the beginning of drying. In other words, the wood became more prone to surface checking compared to untreated boards.

There was a slight reduction in checking after 15 days soaking in water. But it was not statistically significant. Probably the amount of extractives removed from the wood was too small. Therefore the moisture gradient and drying stresses in wood in the beginning of drying was still too high to allow surface checking.

4.3 Conclusion

In this four weeks drying experiment of messmate stringybark back sawn boards, the fastest drying rate was achieved by soaking treatment in 1% sodium hydroxide

solution for up to 15 days, which was almost double the drying rate of the control boards (C boards = 0.05 %/hour). However, their collapse and checks were more severe, respectively about five times and two times as much as the collapse and check of C boards.

Soaking boards in four per cent acetic acid solution for up to 15 days did not reduce shrinkage satisfactorily and caused more drying defects (collapse and checking). This pre-treatment also did not significantly improve the drying rate compared to C boards.

The drying rate of boards soaked in (stagnant or circulated) water for up to 15 days (W15 or D15) was about 1.3 times faster than that of C boards. But, these pre-treatments did not significantly affect check and collapse on boards.

PVA surface coating with preliminary water soaking for seven days (W7C treatment) considerably reduced surface checking. So, the check grading value of W7C boards was about one-fifth of that of C boards.

Chapter 5

Surface coating with polyvinyl acetate and urea formaldehyde resin

Surface coating technique has been successfully in reducing drying defects (checking) in mature Tasmanian oak (*Eucalyptus delegatensis* and *E. regnans*). Schaffner (1981) used a hand held sprayer to apply a coating material (a mix of gelatine and talcum powder). The coating material required a temperature of 50°C during spraying to maintain viscosity. This was a complicated process. In addition, after eight weeks air drying (under shelter) followed by two weeks kiln drying at 30°C and 50% relative humidity, then reconditioning for seven to ten hours and air drying again, the gross shrinkage and cupping occurred on the coated boards was more than on the control boards. However, the checking in coated boards was only 20% of that in the control boards.

Surface coating with PVA after water soaking caused a better result than chemical treatments using sodium hydroxide and acetic acid in terms of reducing surface checking. But collapse in boards was not significantly affected by this treatment (see **Chapter 4**).

In this experiment, surface coating pre-treatments with urea formaldehyde resin (UF) and PVA without preliminary water soaking were assessed in the drying of the back-sawn boards of *Eucalyptus obliqua* L'Herit. Their effects on shrinkage, collapse, checking, and drying rate were evaluated.

PVA and UF adhesives are usually used for gluing wood and plywood. However, in some countries UF resin might be not used due to the formaldehyde emission in the use. In this experiment UF resin was only used in the drying process. After drying, the coating material could be removed.

5.1 Methodology

5.1.1 Sample preparation

Five back-sawn timbers of regrowth messmate stringybark (*Eucalyptus obliqua* L'Herit) were randomly selected. Their dimensions were 30 mm wide, 113 mm thick and 2300 mm long. The moisture content and basic density of these timbers were determined using the method described in **Appendix B**.

Seven small boards (300 mm long) were cut from each timber to be used for seven different treatments (including control). The number of replication was five, so totally there were 35 boards. The codes of boards were listed in the following table.

Table 5.1.1.1 *Codes of boards.*

Code	Treatment	Code	Treatment
P1	Single coating with PVA	U1	Single coating with UF
P2	Double coating with PVA	U2	Double coating with UF
P3	Triple coating with PVA	U3	Triple coating with UF
C	Control sample (without treatment)		

All boards were end coated immediately after cutting with Selleys All Clear copolymer sealant and aluminium foil to prevent moisture evaporation from their ends. Next, the boards were wrapped in plastic and stored in a cool place to prevent moisture loss from the boards before surface coating.

5.1.2 Preliminary investigation on check formation

Two fresh back sawn boards of regrowth messmate stringybark were made. Their size was 30 mm wide, 113 mm thick and 300 mm long. Both ends of the boards were coated. Without any pre-treatment, these boards were placed in an open air. Check investigation was done several times per day for about two weeks. The data were recorded and studied.

5.1.3 Surface coating

PVA glue and UF resin used in this experiment had curing times of 45 and 20 minutes respectively. The UF resin had a AV 201 market code which indicated a highly viscous adhesive. Its viscosity was 250 to 550 cps at 25°C. The specific gravity of this glue was 1.25 to 1.30. It contained 60% to 65% urea formaldehyde polymer and 2% to 5% formaldehyde in a water solvent.

PVA adhesive (AV 101) had 35% to 65% solid content and 1.07 to 1.13 specific gravity. This adhesive contained 35% to 55% vinyl acetate polymer, a maximum of 0.1% vinyl acetate, 0% to 10% of inert extender, a maximum of 5% polyvinyl alcohol and water as a solvent.

The coating material was applied with a glue roller on the wide surfaces (tangential surfaces) of the boards before the surface moisture content dropped to below FSP. The edges of the boards were not coated because during kiln drying, the boards were stacked edge to edge in every layer. Therefore the exposure of the boards' edges (radial surface) was very minimal. Most kiln air passed across the tangential surface of the boards. So, the drying process occurred mainly in the radial direction.

Boards P2 or U2 and P3 or U3 had double and triple surface coating respectively. The second and third coatings were applied when the previous coating had been slightly dried to give an even coating spread. The boards were laid on their edges during the curing time of each coating.

The weight of the boards was measured before and after coating, while their dimensions were measured before coating to calculate the spread rate of coating. The thickness of the coating was also measured at several positions of separated board samples with a Baker travelling microscope. The following formula was used to calculate the spread rate:

$$SR = \left(\frac{(m_c - m_o)}{2 \times l \times w} \right) \times cf \qquad \textbf{(5.1.3.1)}$$

where:

SR = spread rate (kg/m^2);

m_c = the mass of board after coating (g);

m_o = the mass of board before coating (g);

l = the length of board (mm);

w = the width of board (mm); and

cf = conversion factor = 1000 $kg.m^{-2}.g^{-1}.mm^2$.

Dimensional measurements (thickness and width) of boards were done on the reference marks as shown in **Figure 4.1.3.1.**

5.1.4 Drying trial

Before loading the boards into the kiln, their initial weight and dimensions were measured. The boards were weighed on an electronic scale with 0.01 g accuracy, while their thickness and width were measured twice for each board at their reference marks with a digital calliper.

The moisture content of boards at any time during kiln drying could be determined by measuring their weight. The moisture content at the time of measurement was calculated by using **Formula 4.1.3.1** in **Chapter 4**. The shrinkage of boards could be determined at any stage of drying by measuring their dimensions and using **Formula 4.3.2.2** in **Chapter 4**.

The drying test was divided into two periods. The first drying period was seven days, using the following schedule: 22°C DBT, 21°C WBT (at 0 to 72 hours drying time); 22°C DBT, 20.5°C WBT (at 72 to 120 hours drying time); then 22°C DBT, 20°C WBT (at 120 to 168 hours drying time). The air velocity was constant at 0.5 m/s. The second drying period used a constant kiln schedule at 22°C DBT, 19°C WBT and 0.5 m/s air velocity.

The assessment of moisture content, shrinkage, collapse and check were done after every drying period. Based on moisture content data, the drying rate of the boards

was also calculated by using **Formula 4.1.3.3.** Visual evaluation of collapse and checks were based on the criteria in **Table 4.1.3.1 (Chapter 4)**.

5.1.5 Data analysis

Analysis ToolPak in the Microsoft Excel program was used for the data processing. The significance of the effect of surface coating treatments on wood drying properties was tested using analysis variance (ANOVA) and paired t-test.

5.2 Result and discussion

5.2.1 The check formation in the back sawn boards of messmate stringybark

An intensive investigation on checking on two back sawn boards of regrowth messmate stringybark was done during an air-drying trial. A lot of surface checks were detected after ± 26 hours (**Figure 5.2.1.1**). Corrugated surfaces also occurred on the surfaces of the boards. After 98 hours air drying, some fine checks closed again, while the wide checks began to narrow.

Based on data provided by the Bureau of Meteorology, the mean daily maximum temperature during this preliminary air drying trial was 14.5°C, while the mean 3 p.m. relative humidity was 62%.

As a comparison, Alexiau et al. (1990) reported that in *Eucalyptus piluraris* Sm, surface checks occurred after two or four days when strain reach about 0.2%, while stress reversal occurred at 25 to 50 days (Alexiau et al., 1990). The boards' checks might close again because of surface tensile reduction, when the middle part of the board began to shrink due to moisture content decrease below FSP (Oliver, 1991).

Checking generally occurred at opened vessel cells on the boards' surface due to machining. These open vessels could be the weak points where checking started. This supported Oliver (1991) who stated that surface checks usually start from a

weak point, such as the fibres near the vessels or the fibres around knots and gum veins. Then, the checks expand because of the stress concentration at their edges.

Moreover, Innes (1997a and 1997b) declared that an open big vessel cell like in karri (*Eucalyptus diversicolor* F. Muell) (up to 0.25 mm diameter) became a stress riser in check formation. Therefore, checking occurred at lower surface stress and strain. This checking expanded to the middle lamella separating the fibres of the wood.

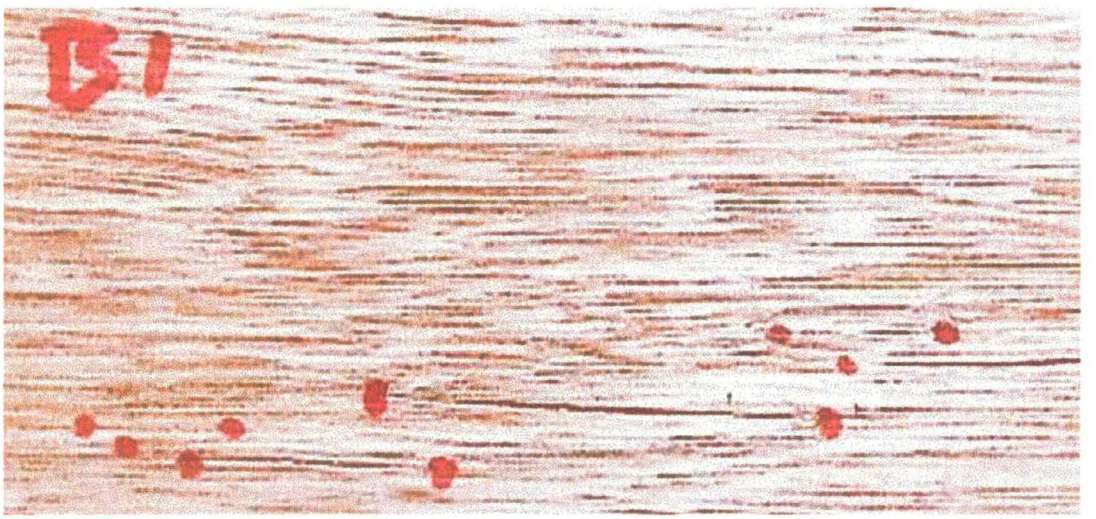


Figure 5.2.1.1 *Surface checking on a board after 26 hours air drying: Some checks were marked between red spots.*

Messmate stringybark typically has multiple or cluster vessels arranged in oblique chains relative to the ray direction. In the earlywood bands, the vessels are bigger and much closer to each other compared to those in latewood bands. The big vessel diameter of the wet wood was ± 0.26 mm. The earlywood with such vessel arrangement was relatively weaker than the latewood to withstand tension stress in tangential direction. Therefore, if the earlywood is on the surface of back-sawn boards, checking is more likely to occur.

The ray cells of messmate stringybark are relatively bulbous with a large proportion of multiseriate cells (Illic, 1997). This typical structure of ray cells might contribute to the susceptibility of checking in this wood, because the walls of ray cells are thinner, weaker and more prone to deformation and fissure than the fibre walls.

According to Wang and Youngs (1996), multiseriate rays have a key role in check development in the drying of *Quercus rubra* and *Cyclobalanopsis longinux.* The deformation of longitudinal parenchyma and the early failures in uniseriate rays, within fibre walls and between rays and adjacent fibres, promoted check development, when the failures moved to the structural elements of wood.

5.2.2 Board and coating properties

Regrowth *Eucalyptus obliqua* L'Herit used in this trial had 578 ± 20 kg/m^3 basic density and 100.0% ± 6.0% moisture content. Green hill (1948) said that oblique (*Eucalyptus oblique*), mountain ash (*Eucalyptus regnans*), and alpine ash (*Eucalyptus gigantean*) were very prone to collapse.

The application of surface coating was quite simple. Coating the two surface of one-meter long board with a manual roller took less than a minute. There would be no formaldehyde emission in the use of these boards, because the coating could be planed after kiln drying.

After coating with UF resin, most board surfaces became white. On the other hand, the boards coated with PVA had a transparent layer on their surfaces (**Figure 5.2.1.2**). The average spread rate and thickness of coating obtained in this trial is shown in **Table 5.2.2.1**. The average spread rate values of P3 and U3 seemed to be less than the values for P2 and U2 respectively. It was affected by moisture loss from wood and coating material during the curing time of the first and the second coatings. However, the thickness of the P3 coating was still thicker than the P2 coating. The thickness of coating at U1, U2 and U3 seemed to be similar, although their spread rates were different.

Table 5.2.2.1 *Average spread rate and thickness of coating material on board surfaces.*

Sample	P1	P2	P3	U1	U2	U3
SR (kg/m^2)	0.210	0.300	0.280	0.293	0.333	0.330
Thickness	0.17	0.16	0.24	0.22	0.22	0.22

SR = spread rate.

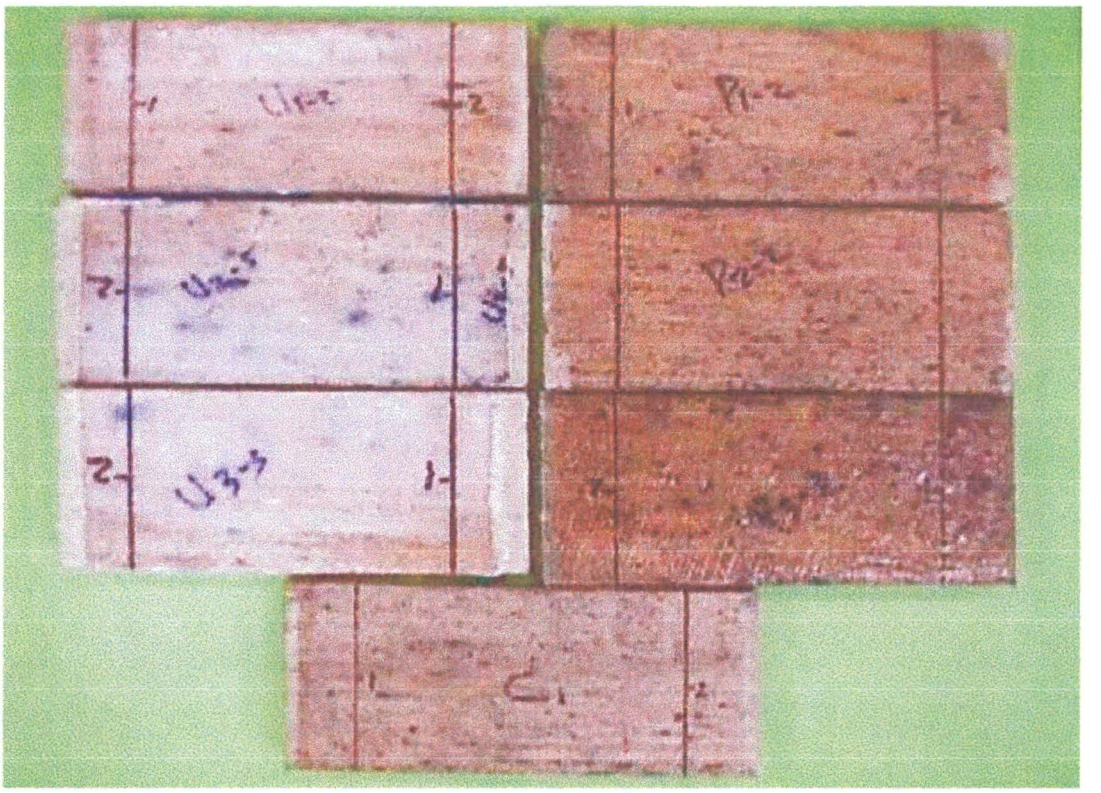


Figure 5.2.1.2 *Boards after coating treatments: U1-1, U2-5 and U3-3 = some boards coated with UF resin; P1-2, P2-2 and P3-2 = some boards coated with PVA glue; and C1 = a control board.*

5.2.3 The moisture contents and drying rates of boards

The moisture content of the boards was evaluated after seven and 14 days of kiln drying. After 14 days, the drying was discontinued because there were a lot of checks on U (1, 2, and 3) and control boards. The statistical analysis of the boards' moisture content data (**Table F.1** in **Appendix F**) revealed that coating treatments significantly affected the drying rate of boards during drying. But only boards coated with PVA had a significant difference of drying rates from that of the control boards. The drying rates of P (1, 2, and 3) boards were slower than that of U (1, 2, and 3) boards and the control boards. In addition, reapplication of PVA coating (P2 and P3) caused a slower drying rate than the single application (P1).

In this two weeks kiln drying the average drying rate of the control boards was 0.1 %/hour, which was about 1.4 times the drying rate of P1 boards and twice as fast as P2 and P3 boards. The chart in **Figure 5.2.3.1** also shows that the control boards

and U (1, 2, and 3) boards. The slopes of the curves in this chart indicate the drying rates of the boards. The steeper the slope of the curve, the faster the drying rate.

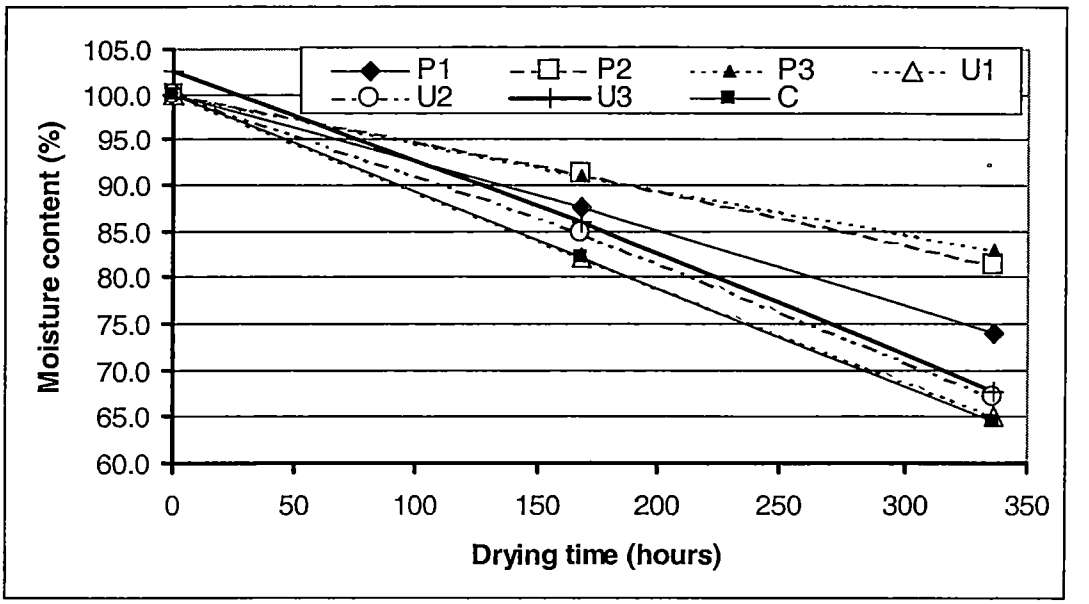


Figure 5.2.3.1 *Average moisture content of boards.*

The slow drying rates of P (1, 2, and 3) boards were caused by the reduction of moisture evaporation rate from the surface of the boards. So, the moisture contents of the surface fibres were maintained relatively higher. As a result, the rates of moisture movements from the inner zones to the surfaces of boards were also reduced.

The statistical analysis also revealed that the drying rates difference between the first and the second drying periods for all boards were not significant at 95% confidence level.

5.2.4 The shrinkage property of boards

Shrinkage values of boards in the thickness and width were calculated from the dimension data of boards before and after 14 days of kiln drying. However, the magnitude of shrinkage of the treated and control boards could not be compared, because the final moisture contents of boards were not the same. **Figure 5.2.4.1** shows the shrinkage of boards in the width and the thickness.

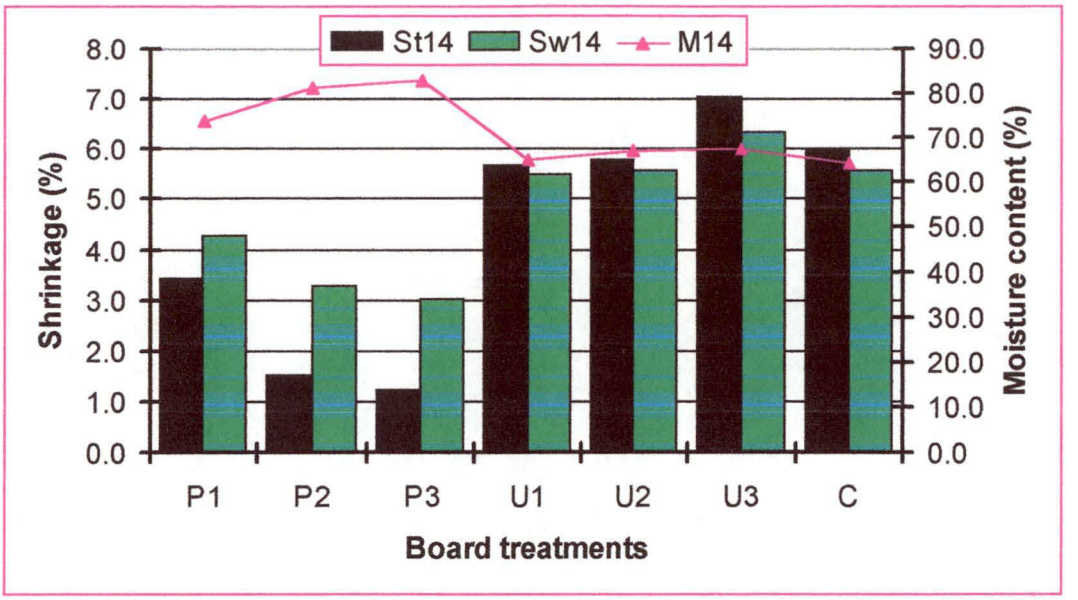


Figure 5.2.4.1 *Shrinkage and moisture content of boards after 14 days kiln drying: St14 = shrinkage in thickness; Sw14 = shrinkage in width; and M14 = moisture content.*

Although C boards, U boards and P boards were cut from the same long boards, the C boards and U boards shrank differently from P boards did. C boards and U boards shrank more in their thickness than in their width, while P boards had more width shrinkage than thickness shrinkage.

In this drying experiment all boards had average moisture contents above FSP. Therefore, most boards' cores were still wet, while their surfaces had dried to below FSP. Particularly in C and U boards, the moisture evaporation seemed to be fast, whereas the moisture movement from the inner zones to the surfaces of boards was relatively slow. Moisture gradient between surfaces and cores of boards resulted in differential shrinkage and drying stresses. Surface shrinkage (in width direction) of C and U boards was rather restrained by the still wet core zones and led to the increase of the shrinkage in their thickness that was not restrained, following the Poisson's effect theory. As the consequence, the shrinkage in the thickness of these boards was greater than that of the width. The width shrinkage would possibly increase and exceed the thickness shrinkage when all parts of the boards dried to a certain moisture content below FSP, because the tangential shrinkage is normally larger than the radial shrinkage.

P boards experienced more width shrinkage than thickness shrinkage. This indicated that PVA coating had reduced drying stresses. PVA coating was likely more effective than UF coating in maintaining high moisture content in the surface zones of boards for a period of time in the early drying. Therefore, differential shrinkage and drying stresses in P boards were relatively small. So, in P boards, tangential shrinkage was still greater than radial shrinkage, a shrinkage pattern that was similar to the shrinkage of thin samples.

5.2.5 Collapse in boards

After seven days kiln drying, the boards' collapse was visually evaluated. **Figure 5.2.5.1** shows a collapsed board that was not purely back sawn. The left side was more like quarter sawn board; the right side was more like back sawn board. More collapse occurred in the right side of the board. The averages of collapse grading values are shown in **Table 5.2.5.1**.

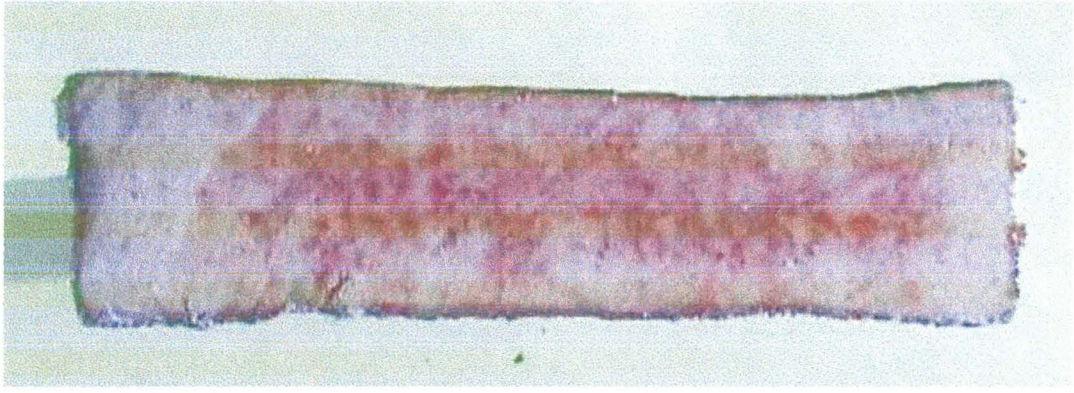


Figure 5.2.5.1 *A collapsed board.*

Statistical analysis in **Table F.2** in **Appendix F** shows that in U boards and control boards, the severity of surface collapse and edge collapse were not significantly different. In addition, there was no collapse on the surface of P boards, except on their edges. In this drying period, PVA coating was still effective in preventing surface collapse. Relatively slow moisture movement and loss in their radial direction might cause it. The effect of reapplication of coating with PVA or UF on collapse in boards was not clear.

Table 5.2.5.1 *The average grading values of collapse in the boards (5 replication) after seven days kiln drying.*

Sample	Collapse value		Sample	Collapse value	
	S	E		S	E
P1	0	0.4	U1	1	0.8
P2	0	1.2	U2	0.2	0
P3	0	0	U3	0	0.2
C	0.6	0.4			

S = collapse evaluation on board's surfaces; E = collapse evaluation on board's edges.

5.2.6 The checks of boards

Preventing checking was the major concern in these coating treatments. Checking was evaluated visually after 14 days of kiln drying. The results are shown in the following table.

Table 5.2.6.1 *The average grading values of checks occurred on the boards (5 replication).*

Sample	Check value		Sample	Check value	
	S	E		S	E
P1	0	0.8	U1	2.2	1.2
P2	0	1.4	U2	1.8	1
P3	0	1.2	U3	1	1.4
C	1.8	1.6			

S = check evaluation on board's surfaces; E = check evaluation on board's edges.

Coating treatments had a significant effect on the formation of checks on boards. **Table F.3** in **Appendix F** shows statistical analysis of the effect of coating treatments on board checking. Surface coating with PVA successfully prevented surface checking on the boards. This coating also greatly reduced checking on the boards' edges. Check grading value of P1 boards was only a quarter of the check value of control boards. However, the reapplication (double or triple) of PVA coating did not result in a further reduction of edge checking.

PVA coating maintained the moisture content of the fibres on the boards' surfaces at or higher than the FSP for a period of time at the beginning of the drying period. This supports Schaffner's (1981) findings on the coating of boards with collogen and talcum powder. Therefore the differential shrinkage and drying stresses in P boards were less than in U boards.

Surface coating with UF did not significantly reduce checking on boards. In fact, in some boards coated with UF, the checking was slightly worse than that on the control boards. Overall, checking on U boards was significantly more than that on P boards. In addition, the surface checking on U boards was slightly more than the edge checking. Likewise in the control boards, surface checking seemed to be greater than edge checking.

In the control boards and some U boards, the moisture content on the boards' surfaces was decreasing more rapidly than that in the inner zone. When the surface moisture content dropped below FSP, the fibres on the surfaces could not shrink normally because the still wet fibres in the inner zone restrained them. Then the tension stress acted in the surface zones of the boards. As a counter balance, the compression stress acted in the inner zones. Furthermore, checks occurred when the tension stress exceeded the tensile strength perpendicular to the grain.

5.3 Conclusion

Surface coating with urea formaldehyde resin (UF) did not significantly reduce drying defects (collapse and checks) on the back sawn boards of regrowth messmate stringybark. On the other hand, surface coating with polyvinyl acetate adhesive (PVA) successfully prevented surface checking, which usually occurred in the early drying. This technique also significantly reduced edge checking and collapse. Some small checks on PVA coated boards occurred only on the uncoated edges, which were only a quarter the check value of the control boards (C boards).

The drying rate of P boards in this two weeks kiln drying was about 0.7 times the average drying rate of the control boards (C boards = 0.1 %/ hour). In this trial, the

reapplication of PVA coating was not required, as it did not result in more significant improvement in the quality of the dried boards.

Chapter 6

PVA surface coating and soaking in water and urea solution

Checking can be caused by severe collapse and high drying stresses that occur in a board during drying. Therefore, preventing severe collapse and maintaining low drying stresses (below the wood strength) may prevent checking. The effect of PVA surface coating has been reported in **Chapter 4** and **Chapter 5**. In **Chapter 4**, one coating application of PVA was done after wood was soaked in water for seven days. In **Chapter 5**, three sorts of application or thicknesses of PVA coating were compared. The results of those experiments prompted another trial of PVA surface coating with a larger size and number of samples. One coating application without pre-water soaking was selected. The drying rate was not too slow and the process was relatively simple. The same wood species, *Eucalyptus obliqua* L'Herit was used in this experiment.

