A Review of Eucalyptus Wood Collapse and its Control during Drying

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The relevant literature is reviewed concerning eucalyptus wood collapse, with a focus on lumber drying technology. Potential future research is summarized regarding where potential future work may focus. Eucalyptus is often limited as a solid wood products material due to microstructural collapse and interior cracking that may occur during drying. To prevent the drying collapse, studies have focused on the mechanism of collapse, the morphological characteristics