Another effort used to control checking was urea soaking. According to Campbell (1959), urea solution might reduce the vapour pressure at the board surfaces. Therefore, the surface zone would be maintained in a relatively moist condition and the moisture gradient would be relatively smaller than that in untreated timber for the first few days of drying. It was hoped that check prone timber might be dried successfully with the application of this technique in green condition prior to air or kiln drying.

In addition, if urea solution successfully penetrated to the core of the boards, it might cause a bulking effect that would reduce the differential shrinkage and stresses in the board during drying. Therefore, checking might be prevented or reduced.

This experiment analysed and compared some physical and drying properties of regrowth messmate stringybark (*Eucalyptus obliqua* L'Herit) back-sawn boards after pre-treatments with urea soaking and PVA surface coating.

6.1 Methodology

6.1.1 Board preparation

Forty fresh back sawn timbers were taken randomly from a pack of *Eucalyptus obliqua* L'Herit timber bought from the Clennett Timber company. Their size was 30 mm long, 113 mm and 4500 mm long. These timbers were divided into five groups for different treatments. So, there were eight replications for treatment.

A 200 mm long sample was taken from the middle of every timber for basic properties measurement. The two remaining long boards (± 2150 mm) were used as treated board and control board. After cutting, all boards were immediately end sealed with Selleys All Clear copolymer sealant and aluminium foil to prevent moisture evaporation from their ends. These boards were coded properly with a permanent marker. The codes were listed in the following table.

Table 6.1.1.1 *Codes of boards.*

Code	Treatment	Code	Treatment
P(x)	Surface coating with PVA	CP(x)	Control board for P(x)
S8W(x)	Eight weeks soaking in urea solution.	CS(x)	Control board for S8W(x)
S2W(x)	Two weeks soaking in urea solution.	CU(x)	Control board for S2W(x)
C(x)	One day soaking in urea solution followed by eight weeks close stacking (without sticker) and wrapping with heavy plastic	CC(x)	Control board for C(x)
W(x)	Eight weeks water soaking	CW(x)	Control board for W(x)

"x" = the replication number of treatment in each group (1, 2, 3, 4, 5, 6, 7 and 8).

Figure 6.1.1.1 shows an example of board coding. The boards were then wrapped in heavy plastic and placed in a cool place.

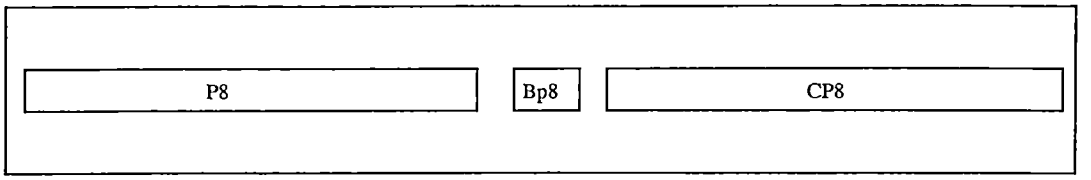


Figure 6.1.1.1 *An example of board coding: P8 = the eighth (replication) board for P treatment; Bp8 = the eighth sample for basic properties assessment; and CP8 = the eighth board for the control board of P treatment.*

6.1.2 Wood treatments

6.1.2.1 PVA coating

PVA glue was applied with a glue roller on the wide (tangential) surfaces of eight boards. The application of coating was only done once, resulting in a coating thickness of 0.18 ± 0.06 mm and the spread rate of ± 0.210 kg/m^2. The specification of this PVA glue is shown in **Chapter 5**.

After coating, the boards were laid on their edges in a cool place for about 45 minutes to let the coating cure (dry). Next, they were wrapped together in heavy plastic until the commencement of the drying trial.

6.1.2.2 Soaking in urea solution.

Two soaking tanks were made at the School of Engineering, University of Tasmania. They were made from steel plate and galvanized to prevent rusting. Their size was 0.5 m deep, 0.75 m wide and 2.2 m long. One tank was used for urea soaking; the other one was for water soaking (**Figure 6.1.2.2.1**).

Saturated urea solution was made in a tank using hot water. Urea was added into the solution until urea could not dissolve in that solution. The amount of urea in the tank was more than the need for saturation to maintain saturation condition of the solution over the whole soaking period.

Urea is also called carbonyl diamide with a linear chemical structure H_2NCONH_2. The content of urea was 98.5% urea and 1.5% biuret. Its specific gravity was 1.34

kg/m^3. This high biuret urea was not classified as a hazardous material according to the criteria of Worksafe Australia.

Figure 6.1.2.2.1 *The tanks for soaking timbers in urea solution and water.*

Eight S8W boards were soaked in the tank containing the saturated urea solution. They were not end-coated during the soaking period. Five stickers of 20 mm x 50 mm x 700 mm were placed 0.5 m apart on every layer of wood stacked in the tank. Some concrete blocks were loaded on the top of the stack to ensure that the board stack was submerged under the surface of the solution. The S8W boards were soaked in the saturated urea solution for eight weeks.

The C boards were soaked on the top of the S8W boards for only one day. Next, they were end-sealed with Selleys All Clear copolymer sealant and aluminium foil. Then they were close piled without any stickers, wrapped in plastic and placed in a cool place for eight weeks.

Two weeks before taking the S8W boards out of urea soaking, S2W boards were soaked in the same solution for two weeks. Therefore, all urea treatments could be accomplished on the same day.

6.1.3 Testing sample preparation

Before the drying trial, a 100 mm long sample was cut from the middle of every board for the assessments of physical properties (moisture content, basic density, normal shrinkage, FSP, and collapse), and for the determination of initial moisture profile and initial recoverable strain profile. The remaining two similar length (± 1000 mm) boards were end sealed again. They were also given additional codes 0 and 1 respectively. The coding system of boards is shown in **Figure 6.1.3.1**. Therefore, in total, there were 16 boards per group of boards.

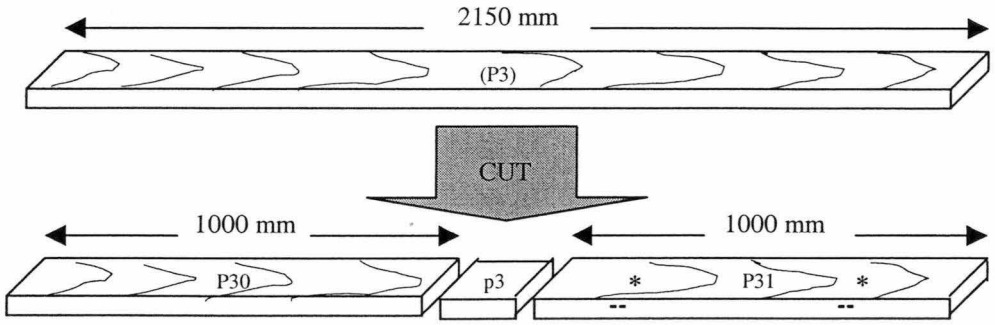


Figure 6.1.3.1 *Coding system of boards; an example on P3 board: (P3) = P3 board before cutting; P30 = the board for moisture profile and strain profile determination; p3 = sample for physical properties test; P31 = the board for the assessment of moisture content, shrinkage and drying defects;* * *= reference mark for thickness measurement; and* -- *= reference mark for width measurement.*

Three boards from 16 boards in each group were used as replication for determining the diffusion coefficient and the profile of moisture content and recoverable strain of the boards during the drying trial. The thirteen other boards were used for the assessment of moisture content, shrinkage and drying defects. The weight, dimensions and defects of these boards were recorded before, during and after the drying trial. The thickness and width measurements were done on reference marks made on the boards.

The methods of physical properties assessments are explained in **Appendix B**, while the determination methods of moisture profile, recoverable strain profile and diffusion coefficient are described in **Appendix C**. The evaluation of boards' condition (moisture content, shrinkage and drying defects) during drying used the same methods that have been explained in the methodology of **Chapter 4 (4.1.3 Drying trial)**.

The moisture profiles of boards, especially in the zones near the surfaces, were analysed using the slicing technique with microtome as described by Schaffner (1981). The diffusion coefficient of the boards were obtained by fitting the moisture profile calculated with program MP Profiles to the moisture profile measured regularly in the boards by slicing technique during the drying trial.

Recoverable strain does not account for all aspects of strain occurring in wood. In this experiment, the assessment of recoverable strain was used for figuring and comparing the general pattern of stresses developed in the treated boards and the control boards during drying. This method was a slightly modified form of the technique used by Mc Millen (1958) in the analysis of drying stresses. The profile of moisture content from the top surface to the bottom surface of the boards was also measured using this technique. Therefore, the two methods of moisture profile determination (slicing technique and Mc Millen technique) could be compared in this wood drying study.

6.1.4 Drying trial

In the kiln, all treated boards and control boards were piled edge to edge randomly in layers. Between the layers, stickers were placed 0.5 m apart. Their size was 20 mm x 50 mm x 750 mm. The boards for the assessment of moisture profile and recoverable strain profile were placed randomly in the fourth, fifth and sixth layers from the top of the stack near the kiln door.

This drying trial was divided into two drying periods. The first drying period used constant drying conditions at 22°C DBT, 20°C WBT (84% RH) and 0.5 m/s air speed until all boards had a moisture content below FSP. Then the second drying

period started with a more severe drying condition. In this drying period, DBT and WBT were changed a few times to increase the drying rate. DBT and WBT were set using KilnSched simulation of Timber Drying Kiln Controller version 1.2. This setting maintained the strain on board surfaces below 0.02 to avoid checking.

When the peak of the moisture profile in every board had dropped to below FSP, all boards were conditioned with steam, using the standard procedure in Tasmanian timber drying. The conditioning took two hours for warming up to 99°C, and then the temperature was maintained at 93°C for five hours

The moisture content, shrinkage and drying defects (check and collapse) of the boards were evaluated after the first drying period (95 days), after the second drying period (122 days) and after conditioning. The moisture content of the boards was calculated from the data of initial moisture content and the mass changes of the boards taken before and during kiln drying. An electronic scale (DIGI Counting Scale DC 80) was used for this regular weighing of the boards. This scale had 0.005 kg accuracy up to 30.000 kg capacity. The shrinkage value was found from dimensional measurements using a calliper on the thickness and the width of the board. The evaluation of drying check and collapse was based on the criteria in **Table 4.1.3.1.** The length of checking and split was also expressed as a percentage of the length of the board.

The profile of moisture content and recoverable strain were assessed several times in the first ten days of drying, then every week during the first month of drying. Furthermore, the moisture profile and recoverable strain profile were evaluated every three weeks and after conditioning.

The evaluation of internal check was done before the conditioning process, because after conditioning internal check might close again. Every board was cross cut at ± 300 mm from one of its ends. Internal checks were inspected on the cross section of the boards after cutting. The board's cupping was also assessed after conditioning. The depth of cup (concave surface of board) was measured using calliper. Then it was classified based on the criteria in **Table 4.1.3.1.**

Finally, all data were scored and analysed statistically using Analysis ToolPak in the Microsoft Excel program. The significance of the effect of PVA surface coating and urea soaking treatments on wood drying properties was tested using an analysis of variance (ANOVA) and paired t-tests.

6.2 Results and discussion

6.2.1 Physical properties of boards

Based on oven drying techniques, the average basic density of messmate stringybark timber used in this trial was 614 ± 22 kg/m^3, while the average initial moisture content was 67.6 ± 4.9 %. The average basic density and moisture content of treated and control boards are listed in **Table 6.2.1.1**.

Table 6.2.1.1 *Average basic density and moisture content of treated and control boards before kiln drying.*

Sample	BD (kg/m^3)	M (%)
P	623	66.3
CP	622	67.9
S8W	741	39.2
CS	609	66.9
S2W	689	48.6
CU	623	64.9
C	626	62.7
CC	619	65.7
W	600	80.8
CW	598	68.9

BD = basic density; and M = moisture content.

Only soaking in urea for two weeks and eight weeks had a significant effect on the basic density of boards. With these treatments, the basic density increased by 11% and 22% respectively from the control boards. This indicates that urea had diffused and increased the mass of the samples. The eight weeks soaking period resulted in a doubling of the amount of urea in the wood compared to the two weeks soaking. As a consequence, these boards became heavier than the other treated and control boards. The increase of basic density due to one-day urea soaking was not much.

In addition, there was not significant effect of PVA coating and water soaking on wood basic density.

Generally, the moisture content of boards after treatments reduced, except after soaking in water. The moisture loss from P boards seemed to occur during the curing process of PVA coating. The reduction of moisture content after urea treatment was caused by the replacement of water in wood by urea molecules. The longer urea-soaking period led to the lower moisture content of the treated boards. After eight weeks urea soaking, the moisture contents of boards became 50% of the original moisture content, while after two weeks urea soaking, the boards' moisture contents were about 75% of their moisture content before the treatment. On the other hand, the increase of moisture content in W boards after soaking was caused by the absorption of water by the boards during.

6.2.2 Drying rate of boards

This drying trial began with a quite broad range of initial moisture contents (39.2 % - 80.8 %). Messmate stringybark timber is known to be a collapse prone species. Drying defects, particularly collapse that may precipitate checks, mostly occur within a few days at the beginning of drying. Therefore, a mild kiln condition was used to dry the board to FSP moisture content, which was then followed by a harder kiln schedule until the boards were ready to be conditioned.

In this trial, the first drying period took ± 2280 hours or 95 days, while the second drying period took ± 648 hours or 27 days. After that, the boards were conditioned for about seven hours, including two hours initial warming up.

Figure 6.2.2.1 shows the average moisture content of the boards at different drying times. The last points between 3500 hours and 4000 hours are the moisture contents after conditioning. The curves are extended to see when they reached 12% moisture content.

The chart demonstrates that although the initial moisture content of W boards was higher than the control boards, W boards were predicted could reach 12% moisture

content about 250 hours earlier than the control boards did. This might be caused by the leaching of some extractives of W boards by water during soaking. The presence of extractives could retard moisture transport in wood during drying.

In contrast, S8W boards had the lowest initial moisture content, but they were predicted would reach 12% moisture content about 200 hours later than the control boards did. The other treated boards (S2W, C and P) were predicted could reach 12% moisture content no more than 100 hours after the control boards did.

Statistical analysis at **Table G1** in **Appendix G** also shows that only W boards dried faster than the control boards, whereas the other treated boards dried relatively slower than the control boards. In this four month kiln drying period, the average drying rate of S8W, S2W, P, C, W and control boards were 0.7 x 10^{-2} %/hour, 1.0 x 10^{-2} %/hour, 1.6 x 10^{-2} %/hour, 1.6 x 10^{-2} %/hour, 2.2 x 10^{-2} %/hour, and 1.7 x 10^{-2} %/hour respectively.

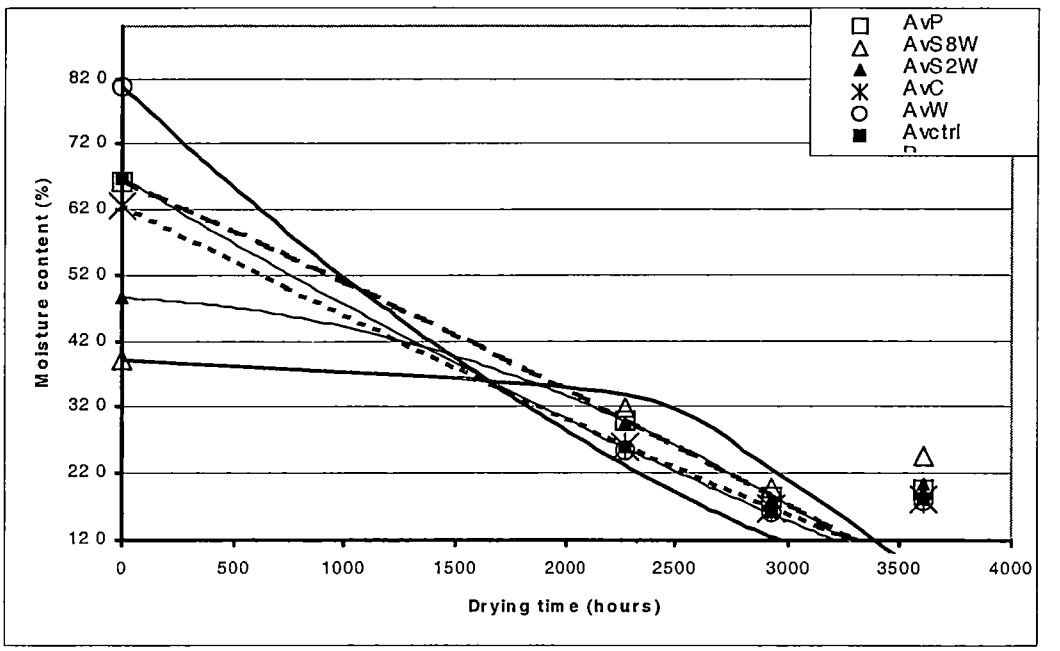


Figure 6.2.2.1 *Average moisture content of boards during kiln drying.*

The surfaces of S8W and S2W boards were maintained wet for a quite long time. This might be caused by urea molecules that penetrated into the zones near the boards' surfaces. The moisture evaporation from the surfaces of these boards seemed to be slower than that from the surface of the control boards. As a

consequence, the rate of moisture transport within the S8W and S2W boards also decreased.

Thin coat of PVA on the surfaces of P boards did not much reduce their drying rate. In addition, a slight reduction of C boards' drying rate was likely caused by the formation of a very thin layer of urea crystals on the surface of the boards.

6.2.3 Normal shrinkage and collapse of woods

Figure 6.2.3.1 and Figure 6.2.3.2 show the measured normal shrinkage and collapse in the tangential and radial directions from green to oven dry condition (0% moisture content), after drying under ambient temperature, followed by oven drying at 103 ± 2 °C. The average values of normal shrinkage of the control boards from green to oven dry condition in the tangential and radial directions were 11.3 ± 1.0 % and 8.8 ± 1.4 % respectively, while their tangential and radial collapse were 1.8 ± 2.6 % and 0.4 ± 1.1 % respectively.

Figure 6.2.3.3 demonstrates the normal shrinkage from green to 12%. These values were obtained by interpolation from measured data of shrinkage and moisture content. Collapse from green to 12% could not be calculated appropriately because the amount of data was too small. The average value of normal shrikage of the control boards from green to 12% mositure content was 6.3 ± 0.7 % and 5.2 ± 0.4 % in the tangential and radial directions respectively.

These charts also show that all the boards had greater tangential shrikage than radial shrinkage. Their tangential collapse also was generally greater than their radial collapse. This is supported by statistical analyses in **Tabel G.2** and **Table G.3** in **Appendix G.** This result agreed with the finding of Bariska (1992) that most collapsed fibres were in radial strings and only a few of them were scattered over the xylem. Fibres usually flatten in the tangential direction and can cause radial / longitudinal splits. Tangential collapsed fibres were up to five to ten times more than the radial ones. This means that collapse stresses are higher in tangential

tangential direction or fibre walls are stronger in radial direction because of reinforcement by wall pits and ray cells.

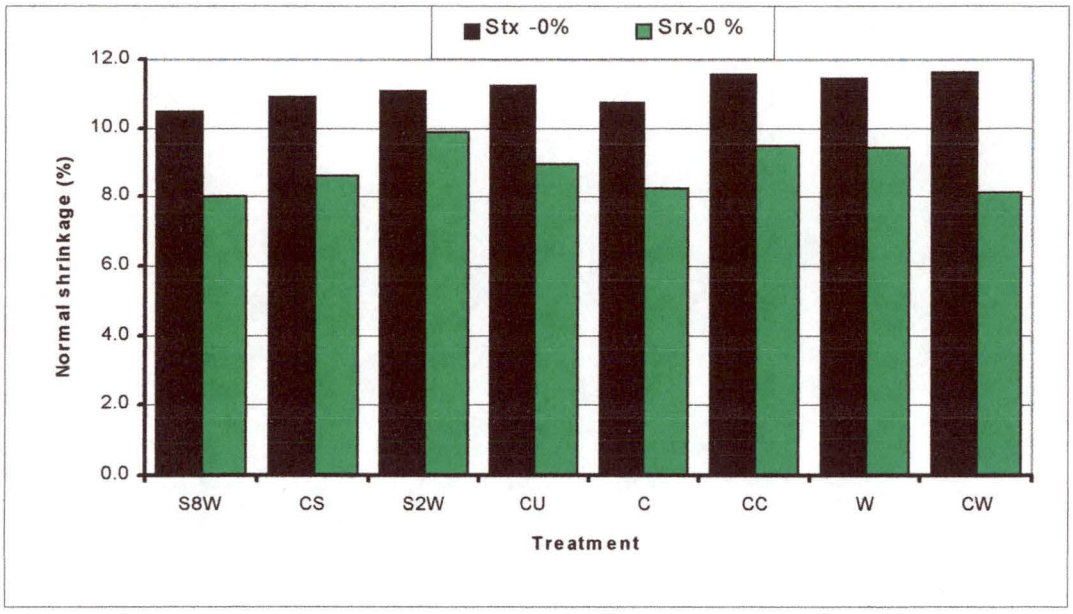


Figure 6.2.3.1 *Normal shrinkage in tangential and radial direction of slices that dried from green to oven dry condition: Srx-0% = radial shrinkage; Stx-0% = tangential shrinkage.*

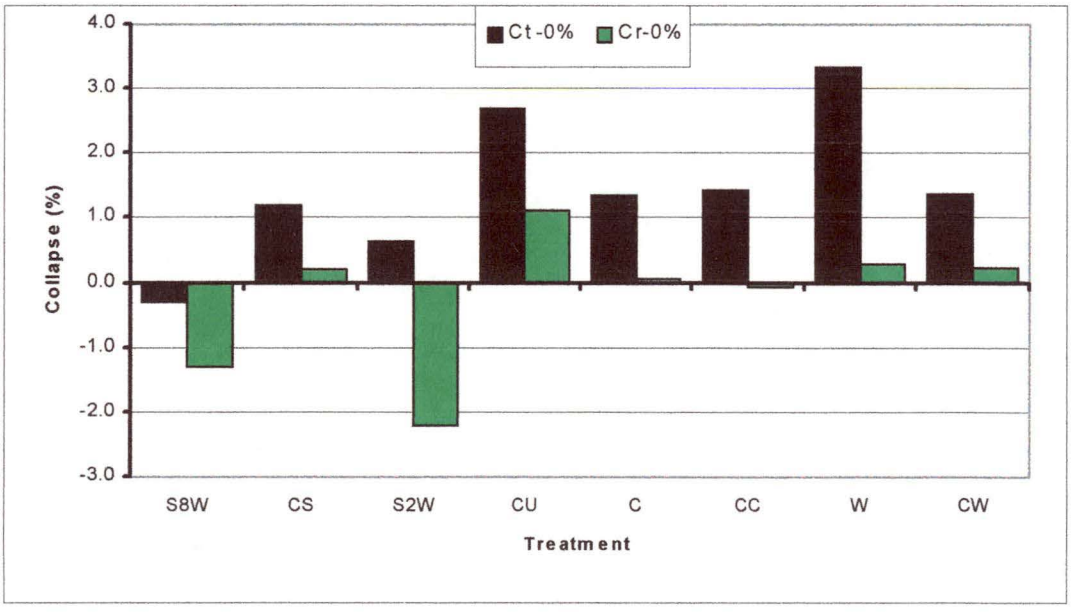


Figure 6.2.3.2 *Collapse of slices that dried from green to oven dry condition: Cr-0% = radial collapse; Ct-0% = tangential collapse.*

In addition, Innes (1995b) said that eucalypts' stiffness in radial direction was twice that in tangential direction. This seemed to be controlled by ray cells that are in radial orientation. The anatomical figure of more collapse tendency in tangential rather than in radial direction has been proved by Wilkins and Wilkes (1986).

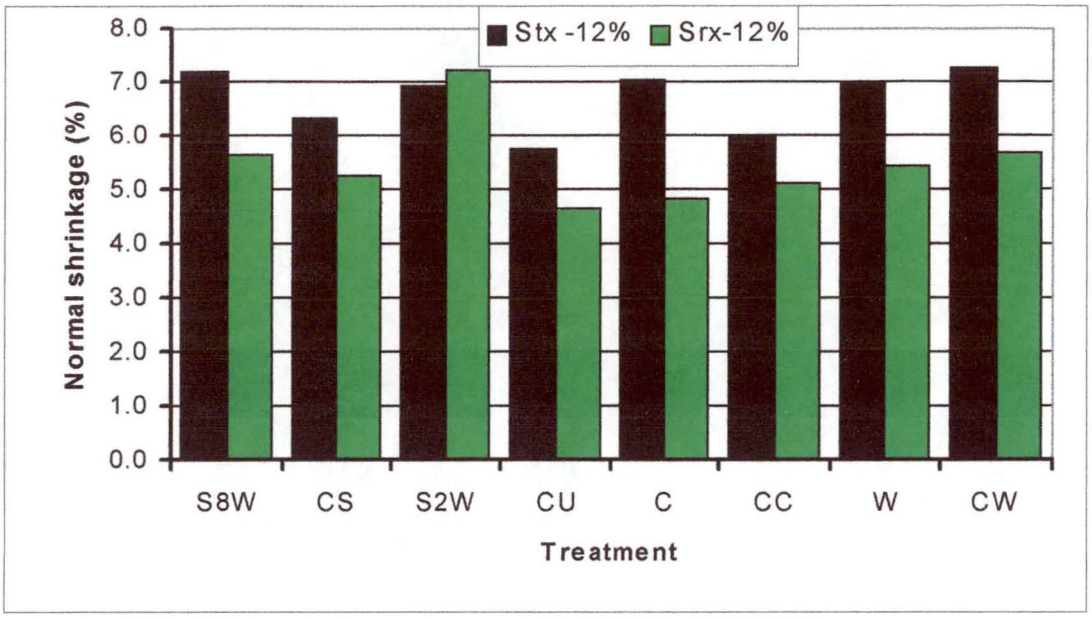


Figure 6.2.3.3 *Normal shrinkage of slices: Srx-12% = radial shrinkage from green to 12% moisture content; Stx-12% = tangential shrinkage from green to 12% moisture content.*

Only the one-day urea soaking (C treatment) resulted in significant reduction in normal shrinkage. In terms of collapse, only S8W and S2W treatments resulted in a significant reduction compared to the control boards at a 95% confidence level. The average collapse values of S8W and S2W slices were negative. This was because the unconfined shrinkage of S8W and S2W slices from their tangential and radial surfaces was less than the shrinkage of the slices from the cross section.

Figure G.1 and G.2 in **Appendix G** show clearly that unconfined shrinkage from tangential slices and radial slices of S8W and S2W were about the same or less than the normal shrinkage from axial slices in both tangential and radial directions. This meant that the bulking effect of urea was working more effectively in undamaged fibres, and prevented the collapse in the slices from tangential and radial surfaces of the boards.

The FSP of wood samples extrapolated from the normal shrinkage data are shown in **Table 6.2.3.2**. Urea soaking caused an increase in the FSP of the wood. Possibly it was affected by the hygroscopicity of urea which is more than wood. When the urea solution diffused into wood, the wood became slightly swollen. The swelling of wood above 30% moisture content due to the presence of urea will be shown in the analysis of recoverable strain later. Furthermore, when the moisture content reduced, the wood shrank slightly, although its moisture content was still above FSP of the untreated wood.

Becasue the dimension change begins from FSP, this moisture content becomes very important in wood drying. Moreover, the physical and mechanical properties of wood also change when the moisture content drops below FSP.

Table 6.2.3.2 *The Fibre saturation point (FSP) of treated and control woods.*

Sample	t (%)	r (%)	Av (%)	Sample	t (%)	r (%)	Av (%)
S8W	32.5	33.9	33.2	CS	26.6	30.8	28.7
S2W	35.9	37.1	36.5	CU	26.4	32.5	29.5
C	41.6	38.0	39.8	CC	26.9	27.6	27.2
W	27.0	29.9	28.4	CW	29.9	35.8	32.9

t = FSP calculated from tangential shrinkage; and r = FSP calculated from radial shrinkage.

6.2.4 The shrinkage of boards

Dimensional change occurring on boards must be different from the normal shrinkage taken from thin cross section slices. The shrinkage of boards is affected by many factors, such as collapse, drying conditions and board dimension. This data is important because shrinkage can degrade the quality of dried wood.

Shrinkage data was calculated from the dimensional data of the boards that was taken before, during and after kiln drying. The width and thickness of the boards represented the tangential and radial shrinkage respectively of back sawn boards used in this trial. In **Figure 6.2.4.1** and **Figure 6.2.4.2**, the boards' shrinkage from green to moisture content between 25% and 30% (95 days kiln drying) and the

shrinkage from green to moisture content between 15% and 20% (122 days kiln drying) are shown.

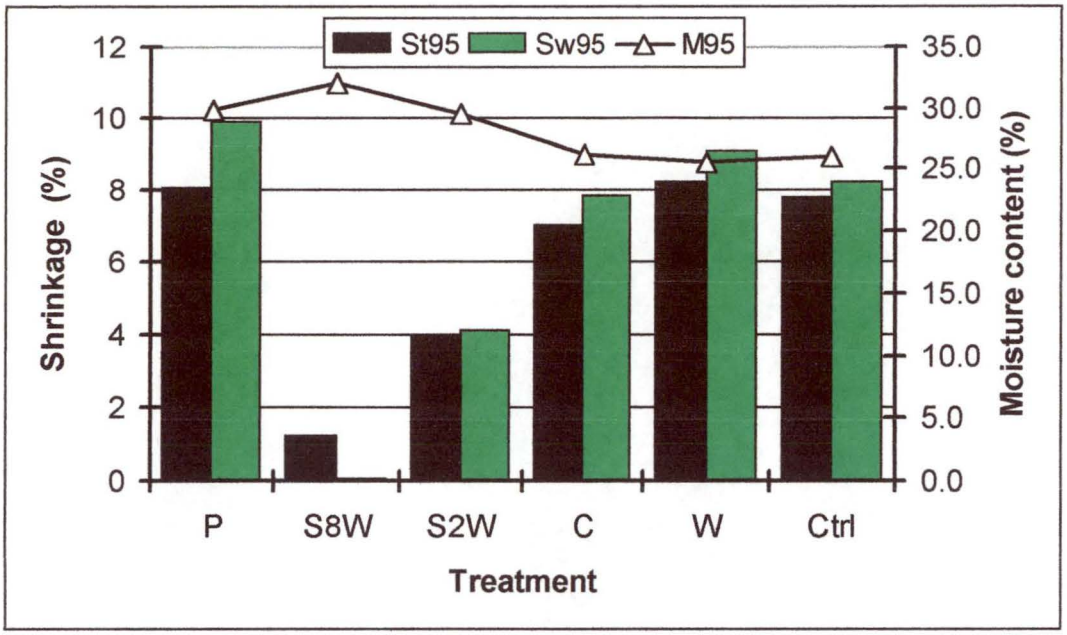


Figure 6.2.4.1 *Shrinkage and moisture content of boards after 95 days kiln drying: St95 = shrinkage in thickness; Sw95 = shrinkage in width; and M95 = moisture content.*

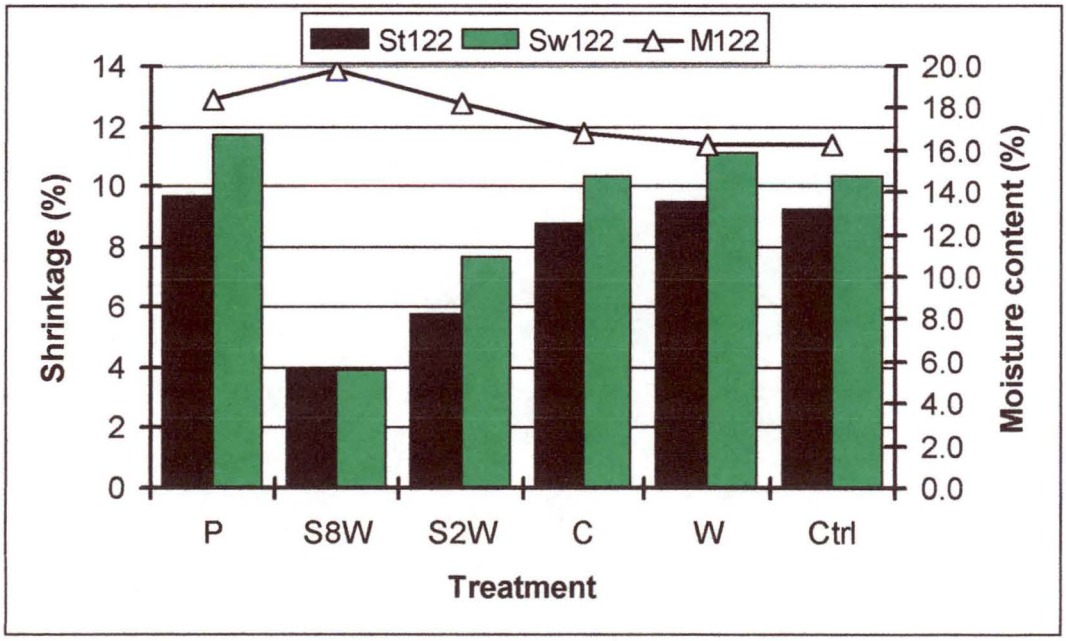


Figure 6.2.4.2 *Shrinkage and moisture content of boards after 122 days kiln drying: St122 = shrinkage in thickness; Sw122 = shrinkage in width; M122 = moisture content.*

Statistical analysis (**Table G.4** in **Appendix G**) revealed that shrinkage in the width was significantly different from the shrinkage in the thickness. On average, the wide shrinkage was larger than the thick shrinkage. There was an exception in S8W where the shrinkage in width and thickness were almost similar. These boards were also dimensionally more stable than the other treated and control boards. After 122 days drying, the control boards had 10 ± 2 % and 9 ± 3 % for shrinkage in width (tangential) and thickness (radial) respectively. This follows the general trend of shrinkage, that tangential shrinkage is usually greater than radial shrinkage, as explained in **Chapter 4**.

Compared to the normal shrinkage, the tangential shrinkage of the control boards was less than the tangential-normal shrinkage (11.3 ± 1.0 %), while the radial shrinkage of the boards was more than the radial-normal shrinkage (8.8 ± 1.4 %). This was because the drying stresses in the width (tangential direction) of the boards were greater than in the thickness (radial direction). The wet fibres in the inner region of the boards restrained some of the high normal shrinkage of surface fibres in the tangential direction. Poisson's Effect causes a contraction at right angles, particularly in the radial direction. Therefore, in control boards, the radial shrinkage was larger than their radial-normal shrinkage.

Among the treatments, only soaking in urea for eight weeks (S8W) and two weeks (S2W) had significant effects on the boards' shrinkage. The tangential and radial shrinkages of S8W boards were less than 50% of the shrinkages in the control boards, while the tangential and radial shrinkages of S2W boards were less than 80% of the shrinkages in the control boards. This was caused by the bulking effect of urea restraining some shrinkage of the boards. Furthermore these boards had a slightly higher moisture content than the other boards because of the slow drying rate.

After conditioning, the boards swelled slightly or the shrinkage reduced due to a small moisture increase in the boards. On average, the moisture content of the boards increased by 2%, whereas the shrinkage decreased by 3% to 5% after conditioning.

6.2.5 Collapse in boards

Collapse usually occurs when timber dries above FSP. Conditioning at the end stage of drying can relieve collapse. But severe collapse at the beginning of drying may cause checking. Based on visual assessment, boards' collapse was graded. The average grading values of collapse of the boards are revealed in **Table 6.2.5.1.**

Statistical analysis on collapse of the boards after 122 days drying (see **Table G.5** in **Appendix G**) revealed that more collapse occurred on the edges of the boards than on the surface, except in S8W boards where edge (tangential) collapse was very rare. In addition, only eight weeks soaking in urea (S8W boards) resulted in significantly less collapse compared to the control boards. The reduction of collapse by water soaking was not significant. PVA coating significantly reduced collapse on the boards' surface (radial collapse), but the reduction of the edge collapse was not significant at a 95% confidence limit. On average, 25% of the control boards were free of collapse. The percentage of collapse free board in S8W and W boards were 44%, in P and S2W boards were 31% and in C boards was 19%.

Table 6.2.5.1 *The average grading values of collapse on the boards (16 replication boards per group of treatment or control).*

Treated board	Collapse value		Matched	Collapse value	
	Surfaces	Edges		Surfaces	Edges
P	0.3	0.6	CP	0.6	0.7
S8W	0.6	0.6	CS	0.9	0.9
S2W	0.4	0.7	CU	0.3	0.6
C	0.5	1.1	CC	0.7	0.9
W	0.3	0.6	CW	0.6	0.6

After conditioning, collapse free boards of control, P, S8W, S2W, C, and W boards were 99%, 88%, 88%, 94%, 75%, and 94% respectively. This meant that most collapse was relieved by conditioning.

6.2.6 Checking on boards

Checking is the separation of wood cells that is seen as cracking on the surface, edge, end, or inside of a board. Checking that extends to the opposite surface of a board is called split. Checks and splits are serious problems in timber drying, which degrade the quality of wood products. Severe checks and splits will considerably reduce the mechanical properties of wood and its market value. The check values of the boards in this experiment are exposed in the following table.

These analyses revealed that PVA coating could prevent surface check and significantly reduce edge checking. There were only two P boards with edge checking and 88% of P boards were free of checking. These tiny checks were found after 37 and 95 days of drying. After 122 days drying, the checks could not be seen.

Table 6.2.6.1 *The average grading values of checks on the boards.*

Board	Check-37		Check-95		Check 122		Check length percentage
	Surface	Edge	Surface	Edge	Surface	Edge	
P	0	0.1	0	0.1	0	0	4
CP	1.6	0	1	0	1.6	0.2	29
S8W	0	0	1.1	0	2.3	0.2	57
CS	1.1	0	0.9	0	1.3	0	22
S2W	0.8	0.1	0.9	0	1.8	0.4	31
CU	0.9	0	1.1	0	1.5	0	29
C	0.5	0	0.8	0	1.2	0.1	10
CC	1.3	0	1.1	0	1.6	0	22
W	1.3	0	0.9	0	1.3	0	21
CW	1.3	0	1.3	0	1.5	0	25

Broadly, checking on the boards' surfaces was more than on the boards' edges, except in P boards that had no surface checking (see **Table G.6**, **Table G.7** and **Table G.8** in **Appendix G**).

In the first 37 days of drying, there was no checking on S8W boards. After 95 days drying, checking on S8W boards was as severe as on the control boards. After the application of the harder drying condition (evaluated after 122 days drying), checking on S8W boards was more pronounced than on the control boards.

W boards had significantly less checking than the control boards after 95 days drying. But after the application of more severe drying condition (examined after 122 days drying), the check reduction by water soaking was not significant. The check reduction by C treatment was not significant either. S2W boards also had more checking after this severe drying condition, compared to the control boards.

After 122 days kiln drying, 19% of the control boards were free of checks. The percentage of check-free boards in S8W and S2W was the same as the control boards. The percentage of check-free boards in W, C and P boards was 25%, 38% and 100% (88%, if the closed edge-check was calculated) respectively.

Statistical analysis on the check percentage from the boards' length (**Table G.9** in **Appendix G**) revealed that S8W boards had more checks than the control boards. In contrast, P and C boards had significantly less checking than the control boards. In fact, the split in P boards had been apparent since before coating treatment. Moreover, the effect of two weeks urea soaking (S2W) and eight weeks water soaking (W) on checking was not significant.

After conditioning all of the control boards, C and W boards had checks, while the percentage of checked boards in P, S8W and S2W boards were 69%, 69% and 92% respectively. These checks were scattered over the surface and edges of the boards, except on P boards, where fine checks were found only on their edges. As explained in **Chapter 4,** PVA coating could maintain a relatively safe moisture gradient at the surface zone of boards for a period in the early stage of drying when checking usually initiates.

In this trial, there was no internal check found in any of the boards, probably because the internal tension was not high enough and did not exceed the tensile strength of the wood. This also might indicate that no large tensile set or severe case hardening occurred in the low temperature drying practiced in this experiment.

Therefore, when the inner zones of the boards dried and shrank, the restraint by the boards' surfaces was not much.

Table 6.2.6.1 The *percentage of cupping free boards in the treated and control boards.*

Treated boards	Cupping free board (%)	Matched control board	Cupping free board (%)
P	69	CP	54
S8W	69	CS	69
S2W	31	CU	54
C	77	CC	77
W	85	CW	77

Table 6.2.6.1 indicates that PVA coating and water soaking caused a slight increase of cup free boards. But, it was not statistically significant. Statistical analysis at **Table G10** in **Appendix G** concluded that there was no significant difference of cupping defect between treatments and their control. All treatments in this experiment did not prevent cupping on boards.

6.2.7 Moisture profile and recoverable strain in boards

Some charts of moisture profile and recoverable strain of boards are shown in **Figure G.3** and **Figure G.4** in **Appendix G.** The negative or positive value of recoverable strain indicates that after cutting, the specimen was released from tension or compression stress respectively. The charts of reversible strain and moisture profile were analysed. The results are shown in **Table 6.2.7.1.**

The average diffusion coefficients of the treated boards and the control boards are shown in **Table 6.2.7.2.** Untreated boards of regrowth messmate stringybark used in this experiment had less diffusion coefficient than the diffusion coefficient of mature 'Tasmanian oak' reported by Schaffner (1981), which was between 1×10^{-7} and 2×10^{-7} m^2/hour. **Table 6.2.7.2** also shows that PVA coating and urea soaking caused slower moisture diffusion in boards compared to that in their control boards.

Table 6.2.7.1 *Some critical times during kiln drying of boards obtained from two analysis.*

Sample	Rep.	Recoverable strain analysis									Moisture profile analysis		
		T-S<30%	T-MSTS	MSTS	T-MITS	MITS	T<FSP	T-MICS	MICS	T-MSCS	T-S<30%	T-HMG	T-MMG
		(hours)	(hours)	(%)	(hours)	(%)	(hours)	(hours)	(%)	(hours)	(hours)	(hours)	(hours)
P	1c	373	233	-0.28	2662	-0.15	2104	373	0.43	2104	43	≤ 233	43
	1w										373		
	2c	1519	185	-0.37	2678	-0.13	2128	803	0.47	2678	185	≤ 301	185
	2w										301		
	3c	971	397	-0.24	971	-0.26	2009	971	0.26	2009	0	≤ 164	164
	3w										164		
CP	1	564	233	-0.47	2662	-0.18	1496	994	0.47	994	136	≤ 233	136
	2	301	469	-0.37	2678	-0.18	1519	301	0.37	2678	301	≤ 185	90
	3	541	164	-0.26	2648	-0.24	2648	756	0.37	2648	164	≤ 281	164
S8W	1	1496	2662	-0.22	43	-0.23	2662	2662	0.3	*	1500	≤ 1900	43
	2	2678	2678	-0.2	90	-0.35	2678	2678	0.2	90	1520	≤ 1900	185
	3	2648	2648	-0.16	541	-0.27	2648	2648	0.45	164	1900	≤ 1900	281
CS	1	373	564	-0.36	2104	-0.13	1496	564	0.3	2104	43	≤ 233	43
	2	301	301	-0.47	1519	-0.38	1519	469	0.68	2678	90	≤ 185	90
	3	756	397	-0.43	281	-0.27	1472	971	0.46	541	164	≤ 281	164
S2W	1	1496	1496	-0.17	2104	-0.15	2104	994	0.31	*	373	≤ 780	43
	2	1519	2128	-0.36	637	-0.33	2128	1018	0.44	2128	301	≤ 301	90
	3	1472	281	-0.31	164	-0.23	2009	1472	0.48	2648	397	≤ 541	164
CU	1	3730	373	-0.46	2104	-0.18	1496	564	0.41	2104	43	≤ 234	136
	2	469	185	-0.35	2128	-0.18	1519	185	0.54	2678	185	≤ 185	90
	3	397	281	-0.63	2009	-0.27	1472	541	0.31	2009	164	≤ 281	0

Sample	Rep.	Recoverable strain analysis									Moisture profile analysis		
		T-S<30%	T-MSTS	MSTS	T-MITS	MITS	T<FSP	T-MICS	MICS	T-MSCS	T-S<30%	T-HMG	T-MMG
		(hours)	(hours)	(%)	(hours)	(%)	(hours)	(hours)	(%)	(hours)	(hours)	(hours)	(hours)
C	1	373	136	-0.2	2662	-0.1	2662	42	0.15	2662	136	≤ 234	136
	2	803	637	-0.3	2678	-0.12	1519	637	0.54	2678	185	≤ 185	90
	3	971	397	-0.26	1472	-0.22	1472	397	0.4	2009	164	≤ 281	164
CC	1	233	564	-0.18	2662	-0.2	2662	136	0.23	780	43	≤ 234	136
	2	637	469	-0.41			1519	637	0.23	1018	90	≤ 185	90
	3	756	281	-0.23	2648	-0.17	1472	756	0.34	2648	164	≤ 281	164
W	1	373	373	-0.58	2662	-0.17	2662	373	0.22	2662	234	≤ 234	136
	2	469	637	-0.37	2128	-0.17	1519	637	0.53	2128	90	≤ 185	90
	3	541	281	-0.27	2648	-0.17	2009	541	0.33	2648	164	≤ 281	164
CW	1	373	373	-0.38	2662	-0.3	2662	2662	0.46	2662	43	≤ 234	43
	2	301	301	-0.56	2678	-0.12	1519	469	0.43	1519	90	≤ 185	90
	3	397	397	-0.18	2009	-0.26	1472	397	0.44	2009	164	≤ 281	164

T-S<30% = time of the surface moisture content of board dropped to below 30%; T-MSTS = time of maximum surface recoverable tension strain; MSTS = maximum surface recoverable tension strain; T-MITS = time of maximum internal recoverable tension strain; MITS = maximum internal recoverable tension strain; T<FSP = time when the moisture content of board dropped to below FSP; T-MICS = time of maximum internal recoverable compressive strain; MICS = maximum internal recoverable compressive strain; T-MSCS = time of maximum surface recoverable compressive strain; T-HMG = time of high moisture gradient; and T-MMG = time of maximum moisture gradient.

On the other hand, water soaking resulted in relatively faster moisture diffusion in the boards.

Table 6.2.7.2 *Diffusion coefficients of boards.*

Treated Sample	Diffusion coefficient (m^2/hour)	Matched control sample	Diffusion coefficient (m^2/hour)
P	3 x 10-8	CP	5 x 10-8
S8W	3 x 10-8	CS	5 x 10-8
S2W	3 x 10-8	CU	5 x 10-8
C	4 x 10-8	CC	5 x 10-8
W	6 x 10-8	CW	5 x 10-8

Table 6.2.7.1 shows the drying times when the moisture contents on the boards' surfaces dropped below 30%. At these times, the fibres on the surface presumably began to shrink, but the inner part of the board restrained them. This resulted in drying stresses. Tensile stress occurred on the surface, while compressive stress occurred in the inner zone of the board. These drying stresses tended to increase until the moisture content in the inner region dropped to below FSP and began to shrink.

The data obtained by the slicing technique were more accurate than the data taken by McMillen's technique because in the slicing technique, moisture content was measured at every ± 1 mm thick from the board's surfaces, while McMillen's technique measured the moisture content per ± 5 mm thickness of the board. In fact, the moisture content of fibres within ± 1 mm from the surface dropped more quickly (earlier) to below 30% than the fibres in the inner region. This evidence was detected by the slicing technique, while McMillen's method did not detect this.

Based on the slicing technique data, after 43 hours drying time the surface moisture content of the control boards was below 30%. In P, W, C, S2W and S8W boards, the surface moisture content below 30% occurred after 0, 90, 136, 301, and 1500 hours of drying time respectively. In P boards, the surface moisture content was not the moisture content of wood fibres, but the moisture content of the coating material (PVA). So, the moisture content of fibres on the surface of P boards decreased to below 30% a few days later. After 164 hours drying time, a P board had a moisture content below 30% on its wood surface. In two other P boards this

occurred after more than 300 hours drying time. This meant that PVA coating delayed the development of drying stresses and prevented the surface checking in the early stage of drying.

Table 6.2.7.1 also shows the time of maximum recoverable tensile strain at the boards' surface obtained by McMillen's technique. This data might be used to explain the occurrence of surface checking on boards. In fact, the earliest that maximum recoverable tensile strain was detected in the control boards was after 164 hours drying, while the surface check had been seen since the third day of drying. Therefore the prediction of surface check by this technique was too late. Possibly the samples cut parallel to the board's surface were too thick (± 5 mm). The fibres within ± 1 mm of the board surface experienced tension stress earlier than the fibres in the inner zone.

By analysing the moisture profile from the slicing technique and comparing it with the moisture profile program in the Clever Kiln Controller, the surface check occurrence in the boards could be explained more reasonably. Surface check usually occurs when severe drying stresses exceed the tensile strength of the fibres. The severe drying stresses correlate with the high moisture gradient, particularly in the surfaces of the boards.

The time of maximum moisture gradient in the surface zones and the time of the boards' surfaces reached below 30% are shown in **Table 6.2.7.1.** These data were determined from the moisture profile chart. In many of the control boards, the maximum moisture gradient occurred in a few days early in the drying (43, 90, 136 or 164 hours drying) when the surface moisture content had been below 30%. The moisture gradient remained high for a few days after these peak points. As a consequence, high differential shrinkage occurred and tensile stress might exceed the tensile strength of fibres and caused surface checking. At these times, surface checks could be clearly seen on most of the control boards.

Maximum moisture gradient in P boards occurred when fibres on the surface were still above FSP. The wood surface reached moisture content below FSP without the moisture gradient becoming too steep. The drying stresses were relatively smaller

compared to those in the control boards. As a result, the P boards were free of surface checking.

The surface of S8W boards did not check in the early stage of drying because the moisture content on the boards' surfaces remained above FSP until 1500 hours drying. The high moisture gradient on the boards' surface occurred until about 1900 hours drying. So, surface checks might occur after the surface moisture content dropped below FSP while the moisture gradient was still high, resulting in high enough drying stresses especially on the boards' surfaces.

Similarly, with S2W boards, the surface moisture content remained above FSP until 301 hours drying, while the steep moisture gradient was still high until a few days later (± 780 hours drying). Therefore, surface check in these boards occurred later than in the control boards.

In C and W boards, one of three boards had a maximum moisture gradient when the surface moisture content was still above 30%. In the two other boards, the maximum moisture gradient occurred when the surface moisture content was less than 30%. Therefore, after 122 days kiln drying, the proportion of checked boards was significantly less in C boards compared to the control boards. The numbers of check-free boards after 122 days drying in C and W boards were also more than that in the control boards.

Internal checks could not be found in any of the treated boards and control boards. The analysis of recoverable strain revealed that the maximum internal tensile strain was much less than the maximum surface tensile strain (see **Table G.11**). On average, the maximum internal recoverable tensile strain was only 63% of the average maximum surface recoverable tension strain. This was understandable since the maximum surface tension occurred because the shrinkage on the boards' surfaces was restrained by the wet inner part that had not shrunk yet in the early drying. On the other hand, the maximum internal tension occurred because the shrinkage of fibres inside the board was restrained by the outer part, which had already shrunk and experienced tension set. Internal check might occur when there

was severe collapse in the early drying stage when the drying was too severe, causing large permanent set and case hardening on the surface region.

After conditioning, the surface checks re-opened. At this time, the recoverable strain analysis indicated tensile stress occurred on the surface of the boards.

Maximum recoverable internal compressive strain occurred when the moisture contents of the boards were still above FSP. Wet fibres usually have less compressive strength than dry fibres. Therefore, at these times, the internal compressive stress might influence the severity of collapse in the boards.

The maximum surface recoverable compressive strain occurred mostly after the boards' moisture contents fell below FSP. Therefore, the fibres on the surfaces of the boards were relatively strong enough to withstand the compressive stress. However, in S8W boards, the maximum recoverable compressive strain occurred in the early stage of drying, when their moisture content was still above FSP (at 90 and 164 hours drying time). This compressive strain was not due to the shrinkage inside the boards, but because of a slight swelling of the surface zone due to moisture absorption by the boards' surfaces, which contained urea. Urea is a hygroscopic material that binds a certain amount of water in its molecules at certain temperature and relative humidity. Urea seemed to be more hygroscopic than wood fibres. This meant that, at the same ambient temperature and relative humidity, there were more water molecules bound by urea than by wood fibres. Although the wet surface of the boards experienced maximum compression stress, the fibres did not collapse. This was possibly due to the bulking effect of urea in the fibres in this region.

6.3 Conclusion

In this four-month drying trial of messmate stringybark back sawn boards; the significant reduction of checking was only achieved by PVA surface coating (P boards). P boards had five times as many check free boards as the control boards (Ctr boards). Most tiny checks on uncoated edges of P boards closed in the end of drying, but they reopened after conditioning.

One-day urea soaking followed by eight weeks close stacking (C treatment) reduced the length of board's check, but did not affect the board's collapse. Insignificant reduction of checking resulted by water soaking for eight weeks (W treatment). The check free boards of C and W were 38% and 25%, while the check free boards of Ctr, S8W and S2W boards were the same, 19%.

The significant shrinkage reduction was achieved only by urea soaking for eight weeks and two weeks (S8W and S2W boards). Both tangential and radial shrinkages of S8W boards were less than half of the shrinkages of Ctr boards, whereas the tangential and radial shrinkages of S2W boards were less than four-fifth of the shrinkages of Ctr boards. S8W boards also had a significant less collapse than Ctr boards. The collapse free boards of S8W were almost double amount of that in Ctr boards.

The fastest drying rate in this experiment was the boards soaked in water for eight weeks (W boards), while the slowest drying rate was S8W boards. The average drying rates of W, S8W, and S2W boards were respectively 1.3 times, 0.4 times, and 0.6 times the drying rate of Ctr boards. The drying rates of other treated boards (P and C boards) were almost the same as that of Ctr boards (1.7×10^{-2} %/hour).

6.4 Further work and suggestion

Further investigation to develop an optimal kiln drying process for PVA coated boards is required, particularly to enable kiln drying in a much shorter time, for example, using high temperature drying in the end (when the moisture content of the boards below 30%) or in the whole period of kiln drying. In addition, the uses of PVA coating on different sizes of timber and on other collapse and check prone species need to be experimented.

This study also recommends a storage system with water soaking or in a log pond for fresh cut collapse prone timbers or logs to prevent severe collapse and checking, when the kiln drying or log processing is delayed.

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Appendix A

Nomenclature

AE	=	acoustic emission
BD	=	basic density
CF	=	collapse factor
CH_3COOH	=	acetic acid
CTT	=	collapse threshold temperature
DBT	=	dry bulb temperature
DIP	=	digital image processor
EMC	=	equilibrium moisture content
FSP	=	fibre saturation point
HHT	=	high humidity treatment
m	=	mass
M	=	moisture content
Mi	=	initial moisture content
ML	=	middle lamella
Mmax	=	maximum moisture content
NaOH	=	sodium hydroxide
n.d.	=	no date (publication)
P	=	percent of cavity containing water
PVA	=	polyvinyl acetate (glue)
RF/V	=	Radio frequency/ vacuum kiln
RH	=	relative humidity
SEM	=	scanning electron microscope
Sr	=	radial shrinkage
St	=	tangential shrinkage
Sv	=	volume shrinkage
S1	=	the outer layer of secondary cell wall
S2	=	the middle layer of secondary cell wall

S3 = the inner layer of secondary cell wall

UF = urea formaldehyde resin

WBT = wet bulb temperature

w/w = percent concentration of a solution based on weight substance per weight of solvent

WBD = wet bulb depression

WBT = wet bulb temperature

ρ = specific gravity

Sample codes:

N1 = samples were soaked in sodium hydroxide solution for 1 day

N3 = samples were soaked in sodium hydroxide solution for 3 days

N7 = samples were soaked in sodium hydroxide solution for 7 days

N15 = samples were soaked in sodium hydroxide solution for 15 days

A1 = samples were soaked in acetic acid solution for 1 day

A3 = samples were soaked in acetic acid solution for 3 days

A7 = samples were soaked in acetic acid solution for 7 days

A15 = samples were soaked in acetic acid solution for 15 days

W7 = samples were soaked in water for 7 days

W15 = samples were soaked in water for 15 days

D15 = samples were soaked in circulated water for 15 days

W7C = samples were soaked in water for 7 days then coated with PVA

C = control samples

Statistical terms:

SS = treatment sum of squares in analysis of variance

df = degrees of freedom

MS = mean squares = a sum of squares divided by the corresponding degrees of freedom

F value= it is obtained by dividing the treatment mean square by the error mean square

P value= probability level

F crit = F criteria to be compared with F value

ANOVA = analysis of variance is used to test the difference among population means

t stat = t value based on calculation

P (T<== t) one tail = probability level for one tail analysis

P (T<== t) two tail = probability level for two tail analysis

t critical one-tail = critical value of t in one tail analysis

t critical two tail = critical value of t in two tail analysis

Appendix B

The assessment methods of some wood physical properties

This appendix describes the assessment methods of some physical properties of wood, such as moisture content, basic density, normal shrinkage, collapse, and the fibre saturation point (FSP).

B.1 Moisture content

Water exists naturally in wood. It affects a lot of wood properties, such as physical properties, mechanical properties, working properties and wood durability. These effects are very significant, especially when the moisture content changes below FSP.

The moisture content of wood is usually expressed as a percentage of the oven-dry mass of wood material. According to Joint Standards Australia/Standards New Zealand Committee TM/3, Timber Grading (1997), wood's moisture content can be measured by several methods, such as distillation method, Karl Fischer titration method, using an electrical moisture meter (resistance type or capacitance type), and oven dry method.

The distillation and titration methods need apparatus that is more complicated than the two other methods. On the other hand, using electrical moisture meters is very quick, but is less accurate. The capacitance type does not mark the timber, while the resistance type makes some small marks on it. Electrical moisture meters are suitable for routine monitoring, particularly for moisture content between 8% and 25%. These electrical moisture meters can be installed in production units or used as hand held units.

The oven-dry method is simple and sufficiently accurate, except if the wood contains a lot of volatile material. However, it is a destructive method, because a sample needs to be cut for the test. In addition, this method takes more time than

using moisture meters. Drying samples with a ventilated or forced (draught) convection oven usually takes ± 24 hours. But according to Mills (1991), with a conventional oven, the drying is usually longer, ± 48 hours.

The temperature of oven drying should be 103 ± 2 °C. Lower than this temperature the samples may not be completely dry. At higher temperatures, the wood starts to char and its extractives evaporate.

In this experiment, only oven-dry method was used for determining moisture content.

B.1.1 Material and apparatus

1. Wood samples with 25 mm long grain, while the cross section size is the same as that of the original board (30 x 112) mm.
2. Electronic scale, Libror EB-330H, with 330.000 g capacity and 0.001 g accuracy.
3. Oven.
4. Desiccator.

B.1.2 Method

Wood samples should be free of defects. In addition, they should be cleared of loose splinters and sawdust by brushing or scraping. Then they were weighed with a scale to determine their mass.

The test samples were dried in a ventilated oven at a temperature of 103 ± 2 °C until their mass was constant (no significant change). Usually this takes 48 hours. When the samples were taken from the oven, they were immediately placed into a desiccator to cool them down and prevent them from taking moisture from the air. The weighing of dry condition should be repeated after two or five hours drying until the difference between the two final weights was less than 0.2% of the first dimension.

The oven should not be filled with any other wet materials during the drying period of the sample, because they could release moisture, raise the humidity in the oven and influence the moisture content of the previous test.

B.1.3 Calculation

The mass data of test samples was used to calculate moisture content using the following formula:

$$M = \left(\frac{m_t - m_d}{m_d} \right) \times 100 \qquad \textbf{(B.1.3.1)}$$

where:

M = the moisture content of wood sample (%);

m_t = mass of wood sample at the time of measurement (g); and

m_d = oven-dry mass of wood sample (g).

B.2 Basic density

According to Standards Association of Australia (1981), wood density is the amount of wood substance present in a piece of timber. The ratio of wood density to the density of water at a standard temperature is named specific gravity. Mostly, the density of wood is expressed as basic density or air-dry density. Basic density is used when the moisture content of wood is at or above the fibre saturation point (FSP), while the air-dry density is used when the wood is below FSP. The basic density is calculated on oven-dry mass and volume at the time of measurement. The air-dry density is determined on oven-dry mass and volume at 12% moisture content.

Basic density is a very useful indicator of wood properties. It is influenced by some factors, such as the proportion of latewood to earlywood, the thickness of cell walls, the diameter of cells and extractives content (Walker, 1993e).

Wood density has a high correlation with the mechanical properties of wood. Like other wood properties, it varies in different species, trees, and in different parts of a tree.

B.2.1 Material and apparatus

1. Wood samples with 25 mm long grain, while the cross section size is the same as that of the original board 30 mm x 112 mm.
2. Water.
3. Electronic scale (Libror EB-330H with 0.001 g accuracy at up to 330.000 g capacity and Precisa 3000 C – 6000 D with 0.01 g accuracy at up to 3000.00 g and 0.1 g accuracy between 3000.00 g and 6000.0 g capacity.
4. Electronic scale with 0.1 g accuracy.
5. Small bucket or plastic container.
6. Needles with handle.
7. Oven.
8. Desiccator.

B.2.2 Method

The volume was measured by the water displacement method. A bucket containing water was placed on an electronic scale. The wood sample was immersed into the water by using a needle. The weights before and after this immersion were obtained and used to calculate the volume of the sample. Then the wood sample was oven dried at 103 ± 2 °C until it had a constant weight, which took approximately 48 hours. When the sample was taken from the oven, it was immediately placed into a desiccator. Finally its oven dry mass was measured.

B.2.3 Calculation

The volume of the sample was calculated as follows:

$$V = \frac{W - W_o}{\rho_w} \qquad \textbf{(B.2.3.1)}$$

where:

V = the volume of sample (mm^3);

W = the weight of container and water when the sample is immersed (g);

W_o = the weight of container and water before immersion (g); and

ρ_w = water density (assumed at 0.001 g/mm^3).

Then the data of mass and volume were used in the following equation:

$$BD = \left(\frac{m_d}{V} \right) \times cf \qquad \textbf{(B.2.3.2)}$$

Where:

BD = basic density of sample (kg/m^3);

m_d = oven dry mass of sample (g);

V = the volume of sample (mm^3); and

cf = conversion factor (10^6 $kg.m^{-3}.g^{-1}.mm^3$).

B.3 Normal shrinkage, collapse and FSP

The objectives of this assessment were:

1. measuring normal shrinkage in tangential and radial directions;
2. measuring collapse in tangential and radial directions; and
3. determining the fibre saturation point (FSP).

B.3.1 Material and apparatus

1. Wood samples with 25 mm long grain, while the cross section size is 30 mm x 25 mm.
2. Permanent fine marker.
3. Wire bridle.
4. Microtome (**Figure B.3.1.1**).
5. Baker travelling microscope (**Figure B.3.1.2**).
6. Electronic scale, Libror EB-330H, with 330.000 g capacity and 0.001 g accuracy.
7. Oven.
8. Desiccator.

B.3.2 Method

A (25 mm x 30 mm x 25 mm) wood sample was cut from each fresh board at least 30 mm clear of the end. Then they were sliced with a microtome to make two cross slices, one tangential slice and one radial slice (**Figure B.3.2.1**). The thickness of slices was ± 0.7 mm. The cross slices were used for normal shrinkage measurements in tangential and radial directions. The tangential slice was used for measuring tangential shrinkage and collapse. The radial slice was used for measuring radial shrinkage and collapse. For further use, the shrinkage of slices from tangential and radial surface is also called unconfined shrinkage because this shrinkage is not restrained by drying stresses that usually occur in drying of thick samples or the boards.

The slices were held with wire bridles to prevent out of plane deformation without resisting shrinkage. Reference marks (**Figure B.3.2.2**) were made with a fine permanent pen on the slices for measuring dimensional changes with a traveling microscope. The dimension of slices reduced with the decrease of their moisture content.

Weighing and dimensional measurement of slices were done periodically every 15 minutes until they reached the equilibrium moisture content (EMC). Next, the

slices were oven dried at 103 ± 2 °C until they reached a constant weight. After that, the slices were cooled in a desiccator. Finally their weight and dimensions were measured again. The mass of the wire bridle was obtained as well.

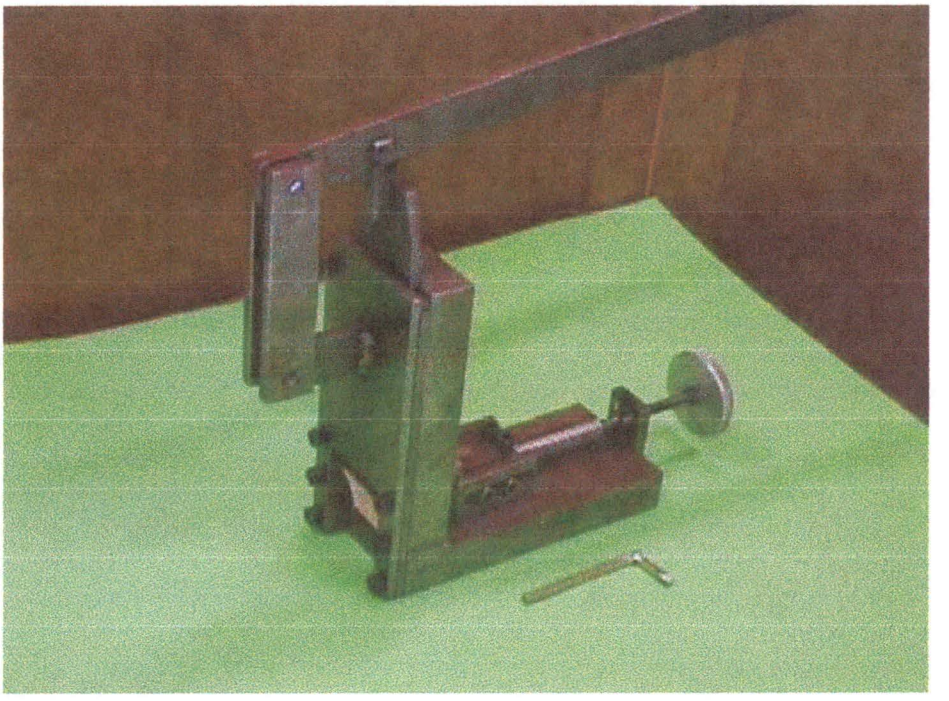


Figure B.3.1.1 *Microtome for slicing sample.*

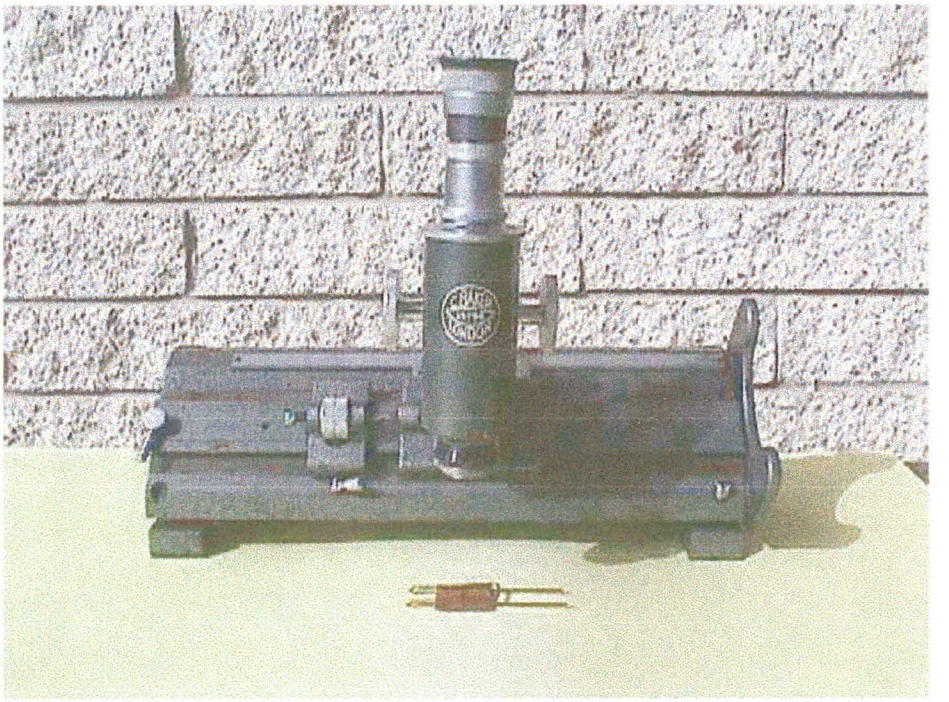


Figure B.3.1.2 *Baker travelling microscope.*

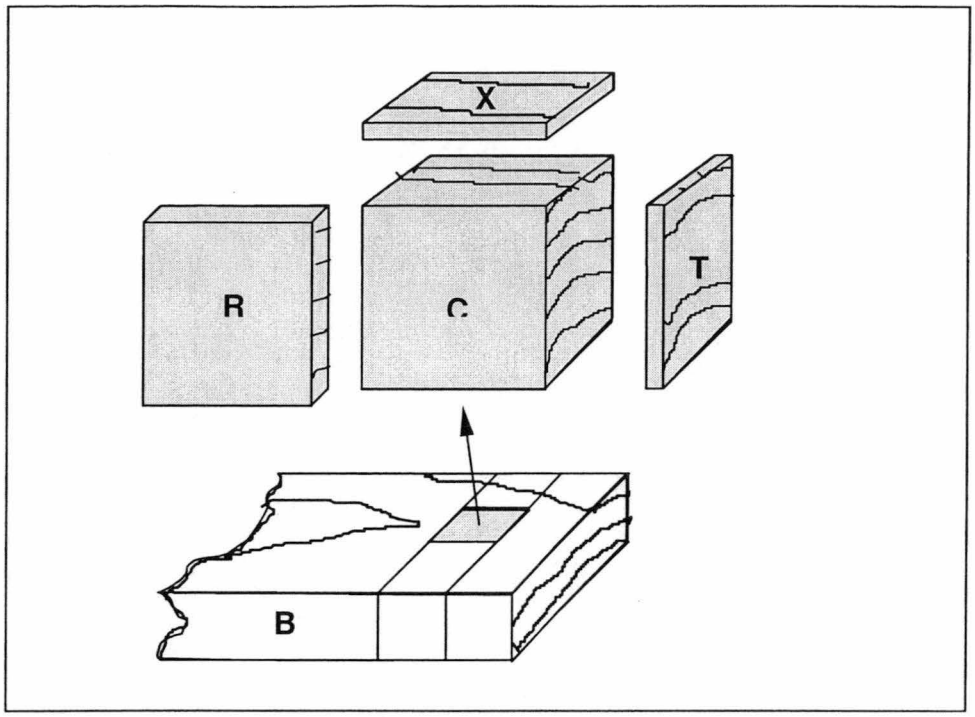


Figure B.3.2.1 *Slices preparation for shrinkage measurement: X = cross slice; R = radial slice; T = tangential slice; C = remaining block after slicing; B = green board from which the block sample was taken.*

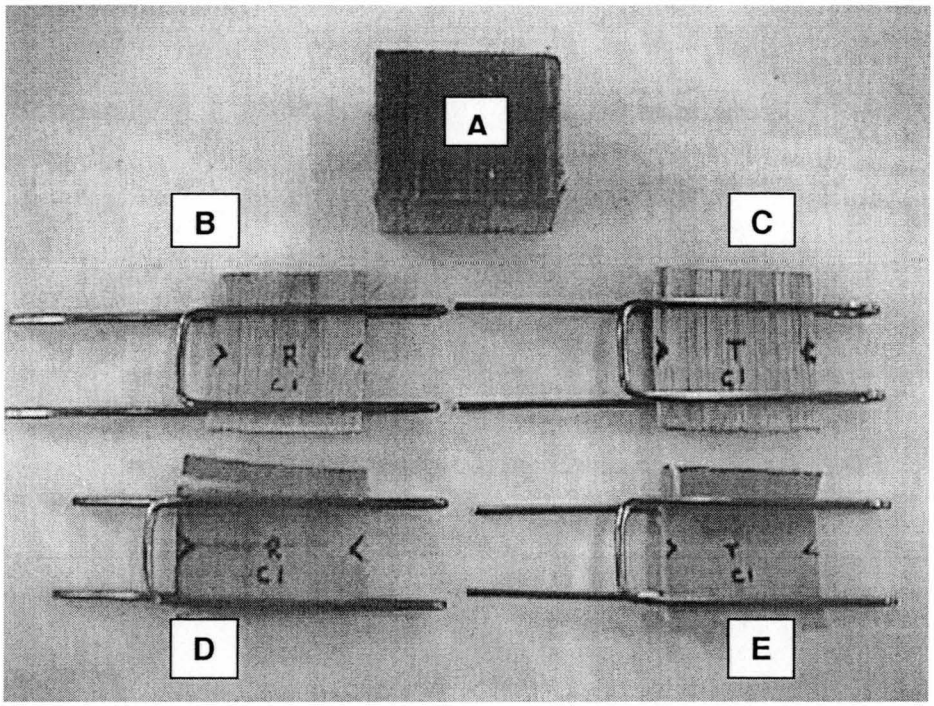


Figure B.3.2.2 *Reference marks on slices for shrinkage and collapse determination: A = block after slicing; B = slice for radial shrinkage (including collapse); C = slice for tangential shrinkage (including collapse); D = slice for normal-radial shrinkage; and E = slice for normal-tangential shrinkage.*

B.3.3 Calculation

B.3.3.1 Moisture content

Formula **B.3.1** was used to calculate the moisture contents of the slices.

B.3.3.2 Dimensional shrinkage

The data of dimensions (tangential and radial) from all thin specimens were used for calculating dimensional shrinkage by using the following equation:

$$S_t = \left(\frac{l_i - l_t}{l_i} \right) \times 100 \qquad \textbf{(B.3.3.2.1)}$$

where:

S_t = shrinkage of the specimen to a certain moisture content at the time of measurement (%);

l_i = initial length (between reference marks) of the sample (mm); and

l_t = the length (between reference marks) of the sample at the time of measurement (mm).

B.3.3.3 Normal shrinkage and collapse

The shrinkage of a slice is free of restraint from surrounding material as it is in the form of a block. So it is called unconfined shrinkage. In addition, theoretically, the cross section slice will not collapse because basically all the fibres have been damaged due to slicing. Therefore, the cross-section slice was assumed to experience only tangential and radial normal shrinkage.

On the other hand, the tangential slice and radial slice collapsed as well as shrank because most of their fibres were undamaged by slicing due to the fact that they lay in the same direction as the slicing blade. Therefore the difference of dimensional change between a cross section slice and a tangential or a radial slice showed the magnitude of tangential and radial collapse respectively.

The magnitude of contraction at 12% moisture content in both cross section slice and tangential or radial slice was determined by interpolation of all moisture content and the shrinkage data was plotted on a chart.

B.3.3.4 Fibre saturation point (FSP)

The dimensional change in a cross section slice occurs when the moisture leaves the cell walls. In other words, it begins when the moisture content decreases from the fibre saturation point (FSP). When all the data of moisture content and shrinkage from a cross section slice were plotted on a chart, the FSP was shown at the intersection point with X-axis (at 0% shrinkage). In this process, the intersection point was extrapolated from the data excluding the first data when the slice had not shrunk yet.

Appendix C

The determination methods of moisture profile and recoverable strain profile

C.1 Moisture profile and diffusion coefficient

Moisture profile is the distribution of moisture in a board. This data is very important in timber drying since the shrinkage strain and stress relate strongly with the moisture content (below FSP) of the fibres within a board. If the moisture profile in a board has a steep gradient or the moisture gradient is very large, the stresses within the board will be very high due to high differential shrinkage. When the tension stress exceeds the maximum tensile strength of the board, check will occur. Surface check usually occurs in the beginning stage of drying, while internal check due to stress reversal occurs later.

Mills (1991) determined moisture distribution by cutting a 30 mm sample from a board. Then the sample was cut into three pieces representing the case, the intermediate and the core of the board. After that, all pieces were oven dried to obtain their moisture content.

The moisture gradient within the board can be calculated using the formula from Kollman and Cote (1984):

$$MG = \frac{2(Mc - Ms)}{s} \qquad \textbf{(2.3.2.1)}$$

where:

MG = moisture gradient (%/mm);

Mc = the moisture content in the core of board (%);

Ms = the moisture content on the board's surface (%); and

s = is wood thickness (mm).

The more accurate method for moisture distribution / moisture profile is the slicing technique, particularly in determining the moisture profile near the board's surface as described by Schaffner (1981). More advanced techniques have been researched for determining moisture content and moisture distribution of a drying board by using infra-red meters (Mills, 1991).

In this experiment the moisture profiles of boards were determined with the slicing technique. The data of moisture profile of a board were used for determining the diffusion coefficient of that board using the MCProfiles program in Clever Kiln Controller.

C.1.1 Material and apparatus

1. Sample boards (30 mm thick, 112 mm wide and 100 mm or 1000 mm long).
2. Sawing machine.
3. Microtome.
4. Permanent fine marker.
5. Wire bridle.
6. Electronic scale, Libror EB-330H, with 330.000 g capacity and 0.001 g accuracy.
7. Digital caliper with 0.01 mm accuracy.
8. Oven.
9. Desiccator.

C.1.2 Method

Some sample boards were chosen randomly from a timber stack. A cube piece was cut from each of this sample board for every assessment of moisture profile. The top surfaces of all sample boards were marked. When the boards were put back into the kiln, their top surfaces were always face up. Therefore, the moisture profiles taken during drying could be compared in the same sequence from the top to the bottom of the board.

A cube piece was cut at least 30 mm clear of the end and edges of the sample board. The sample board was end coated with Selleys All Clear copolymer sealant

and aluminium foil to prevent moisture loss from the end of the board. The cube's size was 25 mm long grain, 25 mm wide and 30 mm thick. Next, the cube was sliced longitudinally on the top tangential surface with a microtome, producing four slices. The cube was then sliced on the bottom tangential surface, producing 10 slices.

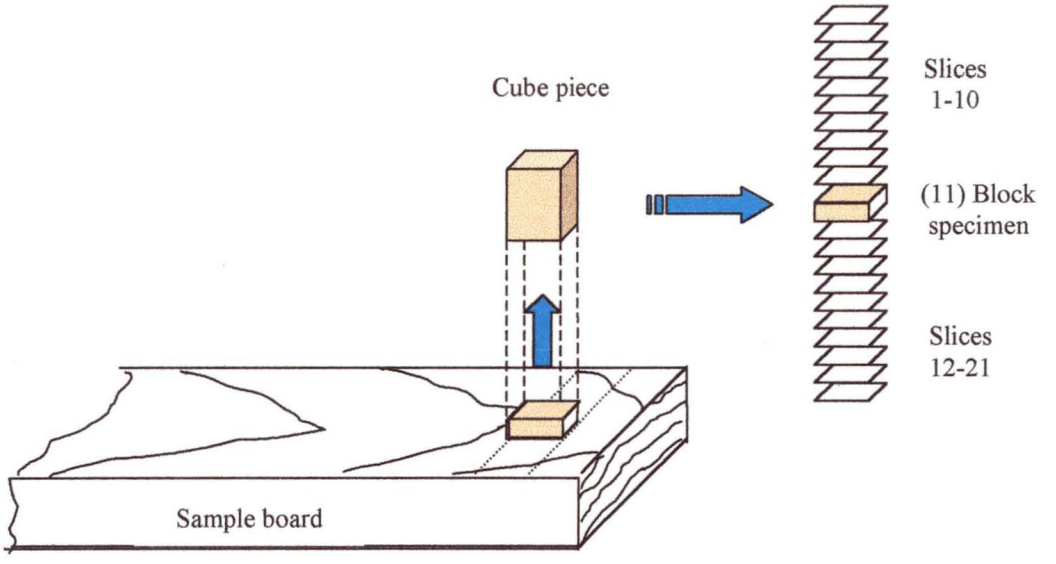


Figure C.1.2.1 *Sample cutting for the assessment of moisture profile.*

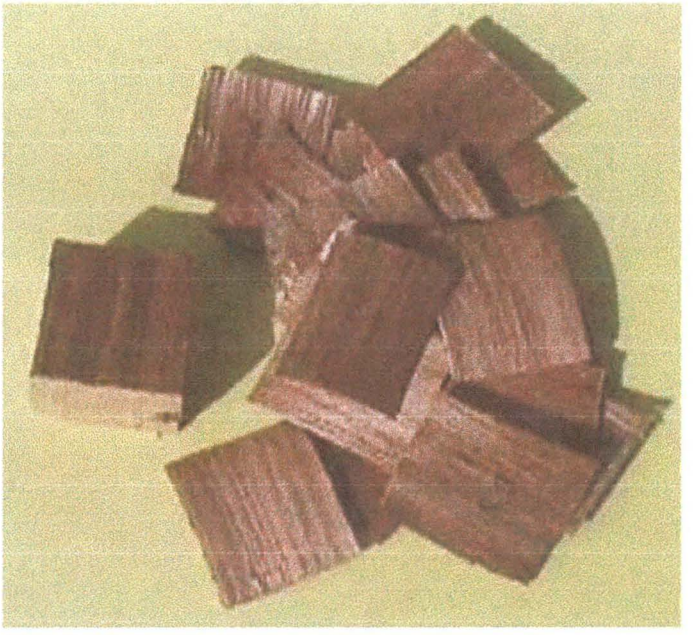


Figure C.1.2.2 *Slices and remaining section after oven drying.*

Finally, the slicing was done on the top tangential surface again, yielding six additional slices. Therefore, there were 10 slices from each tangential surface and one remained block specimen taken from a board in every moisture profile assessment. The thickness of these slices was between 0.7 mm and 1.5 mm (see **Figure C.1.2.1**).

All slices (including the block specimen) were numbered with a permanent pen, 1 to 21 indicating the slice from the top surface to the bottom surface of the cube piece. The weight and thickness of the slices and the block specimen were measured as soon as possible after each slicing. After that, they were dried in the oven at 103 ± 2 °C for about 48 hour (until their weight was constant) (see **Figure C.1.2.2**). Then they were cooled in a desiccator. Their oven dry weight was measured, so that the moisture content of all slices and the block specimen could be determined.

C.1.3 Calculation and data processing

The moisture contents of the slices and block specimen were calculated, using formula **B.1.3.1**. The data of moisture content and thickness of the specimens and the drying time from each data taking were logged into the moisture profile editor in Timber Drying Kiln Controller, University of Tasmania version 1.2. Then a moisture profile graph was developed by the MCProfiles program, showing the measured moisture profiles and the calculated moisture profiles during the drying trial.

The slope of the curve represented the gradient of moisture profile. The steepest surface moisture gradient from each graph was determined and compared to that from other graphs over the drying times. Therefore the period of high surface moisture gradient and the time of maximum surface moisture gradient could be determined.

The diffusion coefficient of a board could be determined using moisture profile data measured regularly during the drying trial. The diffusion coefficient in Properties Dialog of Clever Kiln Controller was adjusted until the moisture profile calculated by MCProfiles and measured moisture profile were well matched.

C.2. The profile of recoverable strain

The term 'recoverable strain' used here defines the portion of strain that is recovered when the stress is released. This occurs when some thin specimens are cut parallel to the wide surface of a dried board. This method followed the technique used by McMillen (1955) with modification. In this experiment, the effect of boards' treatments on the severity of recoverable strain was analysed.

C.2.1 Material and apparatus

1. Sample boards (30 mm thick, 112 mm wide and 100 mm or 1000 mm long).
2. Sawing machine.
3. Cutting blade.
4. Permanent fine marker/pen.
5. Electronic scale, Libror EB-330H, with 330.000 g capacity and 0.001 g accuracy.
6. Digital caliper with 0.01 mm accuracy.
7. Aluminium foil.
8. Oven.
9. Desiccator.

C.2.2 Method

Some sample boards were randomly selected to represent the average condition of all the boards in the stack. The top surfaces of these boards were marked. When the boards were returned to the stack, their top surface should face up again.

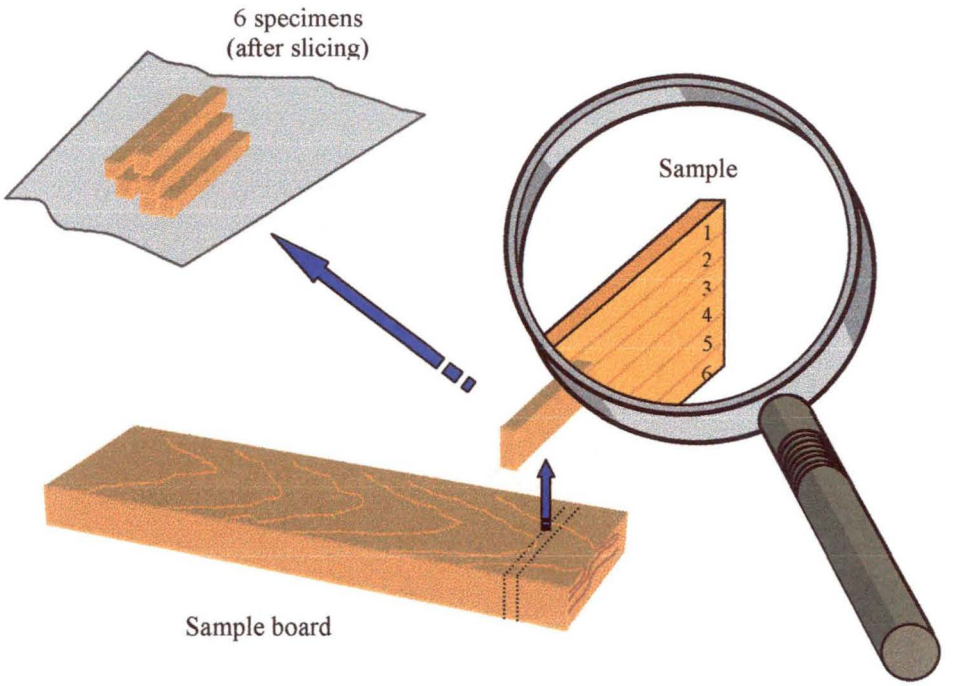


Figure C.2.2.1 *Diagram of sample cutting, from a sample board to six long thin specimens.*

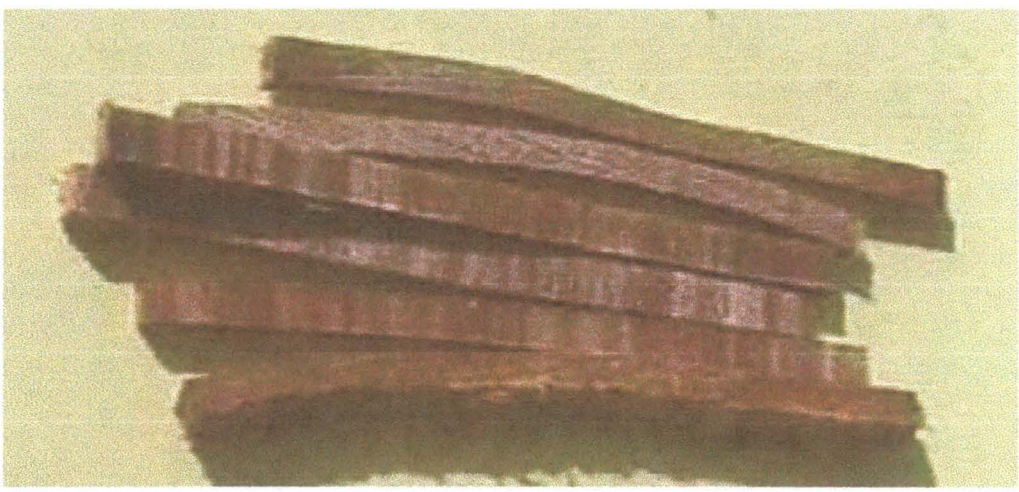


Figure C.2.2.2 *Thin specimens (after drying in the oven at 103 ± 2 °C).*

A sample piece was cut at least 30 mm clear from the end of every sample board. The piece had 5 mm long grain. The cross section size of that piece was the same as the cross section of the original board (30 mm x 112 mm). The sample piece was divided into six parts (± 5 mm wide each) in its width and marked with

numbers from 1 to 6, indicating the thickness zones of the original sample board from the top surface to the bottom surface (**Figure C.2.2.1**). The length (tangential dimension) of each part was measured with a calliper.

The sample piece was cut on the reference marks with a sharp blade separating six long thin specimens one by one. The first cutting was to separate specimen number 1, then slicing continued for specimen number 6, 2, 5, 3 and specimen number 4. The straight length and weight of each specimen was measured immediately after cutting.

All the specimens from the same sample piece were placed on aluminium foil and oven dried at 103 ± 2 °C until their weight was constant (± 48 hours) (**Figure C.2.2.2**). Their final weights were measured again after cooling in a desiccator.

C.2.3 Calculation and data processing

The strain of each specimen was calculated using the following formula:

$$S = \left(\frac{La - Lb}{Lb} \right) \times 100\% \qquad \textbf{(C.2.3.1)}$$

where:

S : recoverable strain of a specimen (%);

La : the length of the specimen after slicing (mm); and

Lb : the length of the specimen before slicing (mm).

The negative value of recoverable strain showed that the specimen experienced tension stress. The positive value indicated that the compression stress acted in that specimen. The recoverable strain data of specimens from each sample piece were plotted in columns on a chart. Therefore it could be compared with the strain profile of other boards at every evaluation time.

The moisture content of each long thin specimen was calculated as well with the same formula as in formula **B.1.3.1** in **Appendix B**.

Appendix D

Experimental timber kiln description

The experimental timber kiln was first designed in 1980 by C. Purdon, a mechanical design engineer, and the Tasmanian Timber Promotion Board, in conjunction with the Department of Mechanical Engineering, University of Tasmania (Schaffner, 1981). Some modification has been made, particularly in the control system using the Clever Kiln Control (CKC) program.

The kiln temperature and relative humidity were sensed by measuring dry bulb and wet bulb temperatures in the inlet and outlet of air circulation in the chamber. A reversible 500 mm fan was used to circulate air equally in the chamber. This fan was driven by a 750 watt variable speed motor. The heating was produced by two 1500 watt electric heating elements. A very fine water jet sprayer and two ventilation dampers were operated automatically to control the relative humidity in the kiln.

The kiln (**Figure D.1** and **D.2**) was constructed entirely from aluminium and was covered with ± 50 mm rock wool insulation and reflective foil on the surface. The capacity of the kiln is ± 0.6 m^3 of timber. The timber stack could be wheeled into the kiln with a hand operated hydraulic pallet truck.

Figure D.1 *Experimental timber kiln (from the front).*

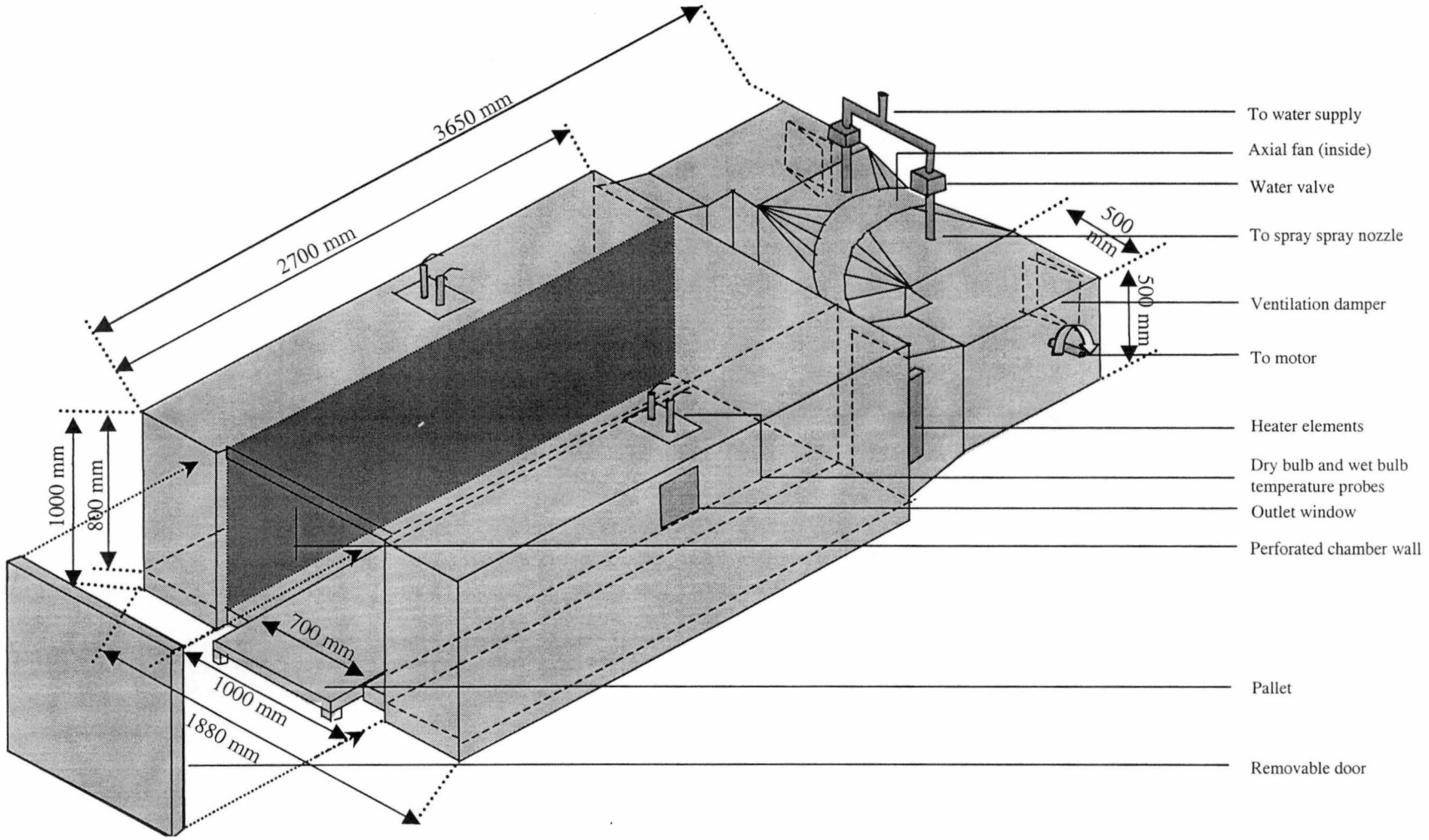


Figure D.2 *Experimental timber kiln.*

Appendix E

Assessment data and analysis of boards treated with sodium hydroxide, acetic acid and water

Table E.1 *Single factor analysis of variance (ANOVA) of basic density of boards.*

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
N1	5	2951	590	1023
N3	5	2970	594	784
N7	5	2946	589	763
N15	5	2937	587	611
A1	5	2959	592	865
A3	5	2984	597	972
A7	5	3018	604	1069
A15	5	3015	603	1012
W7	5	3012	602	973
W15	5	3005	601	657
D15	5	3001	600	1198
W7C	5	2980	596	722
C	5	2972	594	1039

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1842	12	154	0.170751	0.999036	1.943619
Within Groups	46752	52	899			
Total	48594	64				

- P value > 0.05 → basic density was not significantly affected by the treatments.
- N1, N3, N7, N15, A1, A3, A7, A15, W7, W15, D15, and W7C were the codes of treated boards.
- C was the code of control boards.

Table E.2 *Single factor ANOVA of boards' moisture content (expressed in %) after storage with plastic packing.*

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Mi (%)	65	5169.3	79.5	63.8
M0(%)	65	5122.9	78.8	61.3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	16.5	1	16.5	0.26468	0.60781	3.915147
Within Groups	8003.4	128	62.5			
Total	8020.0	129				

- Mi = moisture content before storage; M0 = moisture content after storage; SS = sum of squares; df = degree of freedom; MS = mean squares; F= F test value; P value = probability level.
- P value > 0.05 → moisture content was not significantly affected by the storage in plastic packing.

Table E.3 *Single factor ANOVA of boards' moisture content (expressed in %) before kiln drying.*

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
N1	5	378.7	75.7	32.5
N3	5	379.3	75.9	39.8
N7	5	411.5	82.3	34.9
N15	5	462.3	92.5	65.5
A1	5	368.1	73.6	32.1
A3	5	379.5	75.9	33.6
A7	5	384.4	76.9	35.0
A15	5	387.4	77.5	31.6
W7	5	396.6	79.3	37.5
W15	5	412.8	82.6	35.2
DW15	5	423.0	84.6	44.0
W7C	5	389.0	77.8	36.3
C	5	350.1	70.0	42.6

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1917.8	12	159.8	4.150151	0.000152	1.943619
Within Groups	2002.5	52	38.5			
Total	3920.3	64				

- P value < 0.01 → moisture content of boards was significantly affected by the treatments.

Paired t-test

	C	*N1*
Mean	70.023	75 746
Variance	42.568	32.537
Observations	5	5
Pearson Correlation	0.9777	
Hypothesized Mean Difference	0	
df	4	
t Stat	-8.384	
P(T<=t) one-tail	0.0006	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0011	
t Critical two-tail	2.7765	

	C	*N3*
Mean	70 023	75 864
Variance	42.568	39.768
Observations	5	5
Pearson Correlation	0.5574	
Hypothesized Mean Difference	0	
df	4	
t Stat	-2.163	
P(T<=t) one-tail	0 0483	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0965	
t Critical two-tail	2.7765	

	C	N7
Mean	70.023	82.299
Variance	42.568	34.939
Observations	5	5
Pearson Correlation	-0.107	
Hypothesized Mean Difference	0	
df	4	
t Stat	-2.964	
P(T<=t) one-tail	0.0207	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0414	
t Critical two-tail	2.7765	

	C	N15
Mean	70.023	92.463
Variance	42.568	65.459
Observations	5	5
Pearson Correlation	0.6032	
Hypothesized Mean Difference	0	
df	4	
t Stat	-7.535	
P(T<=t) one-tail	0.0008	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0017	
t Critical two-tail	2.7765	

	C	A1
Mean	70.023	73.629
Variance	42 568	32.112
Observations	5	5
Pearson Correlation	0.9808	
Hypothesized Mean Difference	0	
df	4	
t Stat	-5.493	
P(T<=t) one-tail	0.0027	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0054	
t Critical two-tail	2.7765	

	C	A3
Mean	70.023	75.902
Variance	42.568	33.609
Observations	5	5
Pearson Correlation	0.5865	
Hypothesized Mean Difference	0	
df	4	
t Stat	-2.331	
P(T<=t) one-tail	0.0401	
t Critical one-tail	2 1318	
P(T<=t) two-tail	0.0802	
t Critical two-tail	2.7765	

	C	A7
Mean	70.023	76.885
Variance	42.568	35.023
Observations	5	5
Pearson Correlation	-0.046	
Hypothesized Mean Difference	0	
df	4	
t Stat	-1.704	
P(T<=t) one-tail	0 0818	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.1636	
t Critical two-tail	2.7765	

	C	A15
Mean	70.023	77.483
Variance	42 568	31.567
Observations	5	5
Pearson Correlation	0.7464	
Hypothesized Mean Difference	0	
df	4	
t Stat	-3.786	
P(T<=t) one-tail	0.0097	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0193	
t Critical two-tail	2.7765	

	C	W7
Mean	70.023	79.33
Variance	42.568	37.533
Observations	5	5
Pearson Correlation	-0.119	
Hypothesized Mean Difference	0	
df	4	
t Stat	-2.198	
P(T<=t) one-tail	0.0464	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0928	
t Critical two-tail	2.7765	

	C	W15
Mean	70 023	82.561
Variance	42.568	35.185
Observations	5	5
Pearson Correlation	0.7166	
Hypothesized Mean Difference	0	
df	4	
t Stat	-5.939	
P(T<=t) one-tail	0.002	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.004	
t Critical two-tail	2.7765	

	C	DW15
Mean	70.023	84.603
Variance	42.568	44.048
Observations	5	5
Pearson Correlation	0.7233	
Hypothesized Mean Difference	0	
df	4	
t Stat	-6.659	
P(T<=t) one-tail	0.0013	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0026	
t Critical two-tail	2.7765	

	C	W7C
Mean	70.023	77.795
Variance	42.568	36.279
Observations	5	5
Pearson Correlation	-0.366	
Hypothesized Mean Difference	0	
df	4	
t Stat	-1.675	
P(T<=t) one-tail	0.0846	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.1692	
t Critical two-tail	2.7765	

The moisture content of paired boards were significantly different

The moisture content of paired boards were not significantly different

Table E.4 *Two factor ANOVA of drying rate (expressed in %/ day).*

SUMMARY	N1	N3	N7	N15	A1	A3	A7	A15	W7	W15	DW15	W7C	C	Total
DR 1-8														
Count	5	5	5	5	5	5	5	5	5	5	5	5	5	65
Sum	13	14	18	23	12	13	13	14	14	14	15	8	10	182
Average	3	3	4	5	2	3	3	3	3	3	3	2	2	3
Variance	0.55	0.40	0.38	0.16	0.10	0.41	0.30	0.18	0.18	0.16	0.30	0.08	0.48	0.74
DR 8-29														
Count	5	5	5	5	5	5	5	5	5	5	5	5	5	65
Sum	5	5	5	6	5	5	5	5	5	6	6	5	5	68
Average	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Variance	0.05	0.03	0.04	0.27	0.09	0.04	0.04	0.01	0.05	0.05	0.06	0.04	0.03	0.06
Total														
Count	10	10	10	10	10	10	10	10	10	10	10	10	10	
Sum	18	19	23	30	17	18	18	19	19	20	21	13	15	
Average	2	2	2	3	2	2	2	2	2	2	2	1	1	
Variance	0.89	1.06	2.07	3.44	0.73	0.97	0.98	0.95	0.87	0.85	1.06	0.18	0.50	

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	99.775	1	99.775	581.7	2E-44	3.9324
Columns	19.63	12	1.6358	9.537	3E-12	1.8464
Interaction	13.462	12	1.1218	6.5403	1E-08	1.8464
Within	17.839	104	0.1715			
Total	150.71	129				

- All P values < 0.01 → the effects of treatments, the period of drying and their interaction on drying rate were very significant.
- *DR 1-8* = the drying rate in the first week; *DR 8-29* = the drying rate in the last three weeks.

Paired t-test

	C	N1
Mean	1.2326	1.4
Variance	0.0636	0.0528
Observations	5	5
Pearson Correlation	0.9648	
Hypothesized Mean Difference	0	
df	4	
t Stat	-5.531	
P(T<=t) one-tail	0.0026	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0052	
t Critical two-tail	2.7765	

	C	N3
Mean	1.2326	1 4183
Variance	0 0636	0.059
Observations	5	5
Pearson Correlation	0.4093	
Hypothesized Mean Difference	0	
df	4	
t Stat	-1.542	
P(T<=t) one-tail	0.0989	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0 1978	
t Critical two-tail	2.7765	

	C	N7
Mean	1.2326	1.6436
Variance	0.0636	0.0762
Observations	5	5
Pearson Correlation	0.0403	
Hypothesized Mean Difference	0	
df	4	
t Stat	-2.509	
P(T<=t) one-tail	0.0331	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0661	
t Critical two-tail	2.7765	

	C	N15
Mean	1.2326	2.1228
Variance	0.0636	0.0845
Observations	5	5
Pearson Correlation	0.7297	
Hypothesized Mean Difference	0	
df	4	
t Stat	-9 815	
P(T<=t) one-tail	0.0003	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0006	
t Critical two-tail	2.7765	

	C	A1
Mean	1 2326	1.3315
Variance	0.0636	0.0514
Observations	5	5
Pearson Correlation	0.9137	
Hypothesized Mean Difference	0	
df	4	
t Stat	-2.155	
P(T<=t) one-tail	0.0487	
t Critical one-tail	2 1318	
P(T<=t) two-tail	0.0974	
t Critical two-tail	2.7765	

	C	A3
Mean	1.2326	1.4262
Variance	0.0636	0.0384
Observations	5	5
Pearson Correlation	0.7763	
Hypothesized Mean Difference	0	
df	4	
t Stat	-2.723	
P(T<=t) one-tail	0.0264	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0528	
t Critical two-tail	2.7765	

	C	A7
Mean	1.2326	1 3919
Variance	0.0636	0.0494
Observations	5	5
Pearson Correlation	0.068	
Hypothesized Mean Difference	0	
df	4	
t Stat	-1.097	
P(T<=t) one-tail	0.1671	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.3342	
t Critical two-tail	2.7765	

	C	A15
Mean	1.2326	1.4406
Variance	0.0636	0.0125
Observations	5	5
Pearson Correlation	0 8653	
Hypothesized Mean Difference	0	
df	4	
t Stat	-2.814	
P(T<=t) one-tail	0.0241	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0481	
t Critical two-tail	2.7765	

	C	W7
Mean	1.2326	1.4731
Variance	0.0636	0.0293
Observations	5	5
Pearson Correlation	0.0912	
Hypothesized Mean Difference	0	
df	4	
t Stat	-1.844	
P(T<=t) one-tail	0.0695	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.139	
t Critical two-tail	2.7765	

	C	W15
Mean	1.2326	1.5708
Variance	0.0636	0.059
Observations	5	5
Pearson Correlation	0.8109	
Hypothesized Mean Difference	0	
df	4	
t Stat	-4 96	
P(T<=t) one-tail	0 0039	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0077	
t Critical two-tail	2.7765	

	C	DW15
Mean	1.2326	1.6611
Variance	0 0636	0.0754
Observations	5	5
Pearson Correlation	0.842	
Hypothesized Mean Difference	0	
df	4	
t Stat	-6.403	
P(T<=t) one-tail	0.0015	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0031	
t Critical two-tail	2.7765	

	C	W7C
Mean	1.2326	1.1306
Variance	0.0636	0.0442
Observations	5	5
Pearson Correlation	-0.032	
Hypothesized Mean Difference	0	
df	4	
t Stat	0.6836	
P(T<=t) one-tail	0.2659	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.5318	
t Critical two-tail	2.7765	

The drying rate of paired boards were significantly different

The drying rate of paired boards were not significantly different

Table E. 5 *Single factor ANOVA of normal shrinkage (expressed in %) in tangential direction of cross section slices after soaking treatments.*

SUMMARY

Groups	Count	Sum	Average	Variance
C	4	38.8	9.7	16.7
N1	5	43.9	8.8	14.0
N3	6	59.2	9.9	13.7
N7	6	65.1	10.8	4.5
N15	6	77.3	12.9	14.1
A1	6	57.2	9.5	11.3
A3	4	32.9	8.2	21.3
A7	5	63.3	12.7	1.7
A15	4	52.4	13.1	1.1
W7	4	45.6	11.4	31.0
W15	6	63.5	10.6	18.0
D15	6	71.1	11.8	28.7
W7C	3	41.7	13.9	3.3

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	166.2	12	13.85	0.986	0.475	1.944
Within Groups	730.6	52	14.05			
Total	896.8	64				

❖ P value > 0.05 → the effects of treatments (N1, N3, N7, ..., W7C) on normal shrinkage in tangential direction were not significant.

Table E.6 *Single factor ANOVA of normal shrinkage (expressed in %) in radial direction of slices after soaking treatments.*

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
C	3	26.7	8.9	0.7
N1	4	31.9	8.0	2.1
N3	3	24.1	8.0	0.5
N7	4	34.6	8.7	2.3
N15	4	43.9	11.0	18.4
A1	4	33.0	8.2	0.1
A3	4	28.1	7.0	3.4
A7	3	28.0	9.3	0.2
A15	5	42.9	8.6	1.6
W7	5	50.9	10.2	5.7
W15	4	32.7	8.2	1.9
D15	5	43.9	8.8	1.1
W7C	4	34.5	8.6	4.9

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	49.5252	12	4.1271	1.19086	0.32332	2.01018
Within Groups	135.16	39	3.46565			
Total	184.685	51				

❖ P value > 0.05 → the effects of treatments (N1, N3, N7, ..., W7C) on normal shrinkage in radial direction were not significant.

Table E.7 *Single factor ANOVA of tangential collapse (expressed in %) of cross section slices after soaking treatments.*

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
C	3	5.9	2.0	2.1
N1	4	12.8	3.2	2.5
N3	5	28.1	5.6	22.3
N7	5	29.2	5.8	12.9
N15	5	65.4	13.1	2.6
A1	5	18.9	3.8	4.1
A3	3	15.8	5.3	19.7
A7	3	11.8	3.9	2.1
A15	3	4.2	1.4	1.2
W7	3	9.1	3.0	2.2
W15	5	25.9	5.2	13.2
D15	5	16.1	3.2	8.7
W7C	3	6.5	2.2	4.7

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	472.2	12	39.35	4.692	1E-04	2.01
Within Groups	327	39	8.385			
Total	799.2	51				

❖ P value < 0.01 → the effects of treatments on tangential collapse of slices were very significant.

Paired t-test

	C	*N1*
Mean	1.97456	3.20481
Variance	2.08109	2.4838
Observations	3	4
Hypothesized Mean Difference	0	
df	5	
t Stat	-1.073	
P(T<=t) one-tail	0.16616	
t Critical one-tail	2 01505	
P(T<=t) two-tail	0.33232	
t Critical two-tail	2.57058	

	C	*N3*
Mean	1.97456	5.61673
Variance	2.08109	22.2596
Observations	3	5
Hypothesized Mean Difference	0	
df	5	
t Stat	-1.6056	
P(T<=t) one-tail	0.08463	
t Critical one-tail	2.01505	
P(T<=t) two-tail	0.16927	
t Critical two-tail	2.57058	

	C	*N7*
Mean	1.97456	5.84682
Variance	2.08109	12.9233
Observations	3	5
Hypothesized Mean Difference	0	
df	6	
t Stat	-2.1386	
P(T<=t) one-tail	0.03815	
t Critical one-tail	1.94318	
P(T<=t) two-tail	0 07629	
t Critical two-tail	2.44691	

	C	*N15*
Mean	1.97456	13.0872
Variance	2.08109	2 63946
Observations	3	5
Hypothesized Mean Difference	0	
df	5	
t Stat	-10 054	
P(T<=t) one-tail	8.3E-05	
t Critical one-tail	2.01505	
P(T<=t) two-tail	0.00017	
t Critical two-tail	2.57058	

	C	*A1*
Mean	1.97456	3.77252
Variance	2.08109	4 14308
Observations	3	5
Hypothesized Mean Difference	0	
df	6	
t Stat	-1 4572	
P(T<=t) one-tail	0.09766	
t Critical one-tail	1.94318	
P(T<=t) two-tail	0.19532	
t Critical two-tail	2.44691	

	C	*A3*
Mean	1.97456	5.27836
Variance	2.08109	19.7043
Observations	3	3
Hypothesized Mean Difference	0	
df	2	
t Stat	-1 226	
P(T<=t) one-tail	0.17248	
t Critical one-tail	2.91999	
P(T<=t) two-tail	0 34496	
t Critical two-tail	4.30266	

	C	A7
Mean	1.97456	3.93602
Variance	2.08109	2.14252
Observations	3	3
Hypothesized Mean Difference	0	
df	4	
t Stat	-1.6531	
P(T<=t) one-tail	0 08683	
t Critical one-tail	2.13185	
P(T<=t) two-tail	0.17365	
t Critical two-tail	2.77645	

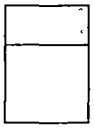
	C	A15
Mean	1 97456	1.4031
Variance	2.08109	1.22682
Observations	3	3
Hypothesized Mean Difference	0	
df	4	
t Stat	0.54422	
P(T<=t) one-tail	0.3076	
t Critical one-tail	2.13185	
P(T<=t) two-tail	0 61521	
t Critical two-tail	2.77645	

	C	W7
Mean	1.97456	3.04155
Variance	2.08109	2.23079
Observations	3	3
Hypothesized Mean Difference	0	
df	4	
t Stat	-0.89	
P(T<=t) one-tail	0 21188	
t Critical one-tail	2.13185	
P(T<=t) two-tail	0.42376	
t Critical two-tail	2.77645	

	C	W15
Mean	1.97456	5 17068
Variance	2 08109	13.1877
Observations	3	5
Hypothesized Mean Difference	0	
df	6	
t Stat	-1.7511	
P(T<=t) one-tail	0.06524	
t Critical one-tail	1.94318	
P(T<=t) two-tail	0.13049	
t Critical two-tail	2.44691	

	C	D15
Mean	1.97456	3.22081
Variance	2.08109	8.70148
Observations	3	5
Hypothesized Mean Difference	0	
df	6	
t Stat	-0.7988	
P(T<=t) one-tail	0.22743	
t Critical one-tail	1.94318	
P(T<=t) two-tail	0.45485	
t Critical two-tail	2.44691	

	C	W7C
Mean	1.97456	2.17974
Variance	2.08109	4.69452
Observations	3	3
Hypothesized Mean Difference	0	
df	3	
t Stat	-0.1365	
P(T<=t) one-tail	0.45003	
t Critical one-tail	2.35336	
P(T<=t) two-tail	0.90005	
t Critical two-tail	3.18245	



The tangential collapse of paired samples were significantly different

The tangential collapse of paired samples were not significantly different

Table E.8 *Single factor ANOVA of radial collapse(expressed in %) of slices after soaking treatments.*

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
C	3	7.3	2.4	6.2
N1	4	10.2	2.6	4.9
N3	3	16.4	5.5	11.5
N7	4	11.6	2.9	9.0
N15	4	24.7	6.2	12.1
A1	4	16.2	4.0	10.8
A3	4	14.6	3.7	9.1
A7	3	7.2	2.4	4.2
A15	5	18.2	3.6	10.6
W7	5	12.7	2.5	2.2
W15	4	12.5	3.1	3.9
D15	5	17.1	3.4	9.2
W7C	4	11.0	2.7	7.3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	60.8827	12	5.07356	0.65286	0.78387	2.01018
Within Groups	303.078	39	7.77122			
Total	363.96	51				

P value > 0.05 → the treatments did not significantly affect radial collapse of slices.

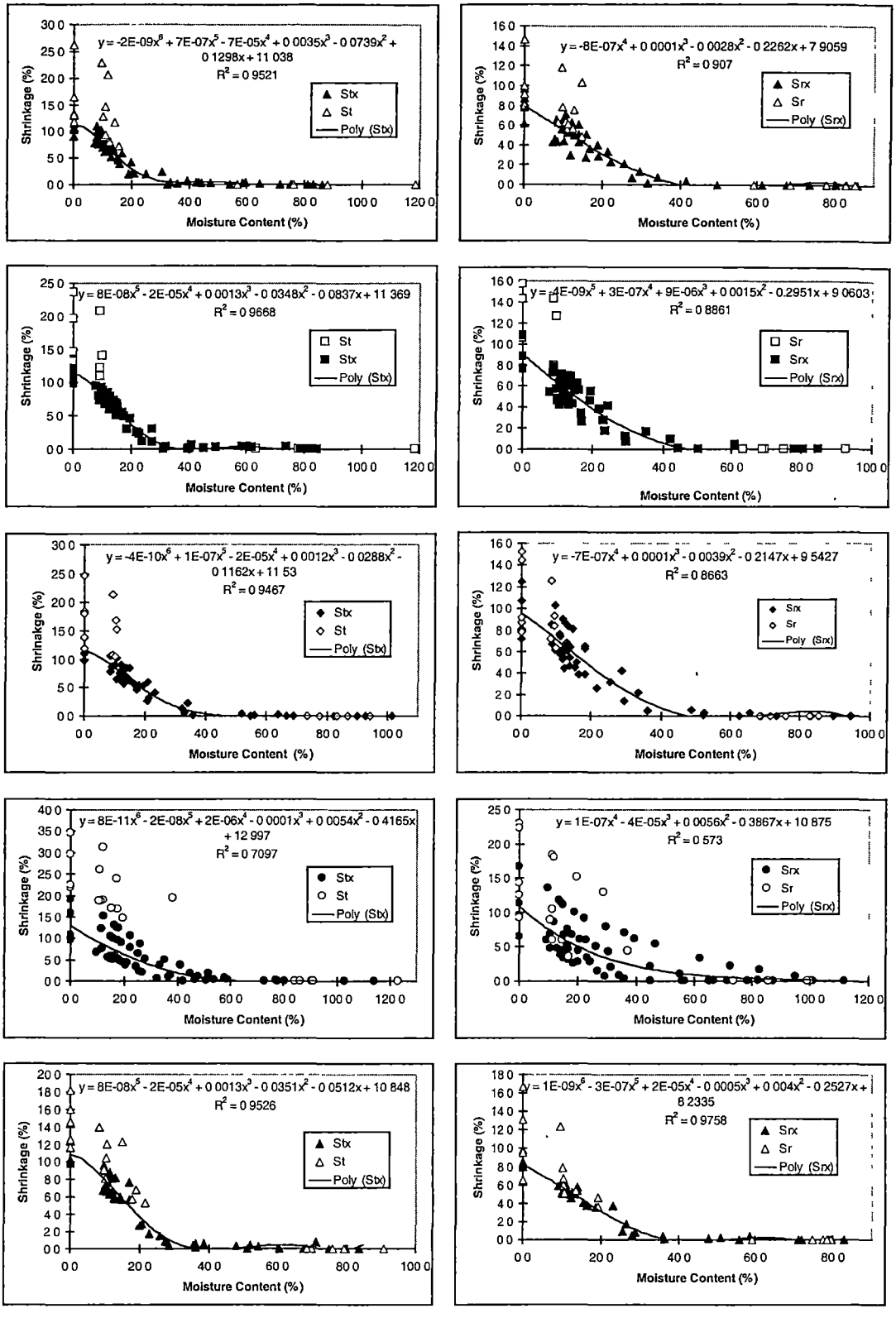


Figure E.1 *Tangential and radial shrinkage of N1, N3, N7, N15 and A1 slices. Stx or Srx = Normal shrinkage in tangential or radial direction; St or Sr = Unconfined shrinkage in tangential or radial direction.*

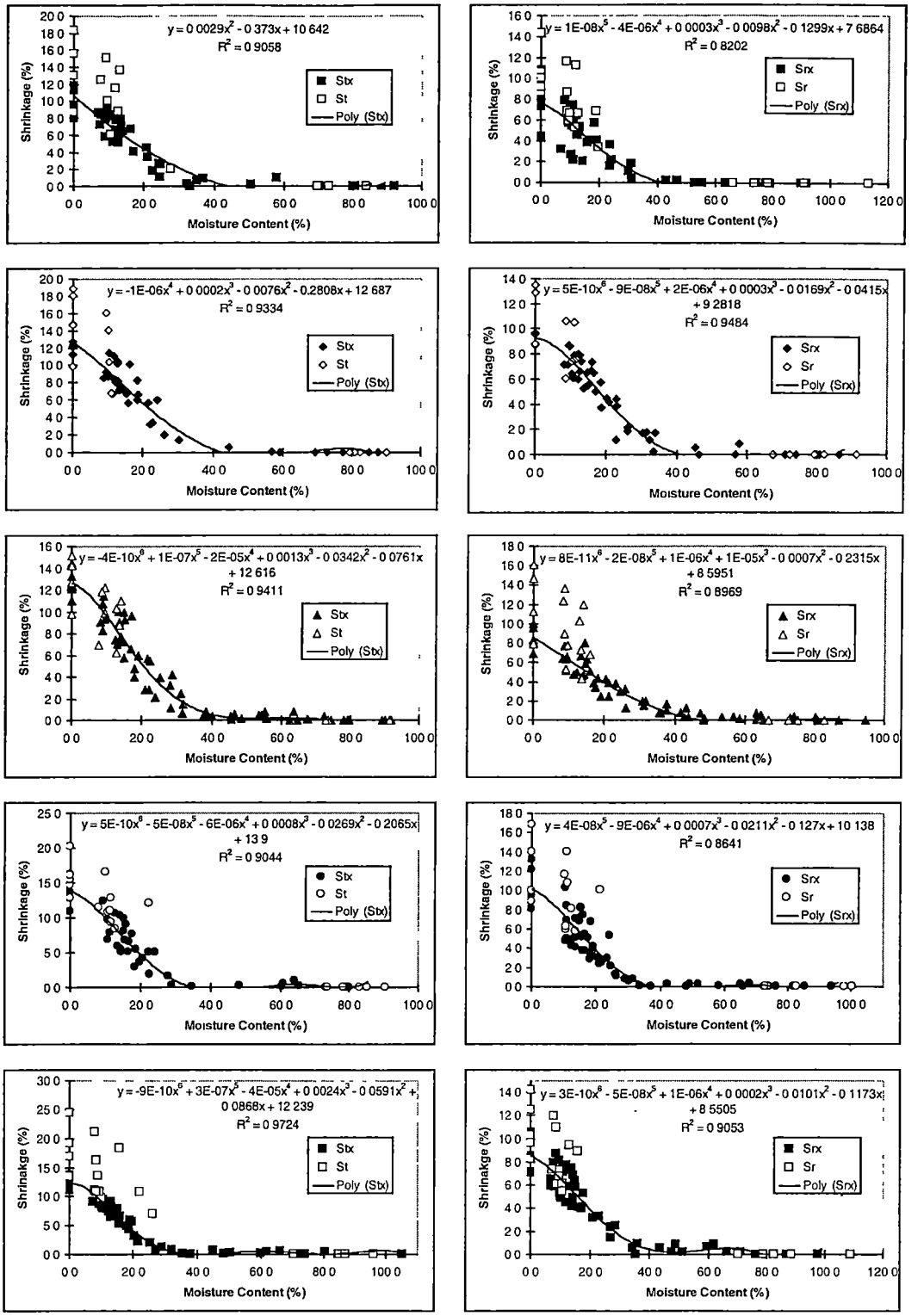


Figure E.2 *Tangential and radial shrinkage of A3, A7, A15, W7 and W15 slices. Stx or Srx = Normal shrinkage in tangential or radial direction; St or Sr = Unconfined shrinkage in tangential or radial direction.*

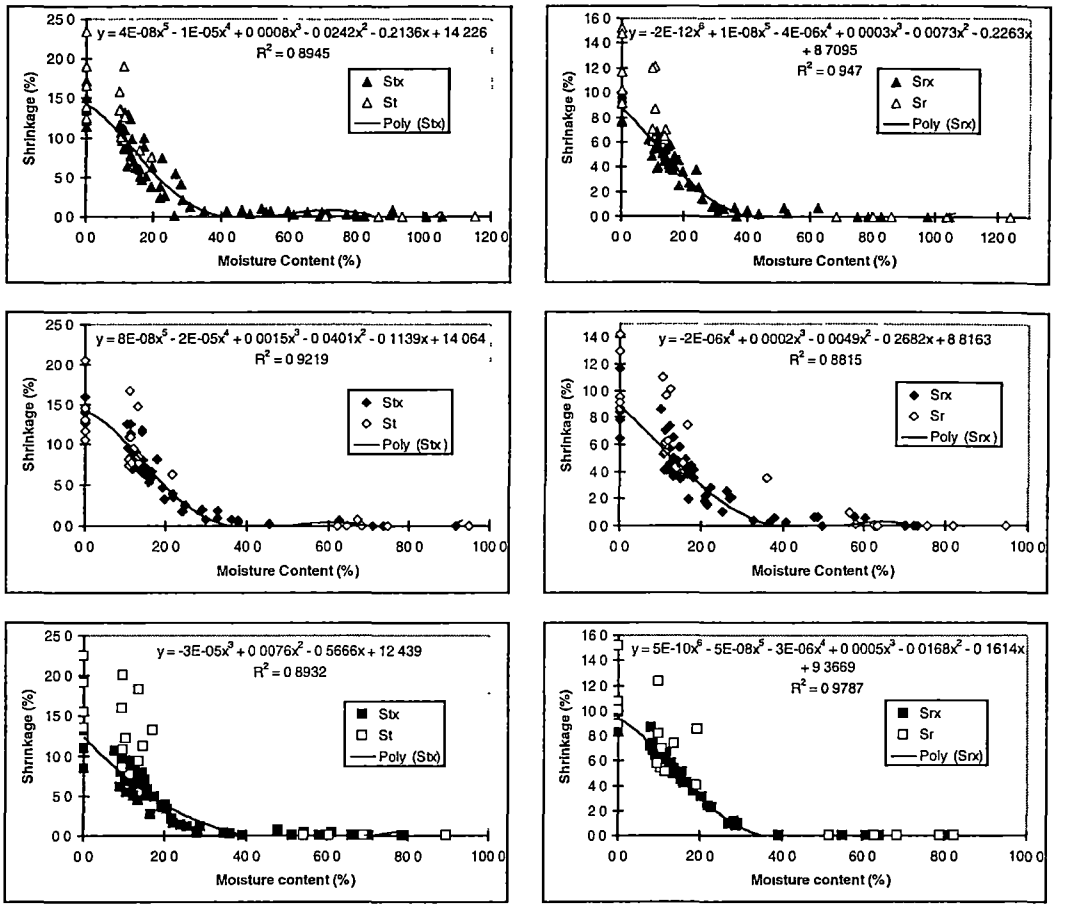


Figure E.3 *Tangential and radial shrinkage of DW15, W7C and C slices. Stx or Srx = Normal shrinkage in tangential or radial direction; St or Sr = Unconfined shrinkage in tangential or radial direction.*

Table E.9 *Two factor ANOVA of collapse value on the boards based on visual grading.*

SUMMARY	N1	N3	N7	N15	A1	A3	A7	A15	W7	W15	DW15	W7C	C	Total
S														
Count	5	5	5	5	5	5	5	5	5	5	5	5	5	65
Sum	0	2	2	2	0	1	2	1	2	2	3	0	0	17
Average	0	0.4	0	0.4	0	0.2	0.4	0.2	0.4	0.4	0.6	0	0	0.3
Variance	0	0.8	1	0.8	0	0.2	0.8	0.2	0.8	0.8	0.8	0	0	0.4
E														
Count	5	5	5	5	5	5	5	5	5	5	5	5	5	65
Sum	0	3	5	9	3	1	3	3	2	4	7	3	2	45
Average	0	0.6	1	1.8	1	0.2	0.6	0.6	0.4	0.8	1.4	0.6	0	0.7
Variance	0	0.8	1	0.2	1	0.2	0.8	0.3	0.8	0.7	0.8	0.8	0	0.7

Total													
Count	10	10	10	10	10	10	10	10	10	10	10	10	10
Sum	0	5	7	11	3	2	5	4	4	6	10	3	2
Average	0	0.5	1	1.1	0	0.2	0.5	0.4	0.4	0.6	1	0.3	0
Variance	0	0.7	1	1.0	0	0.2	0.7	0.3	0.7	0.7	0.9	0.5	0

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	6.031	1	6.031	11.61	9E-04	3.932
Columns	11.83	12	0.986	1.899	0.043	1.846
Interaction	4.569	12	0.381	0.733	0.716	1.846
Within	54	104	0.519			
Total	76.43	129				
Total			88.98	64		

- P values of sample and columns < 0.05 → boards' collapse was significantly affected by the treatments and was different in the thickness and width of the boards.
- *S* = collapse value on the boards' surfaces; *E* = collapse value on the boards' edges.

Paired t-test

	C	*N1*
Mean	0.2	0
Variance	0.1778	0
Observations	10	10
Pearson Correlation	#DIV/0!	
Hypothesized Mean Difference	0	
df	9	
t Stat	1.5	
P(T<=t) one-tail	0.0839	
t Critical one-tail	1.8331	
P(T<=t) two-tail	0.1679	
t Critical two-tail	2 2622	

	C	*N3*
Mean	0.2	0.5
Variance	0.178	0.722
Observations	10	10
Pearson Correlation	-0 31	
Hypothesized Mean Difference	0	
df	9	
t Stat	-0.896	
P(T<=t) one-tail	0.197	
t Critical one-tail	1.833	
P(T<=t) two-tail	0.394	
t Critical two-tail	2.262	

	C	N7
Mean	0.2	0.7
Variance	0.1778	0.9
Observations	10	10
Pearson Correlation	-0.389	
Hypothesized Mean Difference	0	
df	9	
t Stat	-1.342	
P(T<=t) one-tail	0.1063	
t Critical one-tail	1.8331	
P(T<=t) two-tail	0.2126	
t Critical two-tail	2 2622	

	C	N15
Mean	0.2	1.1
Variance	0.178	0 989
Observations	10	10
Pearson Correlation	0.212	
Hypothesized Mean Difference	0	
df	9	
t Stat	-2.862	
P(T<=t) one-tail	0.009	
t Critical one-tail	1.833	
P(T<=t) two-tail	0.019	
t Critical two-tail	2.262	

	C	A1
Mean	0.2	0.3
Variance	0.1778	0.4556
Observations	10	10
Pearson Correlation	0.1562	
Hypothesized Mean Difference	0	
df	9	
t Stat	-0.429	
P(T<=t) one-tail	0.3392	
t Critical one-tail	1.8331	
P(T<=t) two-tail	0.6783	
t Critical two-tail	2.2622	

	C	A3
Mean	0.2	0.2
Variance	0.178	0.178
Observations	10	10
Pearson Correlation	-0.25	
Hypothesized Mean Difference	0	
df	9	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	1.833	
P(T<=t) two-tail	1	
t Critical two-tail	2.262	

	C	A7
Mean	0.2	0.5
Variance	0.1778	0.7222
Observations	10	10
Pearson Correlation	0.6202	
Hypothesized Mean Difference	0	
df	9	
t Stat	-1.406	
P(T<=t) one-tail	0.0967	
t Critical one-tail	1.8331	
P(T<=t) two-tail	0.1934	
t Critical two-tail	2.2622	

	C	A15
Mean	0.2	0.4
Variance	0.178	0.267
Observations	10	10
Pearson Correlation	0.102	
Hypothesized Mean Difference	0	
df	9	
t Stat	-1	
P(T<=t) one-tail	0 172	
t Critical one-tail	1.833	
P(T<=t) two-tail	0.343	
t Critical two-tail	2.262	

	C	W7
Mean	0.2	0.4
Variance	0.178	0.711
Observations	10	10
Pearson Correlation	-0.25	
Hypothesized Mean Difference	0	
df	9	
t Stat	-0.612	
P(T<=t) one-tail	0 278	
t Critical one-tail	1.833	
P(T<=t) two-tail	0.555	
t Critical two-tail	2 262	

	C	W15
Mean	0.2	0.6
Variance	0 178	0.711
Observations	10	10
Pearson Correlation	0.25	
Hypothesized Mean Difference	0	
df	9	
t Stat	-1.5	
P(T<=t) one-tail	0.084	
t Critical one-tail	1.833	
P(T<=t) two-tail	0.168	
t Critical two-tail	2 262	

	C	DW15
Mean	0.2	1
Variance	0.178	0.889
Observations	10	10
Pearson Correlation	0.559	
Hypothesized Mean Difference	0	
df	9	
t Stat	-3.207	
P(T<=t) one-tail	0.005	
t Critical one-tail	1.833	
P(T<=t) two-tail	0.011	
t Critical two-tail	2.262	

	C	W7C
Mean	0.2	0.3
Variance	0.178	0.456
Observations	10	10
Pearson Correlation	0.937	
Hypothesized Mean Difference	0	
df	9	
t Stat	-1	
P(T<=t) one-tail	0.172	
t Critical one-tail	1.833	
P(T<=t) two-tail	0.343	
t Critical two-tail	2.262	

The collapse value of paired boards were significantly different

The collapse value of paired boards were not significantly different

Table E.10 *Two factor ANOVA of check value on the boards during drying.*

SUMMARY	N1	N3	N7	N15	A1	A3	A7	A15	W7	W15	DW15	W7C	C	Total
S7														
Count	5	5	5	5	5	5	5	5	5	5	5	5	5	65
Sum	13	17	15	14	15	11	11	15	10	11	11	0	11	154
Average	2.6	3.4	3	2.8	3	2.2	2.2	3	2	2.2	2.2	0	2	2.37
Variance	0.3	0.3	0.5	1.2	0.5	0.2	0.7	1	4	0.7	0.7	0	1	1.33
E7														
Count	5	5	5	5	5	5	5	5	5	5	5	5	5	65
Sum	10	11	10	10	11	8	9	10	8	5	9	2	7	110
Average	2	2.2	2	2	2.2	1.6	1.8	2	1.6	1	1.8	0.4	1	1.69
Variance	0	0.2	0	0	1.2	0.3	0.2	0	0.3	0.5	0.2	0.8	0	0.5
S28														
Count	5	5	5	5	5	5	5	5	5	5	5	5	5	65
Sum	13	9	13	14	0	1	3	6	2	2	0	2	2	67
Average	2.6	1.8	2.6	2.8	0	0.2	0.6	1.2	0.4	0.4	0	0.4	0	1.03
Variance	0.8	1.7	0.8	3.2	0	0.2	0.3	1.7	0.8	0.3	0	0.8	0	1.72
E28														
Count	5	5	5	5	5	5	5	5	5	5	5	5	5	65
Sum	6	5	9	1	0	0	0	1	0	0	0	0	0	22
Average	1.2	1	1.8	0.2	0	0	0	0.2	0	0	0	0	0	0.34
Variance	0.7	1	0.2	0.2	0	0	0	0.2	0	0	0	0	0	0.48
Total														
Count	20	20	20	20	20	20	20	20	20	20	20	20	20	
Sum	42	42	47	39	26	20	23	32	20	18	20	4	20	
Average	2.1	2.1	2.35	1.95	1.3	1	1.2	1.6	1	0.9	1	0.2	1	
Variance	0.73	1.46	0.56	2.16	2.2	1.05	1.1	1.73	1.79	1.04	1.26	0.38	1	

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	148.2577	3	49.41923	91.77857	7.22E-38	2.648008
Columns	92.08462	12	7.673718	14.25119	1.83E-21	1.798949
Interaction	53.39231	36	1.48312	2.754365	3.66E-06	1.473994
Within	112	208	0.538462			
Total	405.7346	259				

- ❖ All P values < 0.05 → boards' checking was significantly affected by the treatments and was different on the surfaces and edges of the boards.
- ❖ S7 and E7 = check value on the boards' surfaces and edges respectively, after seven days drying; S28 and E28 = check value on the boards' surfaces and edges after 28 days kiln drying.

Paired t – test

	C	*N1*
Mean	1	2.1
Variance	1.0526	0.7263
Observations	20	20
Pearson Correlation	0.2408	
Hypothesized Mean Difference	0	
df	19	
t Stat	-4 222	
P(T<=t) one-tail	0 0002	
t Critical one-tail	1.7291	
P(T<=t) two-tail	0.0005	
t Critical two-tail	2 093	

	C	*N3*
Mean	1	2.1
Variance	1 0526	1.4632
Observations	20	20
Pearson Correlation	0 6786	
Hypothesized Mean Difference	0	
df	19	
t Stat	-5 395	
P(T<=t) one-tail	2E-05	
t Critical one-tail	1.7291	
P(T<=t) two-tail	3E-05	
t Critical two-tail	2.093	

	C	*N7*
Mean	1	2.35
Variance	1.0526	0.5553
Observations	20	20
Pearson Correlation	0.4131	
Hypothesized Mean Difference	0	
df	19	
t Stat	-6.11	
P(T<=t) one-tail	4E-06	
t Critical one-tail	1.7291	
P(T<=t) two-tail	7E-06	
t Critical two-tail	2 093	

	C	*N15*
Mean	1	1.95
Variance	1.0526	2.1553
Observations	20	20
Pearson Correlation	0 1747	
Hypothesized Mean Difference	0	
df	19	
t Stat	-2.594	
P(T<=t) one-tail	0.0089	
t Critical one-tail	1.7291	
P(T<=t) two-tail	0.0178	
t Critical two-tail	2.093	

	C	A1
Mean	1	1.3
Variance	1.0526	2.2211
Observations	20	20
Pearson Correlation	0.7228	
Hypothesized Mean Difference	0	
df	19	
t Stat	-1 301	
P(T<=t) one-tail	0 1044	
t Critical one-tail	1.7291	
P(T<=t) two-tail	0.2088	
t Critical two-tail	2.093	

	C	A3
Mean	1	1
Variance	1.0526	1 0526
Observations	20	20
Pearson Correlation	0.75	
Hypothesized Mean Difference	0	
df	19	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	1.7291	
P(T<=t) two-tail	1	
t Critical two-tail	2 093	

	C	A7
Mean	1	1.15
Variance	1 0526	1.0816
Observations	20	20
Pearson Correlation	0.6906	
Hypothesized Mean Difference	0	
df	19	
t Stat	-0.825	
P(T<=t) one-tail	0 2097	
t Critical one-tail	1.7291	
P(T<=t) two-tail	0.4194	
t Critical two-tail	2.093	

	C	A15
Mean	1	1.6
Variance	1.0526	1 7263
Observations	20	20
Pearson Correlation	0 7418	
Hypothesized Mean Difference	0	
df	19	
t Stat	-3.04	
P(T<=t) one-tail	0.0034	
t Critical one-tail	1.7291	
P(T<=t) two-tail	0 0067	
t Critical two-tail	2.093	

	C	W7
Mean	1	1
Variance	1.0526	1.7895
Observations	20	20
Pearson Correlation	0 5752	
Hypothesized Mean Difference	0	
df	19	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	1.7291	
P(T<=t) two-tail	1	
t Critical two-tail	2.093	

	C	W15
Mean	1	0.9
Variance	1.0526	1.0421
Observations	20	20
Pearson Correlation	0.5528	
Hypothesized Mean Difference	0	
df	19	
t Stat	0.462	
P(T<=t) one-tail	0.3246	
t Critical one-tail	1.7291	
P(T<=t) two-tail	0 6493	
t Critical two-tail	2.093	

	C	DW15
Mean	1	1
Variance	1.0526	1.2632
Observations	20	20
Pearson Correlation	0.6847	
Hypothesized Mean Difference	0	
df	19	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	1.7291	
P(T<=t) two-tail	1	
t Critical two-tail	2.093	

	C	W7C
Mean	1	0.2
Variance	1 0526	0 3789
Observations	20	20
Pearson Correlation	0.1667	1.
Hypothesized Mean Difference	0	
df	19	
t Stat	3 2377	
P(T<=t) one-tail	0.0022	
t Critical one-tail	1.7291	
P(T<=t) two-tail	0 0043	
t Critical two-tail	2.093	

☐ The check value of paired boards were significantly different

 The check value of paired boards were not significantly different

Appendix F

Assessment data and analysis of boards surface-coated with polyvinyl acetate (PVA) and urea formaldehyde (UF)

Table F.1 *Two factor analysis of variance (ANOVA) of drying rate (revealed in %/hour) of boards after coating treatments.*

SUMMARY	P1	P2	P3	U1	U2	U3	C	Total
DR1-8 (%/hrs)								
Count	5	5	5	5	5	5	5	35
Sum	0.3673	0.2616	0.2677	0.5305	0.4533	0.4988	0.53	2.909173
Average	0.0735	0.0523	0.0535	0.1061	0.0907	0.0998	0.106	0.083119
Variance	0.0002	0.0001	0.0001	0.0009	0.0008	0.0004	0.0007	0.000854
DR8-15 (%/hrs)								
Count	5	5	5	5	5	5	5	35
Sum	0.4071	0.2928	0.2379	0.5054	0.523	0.541	0.5269	3.034063
Average	0.0814	0.0586	0.0476	0.1011	0.1046	0.1082	0.1054	0.086688
Variance	0.0001	4E-05	6E-05	0.0002	0.0002	2E-05	0.0003	0.000648
Total								
Count	10	10	10	10	10	10	10	
Sum	0.7744	0.5544	0.5056	1.0358	0.9762	1.0399	1.0569	
Average	0.0774	0.0554	0.0506	0.1036	0.0976	0.104	0.1057	
Variance	0.0002	8E-05	0.0001	0.0005	0.0005	0.0002	0.0004	

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.0002	1	0.0002	0.7743	0.3827	4.013
Columns	0.0341	6	0.0057	19.748	3E-12	2.2656
Interaction	0.0008	6	0.0001	0.4917	0.8118	2.2656
Within	0.0161	56	0.0003			
Total	0.0513	69				

- P value of sample > 0.05 → drying rate in the first week and second week were not significantly different.
- P value of columns < 0.01 → drying rate was significantly affected by the treatments.
- P1, P2, P3, U1, U2, and U3 → the codes of treated boards
- C → the codes of control boards.

❖ DR-1-8 and DR-15 → the drying rate in the first and second week of drying respectively.

Paired t-test

	C	P1
Mean	0.1056863	0.0774447
Variance	0 0004334	0.0001563
Observations	10	10
Pearson Correlation	0.7349435	
Hypothesized Mean Difference	0	
df	9	
t Stat	6.2050097	
P(T<=t) one-tail	7.896E-05	
t Critical one-tail	1.8331139	
P(T<=t) two-tail	0 0001579	
t Critical two-tail	2.2621589	

	C	P2
Mean	0.1056863	0.0554439
Variance	0.0004334	8.216E-05
Observations	10	10
Pearson Correlation	0.813568	
Hypothesized Mean Difference	0	
df	9	
t Stat	11 002373	
P(T<=t) one-tail	8.035E-07	
t Critical one-tail	1.8331139	
P(T<=t) two-tail	1.607E-06	
t Critical two-tail	2.2621589	

	C	P3
Mean	0.1056863	0.0505582
Variance	0.0004334	0.0001046
Observations	10	10
Pearson Correlation	0.8177904	
Hypothesized Mean Difference	0	
df	9	
t Stat	12.653759	
P(T<=t) one-tail	2.447E-07	
t Critical one-tail	1.8331139	
P(T<=t) two-tail	4.894E-07	
t Critical two-tail	2 2621589	

	C	U1
Mean	0.1056863	0.1035824
Variance	0.0004334	0.0004608
Observations	10	10
Pearson Correlation	0 522383	
Hypothesized Mean Difference	0	
df	9	
t Stat	0.3218587	
P(T<=t) one-tail	0.3774548	
t Critical one-tail	1.8331139	
P(T<=t) two-tail	0 7549096	
t Critical two-tail	2.2621589	

	C	U2
Mean	0.1056863	0.0976211
Variance	0.0004334	0.0004865
Observations	10	10
Pearson Correlation	0 6847909	
Hypothesized Mean Difference	0	
df	9	
t Stat	1.4950158	
P(T<=t) one-tail	0.0845612	
t Critical one-tail	1.8331139	
P(T<=t) two-tail	0.1691224	
t Critical two-tail	2.2621589	

	C	U3
Mean	0.1056863	0.103987
Variance	0.0004334	0.000186
Observations	10	10
Pearson Correlation	-0 0563688	
Hypothesized Mean Difference	0	
df	9	
t Stat	0.2105381	
P(T<=t) one-tail	0.4189686	
t Critical one-tail	1.8331139	
P(T<=t) two-tail	0 8379371	
t Critical two-tail	2.2621589	

	P1	P2
Mean	0.0774	0.0554
Variance	0.0001	7E-05
Observations	5	5
Pearson Correlation	0.9494	
Hypothesized Mean Difference	0	
df	4	
t Stat	10.34	
P(T<=t) one-tail	0.0002	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0005	
t Critical two-tail	2.7765	

	P2	P3
Mean	0.0554	0.0506
Variance	7E-05	9E-05
Observations	5	5
Pearson Correlation	0.9611	
Hypothesized Mean Difference	0	
df	4	
t Stat	3.8005	
P(T<=t) one-tail	0.0095	
t Critical one-tail	2.1318	
P(T<=t) two-tail	0.0191	
t Critical two-tail	2.7765	

The drying rate of paired boards were significantly different

The drying rate of paired boards were not significantly different

Table F.2 *Two factor ANOVA of collapse grading values on the boards.*

SUMMARY	P1	P2	P3	U1	U2	U3	C	Total
S7								
Count (replication)	5	5	5	5	5	5	5	35
Sum (of collapse value)	0	0	0	5	1	0	3	9
Average (of collapse value)	0	0	0	1	0.2	0	0.6	0.26
Variance	0	0	0	0.5	0.2	0	0.3	0.26
E7								
Count	5	5	5	5	5	5	5	35
Sum	2	6	0	4	0	1	2	15
Average	0.4	1.2	0	0.8	0	0 2	0.4	0.43
Variance	0.3	0 7	0	0.7	0	0.2	0.8	0.49
Total								
Count	10	10	10	10	10	10	10	
Sum	2	6	0	9	1	1	5	
Average	0 2	0 6	0	0.9	0.1	0.1	0 5	
Variance	0.18	0.71	0	0.54	0.1	0.1	0.5	
ANOVA								
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*		
Sample	0.51	1	0.51	1.95	0.1685	4.01		
Columns	6.57	6	1.1	4.14	0.0016	2.27		
Interaction	3.89	6	0.65	2 45	0.0357	2 27		
Within	14.8	56	0 26					
Total	25.8	69						

- P value of columns < 0.01 → the treatments significantly affected collapse in boards.
- S7 = collapse grading value on the surfaces of boards after seven days drying; E7 = collapse grading value on the edges of boards after seven days drying.

Two factor ANOVA of collapse in U1, U2, U3 and C boards

SUMMARY	U1	U2	U3	C	Total	
S7						
Count	5	5	5	5	20	
Sum	5	1	0	3	9	
Average	1	0.2	0	0.6	0.45	
Variance	0.5	0.2	0	0.3	0.366	
E7						
Count	5	5	5	5	20	
Sum	4	0	1	2	7	
Average	0.8	0	0.2	0.4	0.35	
Variance	0.7	0	0.2	0.8	0.45	
Total						
Count	10	10	10	10		
Sum	9	1	1	5		
Average	0.9	0.1	0.1	0.5		
Variance	0.54	0.1	0.1	0.5		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.1	1	0.1	0 3	0 59	4.149
Columns	4.4	3	1.47	4.35	0.011	2.901
Interaction	0.3	3	0 1	0.3	0.828	2.901
Within	10.8	32	0.34			
Total	15.6	39				

- P value of sample > 0.05 →collapses on the surfaces and edges of (U and C) boards were not significantly different.
- S7 = collapse grading value on the surfaces of boards after seven days drying; E7 = collapse grading value on the edges of boards after seven days drying.

Paired t-test

	C	*P1*
Mean	0 5	0.2
Variance	0 5	0.177778
Observations	10	10
Pearson Correlation	0.372678	
Hypothesized Mean Difference	0	
df	9	
t Stat	1.405564	
P(T<=t) one-tail	0.096711	
t Critical one-tail	1.833114	
P(T<=t) two-tail	0.193422	
t Critical two-tail	2 262159	

	C	*P2*
Mean	0.5	0.6
Variance	0.5	0.711111
Observations	10	10
Pearson Correlation	0 186339	
Hypothesized Mean Difference	0	
df	9	
t Stat	-0.317999	
P(T<=t) one-tail	0.37887	
t Critical one-tail	1.833114	
P(T<=t) two-tail	0.757740	
t Critical two-tail	2.262159	

	C	P3
Mean	0.5	0
Variance	0.5	0
Observations	10	10
Pearson Correlation	#DIV/0!	
Hypothesized Mean Difference	0	
df	9	
t Stat	2.236068	
P(T<=t) one-tail	0.026089	
t Critical one-tail	1.833114	
P(T<=t) two-tail	0.052177	
t Critical two-tail	2.262159	

	C	U1
Mean	0.5	0.9
Variance	0.5	0.544444
Observations	10	10
Pearson Correlation	0.319438	
Hypothesized Mean Difference	0	
df	9	
t Stat	-1.5	
P(T<=t) one-tail	0.083925	
t Critical one-tail	1.833114	
P(T<=t) two-tail	0.167851	
t Critical two-tail	2.262159	

	C	U2
Mean	0 5	0.1
Variance	0.5	0.1
Observations	10	10
Pearson Correlation	0.248452	
Hypothesized Mean Difference	0	
Df	9	
t Stat	1.8090681	
P(T<=t) one-tail	0.0519441	
t Critical one-tail	1.8331139	
P(T<=t) two-tail	0.1038881	
t Critical two-tail	2.2621589	

	C	U3
Mean	0 5	0.1
Variance	0 5	0.1
Observations	10	10
Pearson Correlation	-0.248452	
Hypothesized Mean Difference	0	
df	9	
t Stat	1.5	
P(T<=t) one-tail	0.0839253	
t Critical one-tail	1.8331139	
P(T<=t) two-tail	0.1678507	
t Critical two-tail	2.2621589	

The collapse of paired boards were significantly different
The collapse of paired boards were not significantly different

Table F.3 *Two factor ANOVA of checks assessment value after 14 days kiln drying.*

SUMMARY	P1	P2	P3	U1	U2	U3	C	Total
S14								
Count	5	5	5	5	5	5	5	35
Sum	0	0	0	11	9	5	9	34
Average	0	0	0	2.2	1 8	1	1.8	0.97
Variance	0	0	0	1.2	1.7	3	0 2	1.56
E14								
Count	5	5	5	5	5	5	5	35
Sum	4	7	6	6	5	7	8	43
Average	0.8	1.4	1 2	1.2	1	1 4	1.6	1.23
Variance	1.2	0.8	1.2	1.2	0.5	0.3	0.8	0.77
Total								
Count	10	10	10	10	10	10	10	
Sum	4	7	6	17	14	12	17	
Average	0.4	0.7	0 6	1.7	1.4	1.2	1.7	
Variance	0.71	0.9	0.93	1.34	1 1556	1.51	0.46	

ANOVA								
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*		
Sample	1.16	1	1.16	1.34	0 2521	4.01		
Columns	17.2	6	2.87	3 32	0.0073	2.27		
Interaction	13 5	6	2.26	2.61	0.0265	2.27		
Within	48.4	56	0.86					
Total	80.3	69						

- P value of columns < 0.01 → the treatments significantly affected boards' checking.
- S14 = check grading value on the surfaces of boards after 14 days drying; E14 = check grading value on the edges of boards after 14days drying.

Paired t-test

	C	*P1*
Mean	1.7	0.4
Variance	0.45556	0.71111
Observations	10	10
Pearson Correlation	0.23426	
Hypothesized Mean Difference	0	
df	9	
t Stat	4.33333	
P(T<=t) one-tail	0.00095	
t Critical one-tail	1.83311	
P(T<=t) two-tail	0.0019	
t Critical two-tail	2.26216	

	C	*P2*
Mean	1.7	0 7
Variance	0.45556	0.9
Observations	10	10
Pearson Correlation	0.36441	
Hypothesized Mean Difference	0	
df	9	
t Stat	3.3541	
P(T<=t) one-tail	0.00423	
t Critical one-tail	1.83311	
P(T<=t) two-tail	0.00847	
t Critical two-tail	2.26216	

	C	*P3*
Mean	1.7	0.6
Variance	0.45556	0.93333
Observations	10	10
Pearson Correlation	0.30672	
Hypothesized Mean Difference	0	
df	9	
t Stat	3.49799	
P(T<=t) one-tail	0.00337	
t Critical one-tail	1.83311	
P(T<=t) two-tail	0 00674	
t Critical two-tail	2.26216	

The check of paired boards were significantly different

The check of paired boards were not significantly different

Two factor ANOVA of checking assessment value of P1, P2 and P3 boards

SUMMARY	P1	P2	P3	Total		
S14						
Count	5	5	5	15		
Sum	0	0	0	0		
Average	0	0	0	0		
Variance	0	0	0	0		
E14						
Count	5	5	5	15		
Sum	4	7	6	17		
Average	0.8	1.4	1.2	1.13		
Variance	1.2	0.8	1.2	0 98		
Total						
Count	10	10	10			
Sum	4	7	6			
Average	0.4	0.7	0.6			
Variance	0.71	0.9	0.93			
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	9.63	1	9.63	18.1	0.0003	4.26
Columns	0.47	2	0.23	0.44	0.6507	3.4
Interaction	0.47	2	0.23	0.44	0.6507	3.4
Within	12.8	24	0.53			
Total	23.4	29				

- P value of sample < 0.01 → checking on the surfaces and edges of P boards were significantly different.
- S14 = check grading value on the surfaces of boards after 14 days drying; E14 = check grading value on the edges of boards after 14days drying.

Two factor ANOVA of checking assessment value of U1, U2, U3 and C boards

SUMMARY	U1	U2	U3	C	Total	
S14						
Count	5	5	5	5	20	
Sum	11	9	5	9	34	
Average	2 2	1.8	1	1.8	1.7	
Variance	1.2	1.7	3	0.2	1.4842	
E14						
Count	5	5	5	5	20	
Sum	6	5	7	8	26	
Average	1.2	1	1.4	1.6	1.3	
Variance	1.2	0.5	0.3	0.8	0.6421	
Total						
Count	10	10	10	10		
Sum	17	14	12	17		
Average	1.7	1.4	1.2	1.7		
Variance	1.34	1.16	1.51	0.46		

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	1.6	1	1 6	1.44	0.2392	4.15
Columns	1.8	3	0.6	0.54	0.6588	2.9
Interaction	3	3	1	0.9	0.4525	2.9
Within	35.6	32	1.11			
Total	42	39				

- P value of sample > 0.05 → checking on the surfaces and edges of (U and C) boards were not significantly different.
- P value of columns > 0.05 → Surface coating with UF resin did not affect checking on boards.
- S14 = check grading value on the surfaces of boards after 14 days drying; E14 = check grading value on the edges of boards after 14days drying.

Appendix G

Assessment data and analysis of boards surface coated with PVA and soaked in water and urea solution

Table G.1 *Two factor ANOVA of the drying rate (revealed in %/day) of boards.*

SUMMARY	P	CP	S8W	CS	S2W	CU	C	CC	W	CW	Total
DRI											
Count	13	13	13	13	13	13	13	13	13	13	130
Sum	5.01451	5 72727	0.96927	5.60918	2.58944	5.238	5.0744	5.63068	7.73332	5 85033	49.4364
Average	0.38573	0.44056	0.07456	0.43148	0.19919	0.40292	0.3903	0.43313	0.59487	0.45003	0.38028
Variance	0 00255	0.00188	0.00031	0.00037	0.00046	0.00204	0.0023	0.00155	0.00339	0.00359	0.02055
DRII											
Count	13	13	13	13	13	13	13	13	13	13	130
Sum	5.46416	4.58809	5.87046	4 63149	5.41364	4.71966	4.4731	4.35384	4.43128	5.01544	48 9611
Average	0.42032	0.35293	0 45157	0.35627	0.41643	0 36305	0.3441	0.33491	0.34087	0 3858	0.37662
Variance	0.00863	0.00808	0 0031	0.00212	0.00214	0.00183	0.0057	0.00093	0.00355	0.00175	0.00498
Total											
Count	26	26	26	26	26	26	26	26	26	26	
Sum	10.4787	10.3154	6.83973	10.2407	8.00308	9.95766	9.5475	9.98452	12.1646	10.8658	
Average	0 40303	0 39674	0 26307	0 39387	0.30781	0.38299	0.3672	0.38402	0 46787	0.41791	
Variance	0.00568	0.00678	0.03859	0 00267	0.01352	0.00227	0.0044	0 0037	0.02011	0.00364	

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.00087	1	0.00087	0.30848	0 57913	3.8805
Columns	0.75948	9	0.08439	29.9651	1.1E-34	1.91903
Interaction	1.85739	9	0.20638	73.2824	8 2E-64	1 91903
Within	0.67588	240	0.00282			
Total	3 29362	259				

- P value of columns < 0.01 → the treatments significantly affected the boards' drying rate.
- P, S8W, S2W, C, and W were codes of treated boards.
- CP, CS, CU, CC, and CW were codes of control boards.
- *DRI* = the drying rate of boards in the three months drying; *DRI* = the drying rate of boards in the forth month kiln drying.

Paired t-test of total drying rate of the boards

	P	CP
Mean	0.3934	0.4212
Variance	0.0013	0.0007
Observations	13	13
Pearson Correlation	0.5436	
Hypothesized Mean Difference	0	
df	12	
t Stat	-3.162	
P(T<=t) one-tail	0.0041	
t Critical one-tail	1 7823	
P(T<=t) two-tail	0.0082	
t Critical two-tail	2.1788	

	S8W	CS
Mean	0.158	0.4148
Variance	0 0002	0.0003
Observations	13	13
Pearson Correlation	0.4513	
Hypothesized Mean Difference	0	
df	12	
t Stat	-56.91	
P(T<=t) one-tail	3E-16	
t Critical one-tail	1.7823	
P(T<=t) two-tail	6E-16	
t Critical two-tail	2.1788	

	S2W	CU
Mean	0.2473	0.3941
Variance	0 0002	0.0012
Observations	13	13
Pearson Correlation	0.8459	
Hypothesized Mean Difference	0	
df	12	
t Stat	-21.65	
P(T<=t) one-tail	3E-11	
t Critical one-tail	1.7823	
P(T<=t) two-tail	6E-11	
t Critical two-tail	2.1788	

	C	CC
Mean	0.3801	0.4114
Variance	0 0008	0.0008
Observations	13	13
Pearson Correlation	0.8623	
Hypothesized Mean Difference	0	
df	12	
t Stat	-7.532	
P(T<=t) one-tail	3E-06	
t Critical one-tail	1.7823	
P(T<=t) two-tail	7E-06	
t Critical two-tail	2.1788	

	W	CW
Mean	0.5387	0.4358
Variance	0.0028	0.0021
Observations	13	13
Pearson Correlation	0.8478	
Hypothesized Mean Difference	0	
df	12	
t Stat	13.178	
P(T<=t) one-tail	8E-09	
t Critical one-tail	1.7823	
P(T<=t) two-tail	2E-08	
t Critical two-tail	2.1788	

The drying rate of paired boards were significantly different

The drying rate of paired boards were not significantly different

Table G.2 *Two factor ANOVA of normal shrinkage (revealed in %) in tangential and radial direction of slices.*

SUMMARY	S8W	CS	S2W	CU	C	CC	W	CW	Total
Stx (%)									
Count	8	8	8	8	8	8	8	8	64
Sum	83.6	87.36	88.57	89.77	85.88	92.49	91.78	93.15	712.6
Average	10.45	10.92	11.07	11 22	10.74	11.56	11.47	11.64	11.13
Variance	1.818	0.356	1.551	0.627	0.57	1.674	0.475	1 69	1.131
Srx (%)									
Count	8	8	8	8	8	8	8	8	64
Sum	64 16	69.15	78.79	71.43	65.85	75.95	75.42	65.1	565.9
Average	8.02	8.644	9.849	8 928	8.232	9.493	9.428	8.137	8.841
Variance	1.173	0.931	2.987	2.184	1.594	1.879	2.91	2.727	2.249
Total									
Count	16	16	16	16	16	16	16	16	
Sum	147.8	156.5	167.4	161.2	151.7	168 4	167.2	158.2	
Average	9.235	9.782	10.46	10.07	9.484	10.53	10 45	9.891	
Variance	2.97	1 982	2.516	2.714	2.682	2.798	2 694	5.339	

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	168.3	1	168 3	107.1	5E-18	3 926
Columns	25.74	7	3 677	2.34	0.029	2.092
Interaction	11.18	7	1.597	1.016	0.424	2.092
Within	176	112	1.572			
Total	381.2	127				

- P value of sample < 0.01 → the difference of normal shrinkages in tangential and radial directions were very significant.
- P value of columns < 0.05 → the treatments affected the normal shrinkage of slices.
- *Stx (%)* = tangential shrinkage; *Srx (%)* = radial shrinkage.

Paired t-test

	S8W	*CS*
Mean	9.235	9.782
Variance	2 97	1.982
Observations	16	16
Pearson Correlation	0.607	
Hypothesized Mean Difference	0	
df	15	
t Stat	-1.55	
P(T<=t) one-tail	0.071	
t Critical one-tail	1.753	
P(T<=t) two-tail	0.143	
t Critical two-tail	2 131	

	S2W	*CU*
Mean	10 46	10.07
Variance	2.516	2 714
Observations	16	16
Pearson Correlation	0.613	
Hypothesized Mean Difference	0	
df	15	
t Stat	1.083	
P(T<=t) one-tail	0.148	
t Critical one-tail	1.753	
P(T<=t) two-tail	0.296	
t Critical two-tail	2.131	

	C	CC
Mean	9.484	10.53
Variance	2.682	2 798
Observations	16	16
Pearson Correlation	0.375	
Hypothesized Mean Difference	0	
df	15	
t Stat	-2.26	
P(T<=t) one-tail	0 02	
t Critical one-tail	1.753	
P(T<=t) two-tail	0.04	
t Critical two-tail	2.131	

	W	CW
Mean	10.45	9.891
Variance	2 694	5.339
Observations	16	16
Pearson Correlation	0.872	
Hypothesized Mean Difference	0	
df	15	
t Stat	1.879	
P(T<=t) one-tail	0.04	
t Critical one-tail	1.753	
P(T<=t) two-tail	0.08	
t Critical two-tail	2.131	

☐ The normal shrinkage of paired samples were significantly different
☐ The normal shrinkage of paired samples were not significantly different

Table G.3 *Two factor ANOVA of tangential and radial collapse (revealed in %) of slices.*

SUMMARY	S8W	CS	S2W	CU	C	CC	W	CW	Total
Cr (%)									
Count	8	8	8	8	8	8	8	8	64
Sum	-10.34	1.479	-17.61	8.716	0.358	-0.542	4.358	1.856	-11.72
Average	-1.292	0.185	-2.201	1 089	0.045	-0 068	0.545	0.232	-0.183
Variance	0.507	0.825	4.21	1.264	2.546	1 424	0.494	1.322	2.393
Ct (%)									
Count	8	8	8	8	8	8	8	8	64
Sum	-2 368	10.48	5 007	21 48	10.78	11 35	25.3	13.5	95 52
Average	-0.296	1.31	0.626	2.685	1.347	1.418	3 162	1.688	1.492
Variance	3.098	1.425	2 136	8.296	3.492	3.325	1.23	14.67	5.234
Total									
Count	16	16	16	16	16	16	16	16	
Sum	-12.7	11.96	-12.6	30 19	11.13	10.8	29.66	15.36	
Average	-0 794	0.747	-0.788	1.887	0.696	0.675	1.854	0.96	
Variance	1 947	1.387	5.093	5.14	3.27	2 805	2.632	8.027	

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	89.85	1	89.85	28.6	5E-07	3.926
Columns	115.8	7	16.55	5.267	3E-05	2 092
Interaction	12.83	7	1.833	0.584	0.768	2 092
Within	351.8	112	3.141			
Total	570.3	127				

❖ P value of sample < 0.01 → the difference between tangential and radial collapse was very significant.

- P value of columns < 0.01 → the effects of treatments on collapse were very significant.
- *Ct (%)* = tangential collapse; *Cr (%)* = radial collapse.

Paired t-test

	S8W	*CS*
Mean	-0.79	0.747
Variance	1.947	1.387
Observations	16	16
Pearson Correlation	0 044	
Hypothesized Mean Difference	0	
df	15	
t Stat	-3.45	
P(T<=t) one-tail	0.002	
t Critical one-tail	1.753	
P(T<=t) two-tail	0.004	
t Critical two-tail	2.131	

	S2W	*CU*
Mean	-0.79	1.887
Variance	5.093	5 14
Observations	16	16
Pearson Correlation	0.181	
Hypothesized Mean Difference	0	
df	15	
t Stat	-3.7	
P(T<=t) one-tail	0.001	
t Critical one-tail	1.753	
P(T<=t) two-tail	0.002	
t Critical two-tail	2.131	

	C	*CC*
Mean	0.696	0.675
Variance	3.27	2.805
Observations	16	16
Pearson Correlation	-0.22	
Hypothesized Mean Difference	0	
df	15	
t Stat	0.03	
P(T<=t) one-tail	0.488	
t Critical one-tail	1.753	
P(T<=t) two-tail	0.976	
t Critical two-tail	2 131	

	W	*CW*
Mean	1.854	0.96
Variance	2.632	8 027
Observations	16	16
Pearson Correlation	0.273	
Hypothesized Mean Difference	0	
df	15	
t Stat	1 252	
P(T<=t) one-tail	0.115	
t Critical one-tail	1.753	
P(T<=t) two-tail	0.23	
t Critical two-tail	2.131	

	The collapse of paired samples were significantly different
	The collapse of paired samples were not significantly different

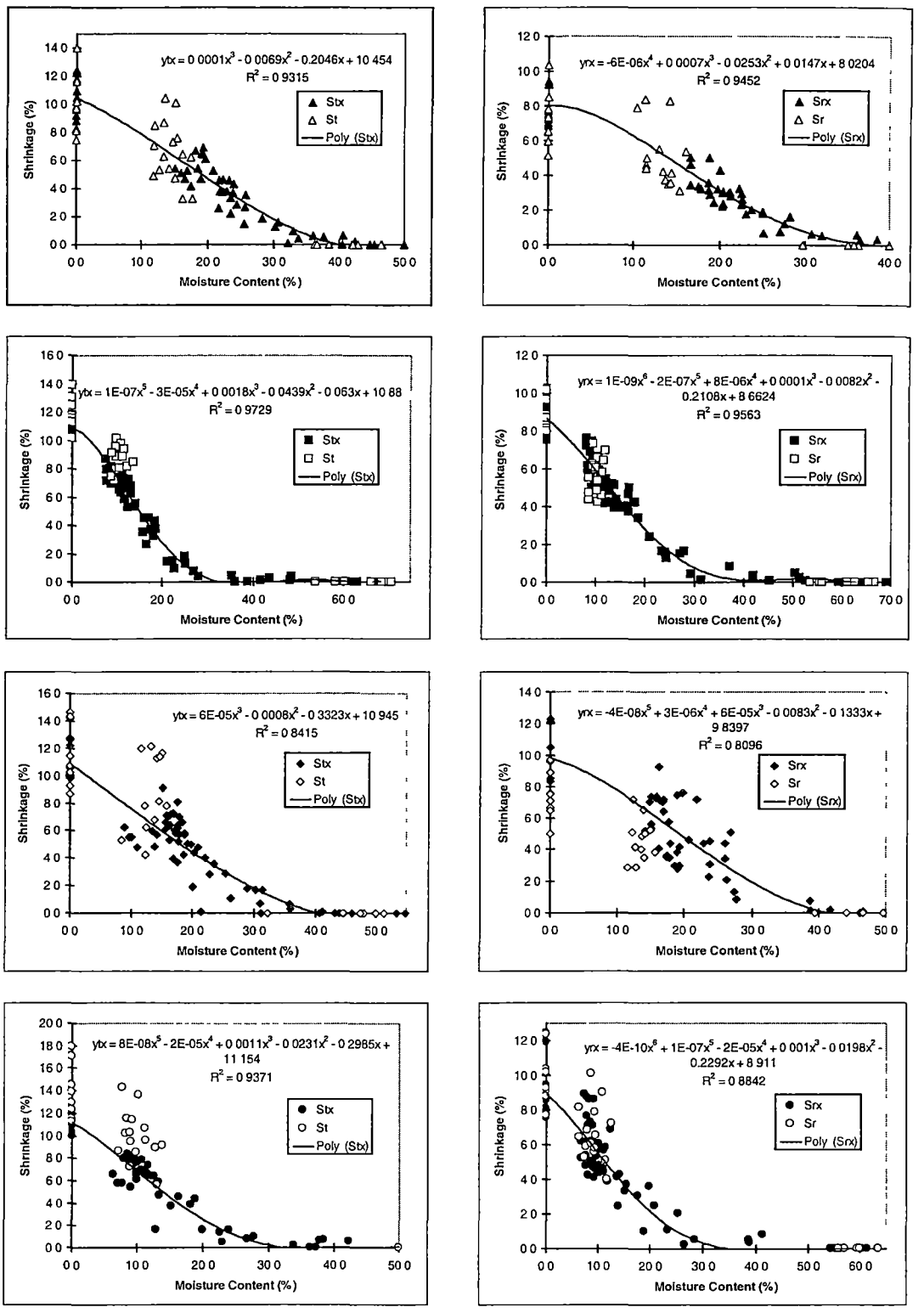


Figure G.1 *Tangential and radial shrinkage of S8W, CS, S2W and CU slices respectively from the top to the bottom of the page: Stx or Srx = normal shrinkage in tangential or radial direction; St or Sr = unconfined shrinkage (including collapse) in tangential or radial direction.*

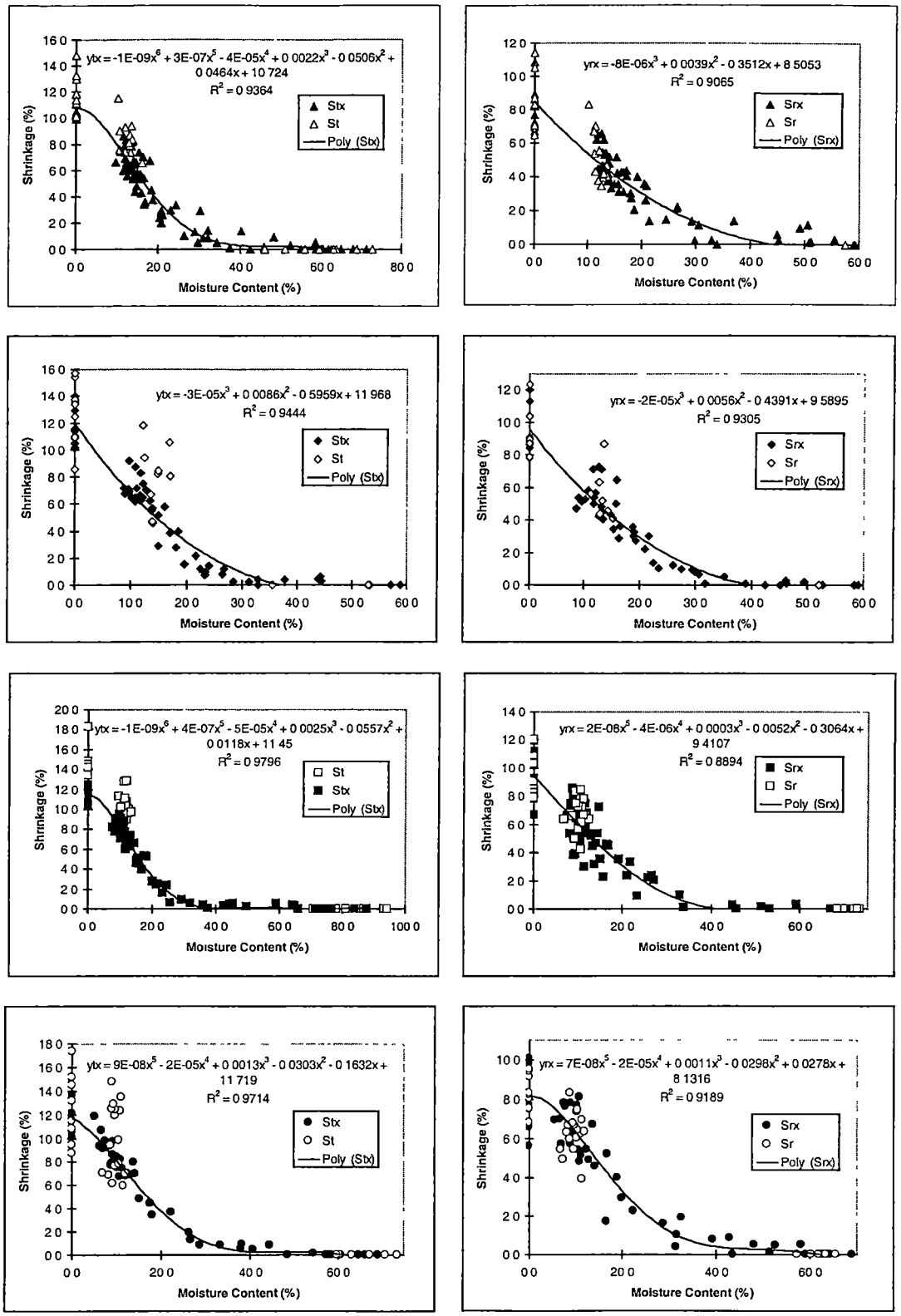


Figure G.2 *Tangential and radial shrinkage of C, CC, W and CW slices respectively from the top to the bottom of the page: Stx or Srx = normal shrinkage in tangential or radial direction; St or Sr = unconfined shrinkage (including collapse) in tangential or radial direction.*

Table G.4 *Two factor ANOVA analysis of board shrinkage (revealed in %) after 122 days kiln drying.*

SUMMARY	P	CP	S8W	CS	S2W	CU	C	CC	W	CW	Total
St122											
Count	13	13	13	13	13	13	13	13	13	13	130
Sum	125.68	136.73	51.207	111.78	74.97	117 43	114.27	117.57	123 14	117.63	1090.4
Average	9.6677	10.518	3.939	8.5986	5.7669	9.033	8.79	9.0442	9 4725	9.0488	8.3878
Variance	11.565	12 262	1.2461	3.7717	4.8893	8.1917	10.686	6.7715	3.4949	3.564	9.7585
Sw122											
Count	13	13	13	13	13	13	13	13	13	13	130
Sum	151.82	147.66	51.212	130.73	99.844	126.78	134.61	129.79	144.61	137.11	1254 2
Average	11.678	11 358	3.9394	10.056	7.6803	9.7524	10.355	9.9842	11.124	10 547	9.6475
Variance	6.7073	7.9031	0.2749	2.1603	6.8958	3.8742	7.8485	5.124	2.2798	2.7806	9.03
Total											
Count	26	26	26	26	26	26	26	26	26	26	
Sum	277.5	284.39	102.42	242.51	174.81	244 21	248 88	247.37	267.75	254.75	
Average	10.673	10.938	3.9392	9.3274	6.7236	9.3927	9.5723	9.5142	10.298	9.7979	
Variance	9 8218	9.863	0.7301	3.3997	6.6088	5.9262	9.533	5.9396	3.481	3.629	

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	103.13	1	103.13	18.368	3E-05	3 8805
Columns	1053.5	9	117.06	20.849	8E-26	1 919
Interaction	22 682	9	2.5202	0.4489	0.9071	1.919
Within	1347.5	240	5.6146			
Total	2526.8	259				

- P value of sample < 0.01 → the difference of boards' shrinkage in width and thickness was very significant.
- *St122* = shrinkage in the thickness of boards after 122 days drying; *Sw122* = shrinkage in the width of boards after 122 days drying.

Paired t-test

	P	*CP*
Mean	10.673	10.938
Variance	9.8218	9.863
Observations	26	26
Pearson Correlation	0.8665	
Hypothesized Mean Difference	0	
df	25	
t Stat	-0.834	
P(T<=t) one-tail	0.2061	
t Critical one-tail	1.7081	
P(T<=t) two-tail	0.4123	
t Critical two-tail	2.0595	

	S8W	*CS*
Mean	3 9392	9.3274
Variance	0.7301	3 3997
Observations	26	26
Pearson Correlation	0.6684	
Hypothesized Mean Difference	0	
df	25	
t Stat	-19 31	
P(T<=t) one-tail	8E-17	
t Critical one-tail	1.7081	
P(T<=t) two-tail	2E-16	
t Critical two-tail	2.0595	

	S2W	CU
Mean	6.7236	9 3927
Variance	6 6088	5.9262
Observations	26	26
Pearson Correlation	0.8174	
Hypothesized Mean Difference	0	
df	25	
t Stat	-8.966	
P(T<=t) one-tail	1E-09	
t Critical one-tail	1.7081	
P(T<=t) two-tail	3E-09	
t Critical two-tail	2.0595	

	C	CC
Mean	9.5723	9.5142
Variance	9.533	5.9396
Observations	26	26
Pearson Correlation	0.8975	
Hypothesized Mean Difference	0	
df	25	
t Stat	0 2114	
P(T<=t) one-tail	0.4172	
t Critical one-tail	1.7081	
P(T<=t) two-tail	0.8343	
t Critical two-tail	2.0595	

	W	CW
Mean	10.298	9.7979
Variance	3.481	3.629
Observations	26	26
Pearson Correlation	0 6821	
Hypothesized Mean Difference	0	
df	25	
t Stat	1.6967	
P(T<=t) one-tail	0.0511	
t Critical one-tail	1.7081	
P(T<=t) two-tail	0 1022	
t Critical two-tail	2.0595	

	Sw122	Swr
Mean	9.647	5 184
Variance	9.03	4 354
Observations	130	130
Pearson Correlation	0.825	
Hypothesized Mean Difference	0	
df	129	
t Stat	29.18	
P(T<=t) one-tail	6E-59	
t Critical one-tail	1.657	
P(T<=t) two-tail	1E-58	
t Critical two-tail	1.979	

	St122	Str
Mean	8.388	5.205
Variance	9.759	5.259
Observations	130	130
Pearson Correlation	0.561	
Hypothesized Mean Difference	0	
df	129	
t Stat	13.74	
P(T<=t) one-tail	3E-27	
t Critical one-tail	1 657	
P(T<=t) two-tail	5E-27	
t Critical two-tail	1 979	

	M122	Mr
Mean	17.1	19 07
Variance	2.007	6 87
Observations	129	129
Pearson Correlation	0.721	
Hypothesized Mean Difference	0	
df	128	
t Stat	-11.9	
P(T<=t) one-tail	9E-23	
t Critical one-tail	1.657	
P(T<=t) two-tail	2E-22	
t Critical two-tail	1.979	

❖ St122 or Str = thickness shrinkage after 122 days drying or conditioning; Sw122 or Swr = width shrinkage after 122 days drying or conditioning; M122 or Mr = moisture content of board after 122 days drying or conditioning.

The shrinkage of paired boards were significantly different

The shrinkage of paired boards were not significantly different

Table G.5 *Two factor ANOVA of collapse value on the boards based on visual grading.*

SUMMARY	P	CP	S8W	CS	S2W	CU	C	CC	W	CW	Total
S											
Count	16	16	16	16	16	16	16	16	16	16	160
Sum	5	10	10	14	7	5	8	11	5	9	84
Average	0.313	0.625	0.625	0.875	0 438	0.313	0.5	0.688	0.313	0.563	0.525
Variance	0.229	0.25	0.517	0.517	0.396	0 363	0 4	0.496	0 229	0.396	0.389
E											
Count	16	16	16	16	16	16	16	16	16	16	160
Sum	9	11	1	14	11	9	17	14	9	10	105
Average	0.563	0.688	0.063	0.875	0 688	0.563	1.063	0.875	0.563	0.625	0 656
Variance	0 396	0 629	0 063	0 65	0.629	0 263	0.729	0 65	0 529	0.383	0.529
Total											
Count	32	32	32	32	32	32	32	32	32	32	
Sum	14	21	11	28	18	14	25	25	14	19	
Average	0.438	0.656	0.344	0.875	0.563	0.438	0.781	0.781	0.438	0.594	
Variance	0.319	0.426	0.362	0.565	0.512	0 319	0.628	0.564	0.383	0.378	

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	1.378	1	1.378	3.164	0.076	3.873
Columns	9.278	9	1.031	2.366	0.014	1.911
Interaction	6.028	9	0.67	1.538	0.134	1.911
Within	130.7	300	0.436			
Total	147.4	319				

- P value of columns < 0.05 → the effects of treatments on the boards' collapse were significant.
- S = collapse on the boards' surface; E = collapse on the boards' edges.

Two factor ANOVA of collapse values (without S8W data)

SUMMARY	P	CP	CS	S2W	CU	C	CC	W	CW	Total
S										
Count	16	16	16	16	16	16	16	16	16	144
Sum	5	10	14	7	5	8	11	5	9	74
Average	0.313	0.625	0.875	0 438	0.313	0.5	0.688	0 313	0.563	0.514
Variance	0.229	0.25	0.517	0 396	0.363	0.4	0 496	0 229	0.396	0.377
E										
Count	16	16	16	16	16	16	16	16	16	144
Sum	9	11	14	11	9	17	14	9	10	104
Average	0.563	0.688	0.875	0.688	0.563	1 063	0.875	0.563	0.625	0.722
Variance	0.396	0.629	0.65	0.629	0.263	0.729	0.65	0.529	0.383	0 538
Total										
Count	32	32	32	32	32	32	32	32	32	
Sum	14	21	28	18	14	25	25	14	19	
Average	0.438	0.656	0 875	0.563	0.438	0.781	0.781	0.438	0.594	
Variance	0.319	0.426	0.565	0.512	0 319	0.628	0 564	0.383	0.378	

ANOVA										
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*				
Sample	3.125	1	3.125	6.916	0.009	3.876				
Columns	7.111	8	0.889	1 967	0.051	1.973				
Interaction	1.75	8	0.219	0.484	0 867	1.973				
Within	122	270	0.452							
Total	134	287								

- P value of sample < 0.01 → the difference of boards' collapse on the surfaces and edges was very significant.
- S = collapse on the boards' surface; E = collapse on the boards' edges.

Paired t-test

	P	*CP*
Mean	0.4375	0.65625
Variance	0.31855	0.42641
Observations	32	32
Pearson Correlation	-0.0164	
Hypothesized Mean Difference	0	
df	31	
t Stat	-1.4222	
P(T<=t) one-tail	0.08248	
t Critical one-tail	1.69552	
P(T<=t) two-tail	0.16495	
t Critical two-tail	2.03951	

	S8W	*CS*
Mean	0.34375	0.875
Variance	0.3619	0.56452
Observations	32	32
Pearson Correlation	0 02676	
Hypothesized Mean Difference	0	
df	31	
t Stat	-3 1639	
P(T<=t) one-tail	0.00174	
t Critical one-tail	1.69552	
P(T<=t) two-tail	0 00348	
t Critical two-tail	2.03951	

	S2W	*CU*
Mean	0.5625	0.4375
Variance	0.5121	0.31855
Observations	32	32
Pearson Correlation	0.56906	
Hypothesized Mean Difference	0	
df	31	
t Stat	1.16096	
P(T<=t) one-tail	0.12726	
t Critical one-tail	1.69552	
P(T<=t) two-tail	0.25452	
t Critical two-tail	2 03951	

	C	*CC*
Mean	0.78125	0.78125
Variance	0.62802	0.56351
Observations	32	32
Pearson Correlation	0.35077	
Hypothesized Mean Difference	0	
df	31	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	1 69552	
P(T<=t) two-tail	1	
t Critical two-tail	2.03951	

	W	*CW*
Mean	0 4375	0.59375
Variance	0.38306	0.37802
Observations	32	32
Pearson Correlation	0 31259	
Hypothesized Mean Difference	0	
df	31	
t Stat	-1 222	
P(T<=t) one-tail	0.11546	
t Critical one-tail	1.69552	
P(T<=t) two-tail	0.23092	
t Critical two-tail	2.03951	

Surface collapse	*P*	*CP*
Mean	0.3125	0.625
Variance	0.22917	0.25
Observations	16	16
Pearson Correlation	0.52223	
Hypothesized Mean Difference	0	
df	15	
t Stat	-2 6112	
P(T<=t) one-tail	0.00983	
t Critical one-tail	1.75305	
P(T<=t) two-tail	0.01966	
t Critical two-tail	2.13145	

Edge collapse	*P*	*CP*
Mean	0 5625	0.6875
Variance	0.39583	0 62917
Observations	16	16
Pearson Correlation	-0.2922	
Hypothesized Mean Difference	0	
df	15	
t Stat	-0.4357	
P(T<=t) one-tail	0 33461	
t Critical one-tail	1.75305	
P(T<=t) two-tail	0.66923	
t Critical two-tail	2.13145	

	The collapse of paired boards were significantly different
	The collapse of paired boards were not significantly different

Table G.6 *Two factor ANOVA analysis of checking on boards after 37 days of kiln drying.*

SUMMARY	P	CP	S8W	CS	S2W	CU	C	CC	W	CW	Total
S											
Count	16	16	16	16	16	16	16	16	16	16	160
Sum	0	26	0	18	12	14	8	21	21	21	141
Average	0	1.625	0	1.125	0.75	0.875	0.5	1.313	1.313	1.313	0.881
Variance	0	1.583	0	1 583	1.4	1.45	1.2	1.429	2.629	1.296	1.476
E											
Count	16	16	16	16	16	16	16	16	16	16	160
Sum	2	0	0	0	2	0	0	0	0	0	4
Average	0.125	0	0	0	0 125	0	0	0	0	0	0 025
Variance	0.25	0	0	0	0.25	0	0	0	0	0	0.05
Total											
Count	32	32	32	32	32	32	32	32	32	32	
Sum	2	26	0	18	14	14	8	21	21	21	
Average	0.063	0.813	0	0.563	0.438	0.438	0 25	0 656	0.656	0.656	
Variance	0.125	1.448	0	1.093	0.899	0.899	0.645	1.136	1.717	1.072	

ANOVA							
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*	
Sample	58.65	1	58.65	89 75	8E-19	3.873	
Columns	21.27	9	2.363	3.615	3E-04	1.911	
Interaction	25.32	9	2.813	4.304	3E-05	1.911	
Within	196.1	300	0 654				
Total	301.3	319					

- P value of sample < 0.01 → the difference of checking on the surfaces and edges of boards was very significant.
- P value of columns < 0.01 → the effects of treatments on checking was very significant.
- S = the grading value of check on the boards' surface; E = the grading value of check on the boards' edges.

Paired t-test

	P	*CP*
Mean	0.0625	0.8125
Variance	0.125	1.44758
Observations	32	32
Pearson Correlation	-0.1232	
Hypothesized Mean Difference	0	
df	31	
t Stat	-3.2758	
P(T<=t) one-tail	0.0013	
t Critical one-tail	1.69552	
P(T<=t) two-tail	0.0026	
t Critical two-tail	2.03951	

	S8W	*CS*
Mean	0	0.5625
Variance	0	1.09274
Observations	32	32
Pearson Correlation	#DIV/0!	
Hypothesized Mean Difference	0	
df	31	
t Stat	-3.044	
P(T<=t) one-tail	0.00236	
t Critical one-tail	1.69552	
P(T<=t) two-tail	0.00473	
t Critical two-tail	2.03951	

	S2W	*CU*
Mean	0.4375	0 4375
Variance	0.89919	0.89919
Observations	32	32
Pearson Correlation	0.35426	
Hypothesized Mean Difference	0	
df	31	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	1.69552	
P(T<=t) two-tail	1	
t Critical two-tail	2.03951	

	C	*CC*
Mean	0.25	0.65625
Variance	0.64516	1 13609
Observations	32	32
Pearson Correlation	0.25433	
Hypothesized Mean Difference	0	
df	31	
t Stat	-1.981	
P(T<=t) one-tail	0.02826	
t Critical one-tail	1.69552	
P(T<=t) two-tail	0.05652	
t Critical two-tail	2 03951	

	W	*CW*
Mean	0.65625	0.65625
Variance	1.71673	1 07157
Observations	32	32
Pearson Correlation	0.71871	
Hypothesized Mean Difference	0	
df	31	
t Stat	0	
P(T<=t) one-tail	0.5	
t Critical one-tail	1.69552	
P(T<=t) two-tail	1	
t Critical two-tail	2.03951	

	CP	*CS*
Mean	0 8125	0 5625
Variance	1.44758	1.09274
Observations	32	32
Pearson Correlation	0.62518	
Hypothesized Mean Difference	0	
df	31	
t Stat	1.43759	
P(T<=t) one-tail	0.08028	
t Critical one-tail	1 69552	
P(T<=t) two-tail	0.16057	
t Critical two-tail	2.03951	

	The check of paired boards were significantly different
	The check of paired boards were not significantly different

Table G.7 *Two factor ANOVA analysis of checking on boards after 95 days of kiln drying.*

SUMMARY	P	CP	S8W	CS	S2W	CU	C	CC	W	CW	Total
S											
Count	16	16	16	16	16	16	16	16	16	16	160
Sum	0	16	18	15	15	17	13	18	15	21	148
Average	0	1	1.125	0.938	0.938	1.063	0.813	1.125	0.938	1.313	0.925
Variance	0	0.667	1.45	0.996	0.996	1.396	1.096	0.783	0.729	0 629	0.938
E											
Count	16	16	16	16	16	16	16	16	16	16	160
Sum	2	0	0	0	0	0	0	0	0	0	2
Average	0.125	0	0	0	0	0	0	0	0	0	0.013
Variance	0.25	0	0	0	0	0	0	0	0	0	0 025
Total											
Count	32	32	32	32	32	32	32	32	32	32	
Sum	2	16	18	15	15	17	13	18	15	21	
Average	0.063	0.5	0 563	0.469	0 469	0.531	0.406	0.563	0.469	0.656	
Variance	0.125	0 581	1.028	0.709	0 709	0.967	0.701	0.706	0.58	0.749	

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	66 61	1	66.61	148 2	6E-28	3.873
Columns	7.25	9	0.806	1.792	0.069	1.911
Interaction	10.95	9	1.217	2 706	0.005	1 911
Within	134.9	300	0 45			
Total	219.7	319				

- P value of sample < 0.01 → the difference of checking on the surface and edges of boards was very significant.
- S = the grading value of check on the boards' surface; E = the grading value of check on the boards' edges.

Paired t-test

	P	CP
Mean	0.0625	0.5
Variance	0.125	0.58065
Observations	32	32
Pearson Correlation	-0 1197	
Hypothesized Mean Difference	0	
df	31	
t Stat	-2.8201	
P(T<=t) one-tail	0.00415	
t Critical one-tail	1.69552	
P(T<=t) two-tail	0.0083	
t Critical two-tail	2.03951	

	S8W	CS
Mean	0.563	0.469
Variance	1.028	0.709
Observations	32	32
Pearson Correlation	0 588	
Hypothesized Mean Difference	0	
df	31	
t Stat	0.619	
P(T<=t) one-tail	0.27	
t Critical one-tail	1.696	
P(T<=t) two-tail	0.54	
t Critical two-tail	2.04	

	S2W	CU
Mean	0.46875	0.53125
Variance	0.70867	0.96673
Observations	32	32
Pearson Correlation	0.42992	
Hypothesized Mean Difference	0	
df	31	
t Stat	-0.3601	
P(T<=t) one-tail	0 36059	
t Critical one-tail	1.69552	
P(T<=t) two-tail	0.72118	
t Critical two-tail	2.03951	

	C	CC
Mean	0.406	0.563
Variance	0.701	0.706
Observations	32	32
Pearson Correlation	0.628	
Hypothesized Mean Difference	0	
df	31	
t Stat	-1.222	
P(T<=t) one-tail	0.115	
t Critical one-tail	1.696	
P(T<=t) two-tail	0.231	
t Critical two-tail	2.04	

	W	CW
Mean	0.46875	0.65625
Variance	0.57964	0.74899
Observations	32	32
Pearson Correlation	0.83993	
Hypothesized Mean Difference	0	
df	31	
t Stat	-2.2523	
P(T<=t) one-tail	0 01577	
t Critical one-tail	1.69552	
P(T<=t) two-tail	0.03153	
t Critical two-tail	2.03951	

	CP	CW
Mean	0 5	0.656
Variance	0.581	0.749
Observations	32	32
Pearson Correlation	0.709	
Hypothesized Mean Difference	0	
df	31	
t Stat	-1 408	
P(T<=t) one-tail	0.085	
t Critical one-tail	1 696	
P(T<=t) two-tail	0.169	
t Critical two-tail	2.04	

The check of paired boards were significantly different

The check of paired boards were not significantly different

Table G.8 *Two factor ANOVA analysis of checking on boards after 122 days of kiln drying.*

SUMMARY	P	CP	S8W	CS	S2W	CU	C	CC	W	CW	Total
S											
Count	16	16	16	16	16	16	16	16	16	16	160
Sum	0	25	36	21	29	24	19	25	20	24	223
Average	0	1.563	2.25	1.313	1.813	1.5	1.188	1.563	1.25	1.5	1.394
Variance	0	0.663	1 933	0 896	1.496	0.667	1.363	0.663	0.733	0.667	1.158
E											
Count	16	16	16	16	16	16	16	16	16	16	160
Sum	0	3	3	0	6	0	1	0	0	0	13
Average	0	0.188	0.188	0	0.375	0	0.063	0	0	0	0.081
Variance	0	0.163	0.163	0	0.383	0	0.063	0	0	0	0.088
Total											
Count	32	32	32	32	32	32	32	32	32	32	
Sum	0	28	39	21	35	24	20	25	20	24	
Average	0	0.875	1.219	0.656	1.094	0 75	0.625	0.781	0.625	0.75	
Variance	0	0.887	2.112	0.878	1.443	0.903	1.016	0.951	0.758	0.903	

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	137.8	1	137.8	279.8	8E-45	3 873
Columns	30.58	9	3.397	6.898	5E-09	1.911
Interaction	19.81	9	2.201	4.47	2E-05	1.911
Within	147.8	300	0 493			
Total	336	319				

- P value of sample < 0.01 → the difference of checking on surfaces and edges of boards was very significant.
- P value of columns < 0.01 → the effects of treatments on checking were very significant.
- S = the grading value of check on the boards' surface; E = the grading value of check on the boards' edges.

Paired t-test

	P	*CP*
Mean	0	0.875
Variance	0	0.8871
Observations	32	32
Pearson Correlation	#DIV/0!	
Hypothesized Mean Difference	0	
df	31	
t Stat	-5.2553	
P(T<=t) one-tail	5.2E-06	
t Critical one-tail	1.69552	
P(T<=t) two-tail	1E-05	
t Critical two-tail	2.03951	

	S8W	*CS*
Mean	1.21875	0.65625
Variance	2.1119	0.87802
Observations	32	32
Pearson Correlation	0.69661	
Hypothesized Mean Difference	0	
df	31	
t Stat	3.04396	
P(T<=t) one-tail	0.00236	
t Critical one-tail	1.69552	
P(T<=t) two-tail	0.00473	
t Critical two-tail	2.03951	

	S2W	*CU*
Mean	1.09375	0.75
Variance	1.44254	0.90323
Observations	32	32
Pearson Correlation	0.75596	
Hypothesized Mean Difference	0	
df	31	
t Stat	2.46965	
P(T<=t) one-tail	0.00962	
t Critical one-tail	1.69552	
P(T<=t) two-tail	0.01923	
t Critical two-tail	2.03951	

	C	*CC*
Mean	0.625	0.78125
Variance	1.01613	0.9506
Observations	32	32
Pearson Correlation	0.66875	
Hypothesized Mean Difference	0	
df	31	
t Stat	-1.0945	
P(T<=t) one-tail	0.14109	
t Critical one-tail	1.69552	
P(T<=t) two-tail	0 28219	
t Critical two-tail	2.03951	

	W	*CW*
Mean	0.625	0.75
Variance	0.75806	0.90323
Observations	32	32
Pearson Correlation	0.89663	
Hypothesized Mean Difference	0	
df	31	
t Stat	-1.6787	
P(T<=t) one-tail	0.05163	
t Critical one-tail	1.69552	
P(T<=t) two-tail	0.10326	
t Critical two-tail	2.03951	

☐ The check of paired boards were significantly different
☐ The check of paired boards were not significantly different

Table G.9 *Two factor ANOVA analysis of check proportion to the length of boards (revealed in %).*

SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
P	13	46.47539	3.57503	77.67754		
CP	13	371.5232	28.57871	306.1733		
S8W	13	742.5358	57.11814	983.2998		
CS	13	287.548	22.11908	388.7077		
S2W	13	403.7645	31.05881	1111.095		
CU	13	373.2813	28.71395	289.5843		
C	13	133.5203	10.2708	115.9581		
CC	13	289.3139	22.25491	162.7958		
W	13	275.8869	21.22207	234.4119		
CW	13	327.7113	25.20856	154.8835		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	23413.17	9	2601.464	6.801947	7.46E-08	1.958764
Within Groups	45895.04	120	382.4587			
Total	69308.22	129				

❖ P value < 0.01 → the effects of treatments on the proportion of check length were very significant.

Paired t-test

	P	*CP*
Mean	3.57503	28.5787
Variance	77.6775	306.173
Observations	13	13
Pearson Correlation	0.14547	
Hypothesized Mean Difference	0	
df	12	
t Stat	-4.8965	
P(T<=t) one-tail	0.00018	
t Critical one-tail	1.78229	
P(T<=t) two-tail	0.00037	
t Critical two-tail	2.17881	

	S8W	*CS*
Mean	57.1181	22.1191
Variance	983.3	388.708
Observations	13	13
Pearson Correlation	-0.5356	
Hypothesized Mean Difference	0	
df	12	
t Stat	2.79789	
P(T<=t) one-tail	0 00805	
t Critical one-tail	1 78229	
P(T<=t) two-tail	0.01611	
t Critical two-tail	2.17881	

	S2W	*CU*
Mean	31.0588	28 7139
Variance	1111.1	289.584
Observations	13	13
Pearson Correlation	-0.3553	
Hypothesized Mean Difference	0	
df	12	
t Stat	0.19907	
P(T<=t) one-tail	0.42277	
t Critical one-tail	1.78229	
P(T<=t) two-tail	0.84554	
t Critical two-tail	2.17881	

	C	*CC*
Mean	10.2708	22.2549
Variance	115.958	162 796
Observations	13	13
Pearson Correlation	0.09287	
Hypothesized Mean Difference	0	
df	12	
t Stat	-2 7153	
P(T<=t) one-tail	0.00939	
t Critical one-tail	1.78229	
P(T<=t) two-tail	0.01877	
t Critical two-tail	2 17881	

	W	CW
Mean	21.2221	25.2086
Variance	234.412	154.883
Observations	13	13
Pearson Correlation	0.25824	
Hypothesized Mean Difference	0	
df	12	
t Stat	-0.8428	
P(T<=t) one-tail	0 20792	
t Critical one-tail	1.78229	
P(T<=t) two-tail	0 41585	
t Critical two-tail	2.17881	

	The check proportion of paired boards were significantly different
	The check proportion of paired boards were not significantly different

Table G.10 *Single factor ANOVA analysis of cupping on boards.*

SUMMARY

Groups	Count	Sum	Average	Variance
P	13	7	0.538462	0.769231
CP	13	12	0.923077	1.076923
S8W	13	10	0.769231	1.025641
CS	13	6	0.461538	0.602564
S2W	13	15	1.153846	0.974359
CU	13	10	0.769231	1.025641
C	13	5	0.384615	0.589744
CC	13	6	0.461538	0.769231
W	13	4	0.307692	0.564103
CW	13	5	0.384615	0.589744

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	8.923077	9	0.991453	1.241306	0.276476	1.958764
Within Groups	95.84615	120	0.798718			
Total	104.7692	129				

❖ P value > 0.05 → the effects of treatments on boards' cupping were not significant.

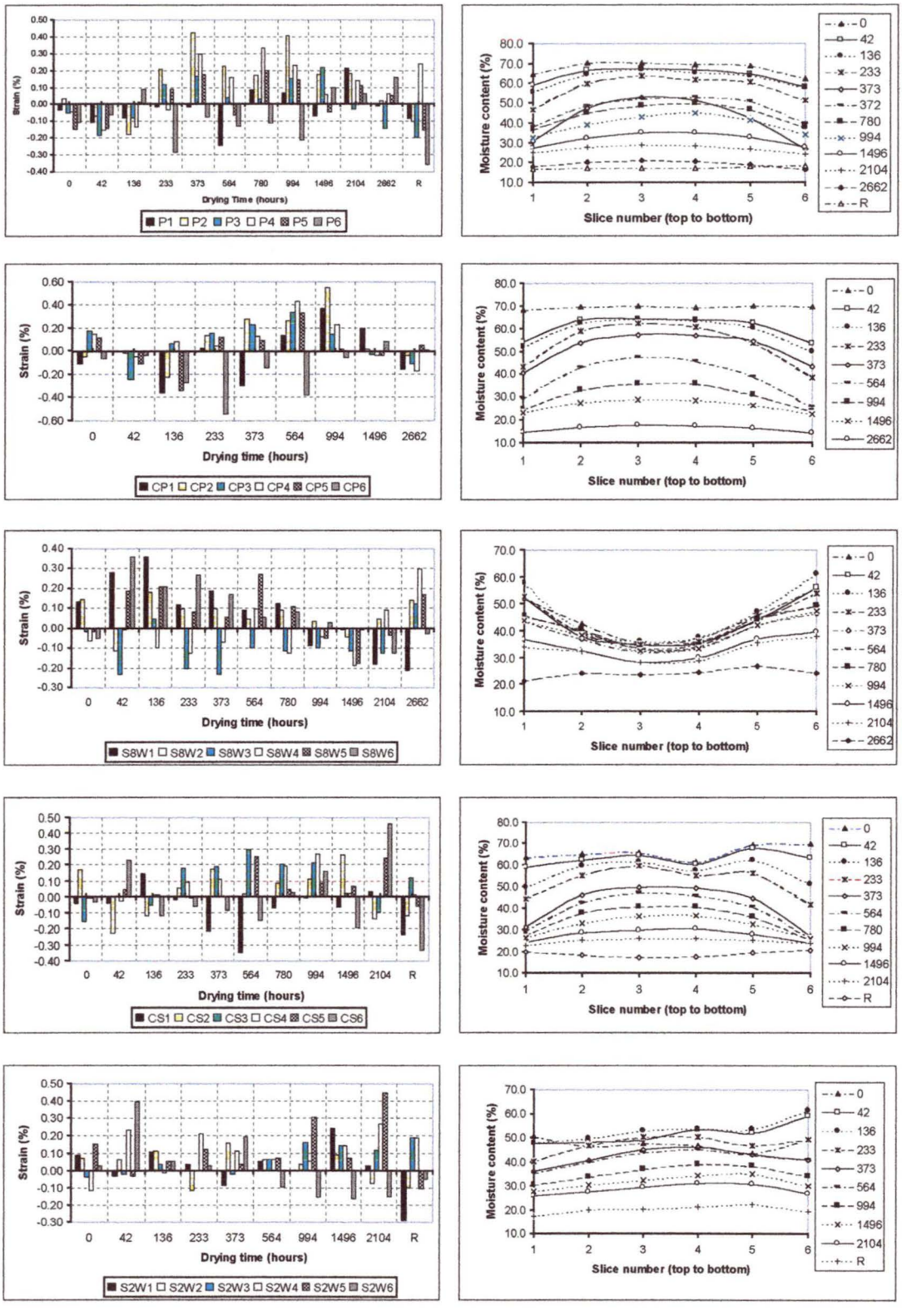


Figure G.3 *Reversible strain and moisture profile of P, CP, S8W, CS, and S2W boards respectively from the top to the bottom of the page obtained by McMillen's method in the first trial.*

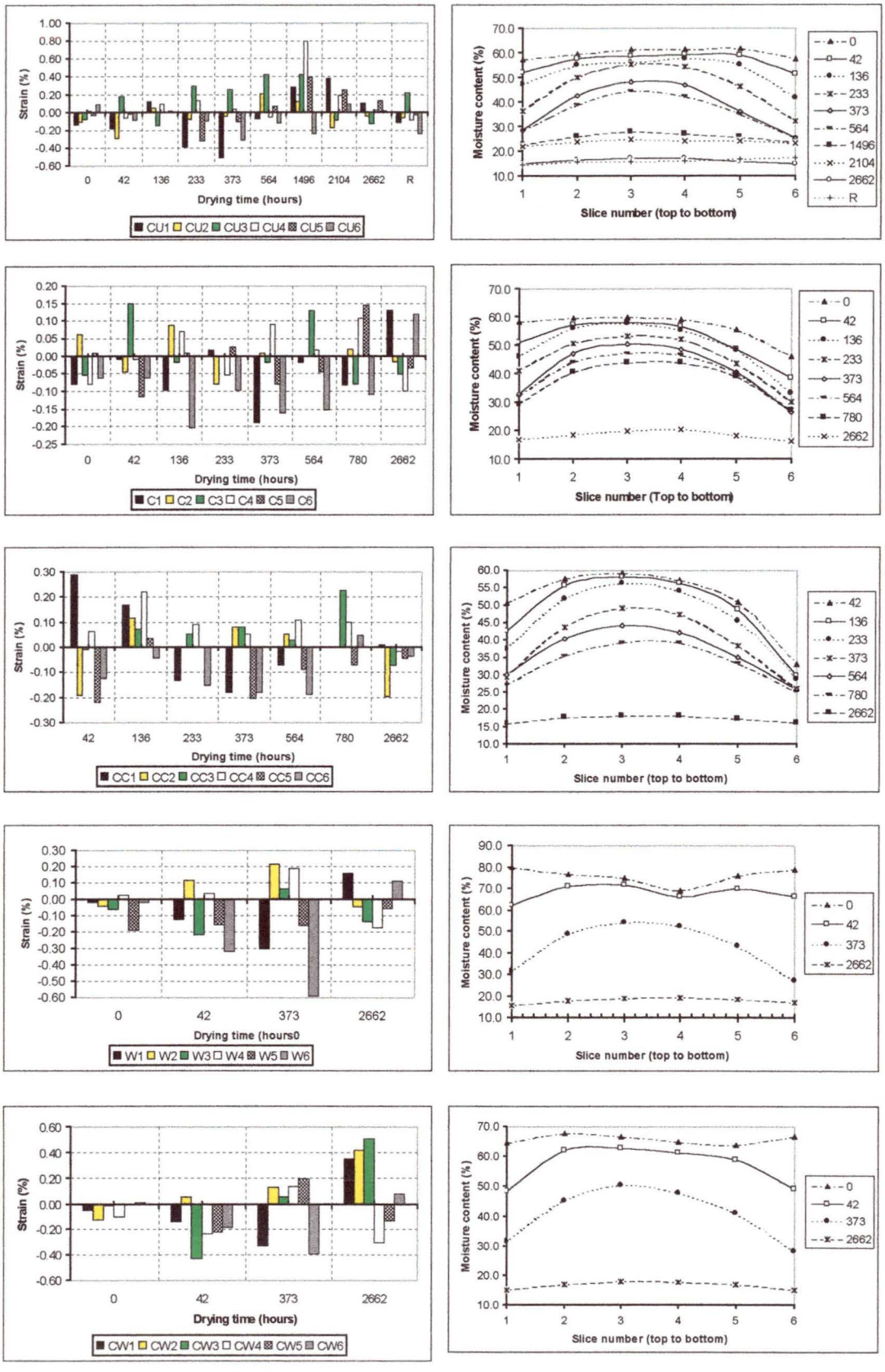


Figure G.4 *Reversible strain and moisture profile of CU, C, CC, W and CW boards respectively from the top to the bottom of the page obtained by McMillen's method in the first trial.*

Table G.11 *Single factor ANOVA of maximum surface recoverable tensile strain (MSTS) and maximum internal recoverable tensile strain (MITS) revealed in %.*

SUMMARY	MSTS	MITS	Total
P			
Count	3	3	6
Sum	-0.89	-0.54	-1.43
Average	-0.29667	-0.18	-0.23833
Variance	0.004433	0.0049	0.007817
CP			
Count	3	3	6
Sum	-1.1	-0.6	-1.7
Average	-0.36667	-0.2	-0.28333
Variance	0.011033	0.0012	0.013227
S8W			
Count	3	3	6
Sum	-0.58	-0.85	-1.43
Average	-0.19333	-0.28333	-0.23833
Variance	0.000933	0.003733	0.004297
CS			
Count	3	3	6
Sum	-1.26	-0.78	-2.04
Average	-0.42	-0.26	-0.34
Variance	0.0031	0.0157	0.0152
S2W			
Count	3	3	6
Sum	-0.84	-0.71	-1.55
Average	-0.28	-0.23667	-0.25833
Variance	0.0097	0.008133	0.007697
CU			
Count	3	3	6
Sum	-1.44	-0.63	-2.07
Average	-0.48	-0.21	-0.345
Variance	0.0199	0.0027	0.03091
C			
Count	3	3	6
Sum	-0.76	-0.44	-1.2
Average	-0.25333	-0.14667	-0.2
Variance	0.002533	0.004133	0.00608
CC			
Count	3	3	6
Sum	-0.82	-0.555	-1.375
Average	-0.27333	-0.185	-0.22917
Variance	0.014633	0.000225	0.008284

SUMMARY	MSTS	MITS	Total
	W		
Count	3	3	6
Sum	-1.22	-0.51	-1.73
Average	-0.40667	-0.17	-0.28833
Variance	0.025033	6.94E-18	0.026817
	CW		
Count	3	3	6
Sum	-1.12	-0.68	-1.8
Average	-0.37333	-0.22667	-0.3
Variance	0.036133	0.008933	0.02448
	Total		
Count	30	30	
Sum	-10.03	-6.295	
Average	-0.33433	-0.20983	
Variance	0.016122	0.00509	

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.123627	9	0.013736	1.551326	0.163712	2.124029
Columns	0.232504	1	0.232504	26.25801	7.96E-06	4.08474
Interaction	0.13735	9	0.015261	1.723532	0.115382	2.124029
Within	0.354183	40	0.008855			
Total	0.847665	59				

- P value of columns < 0.01 → the difference between max surface tensile strain and maximum internal tensile strain was very significant.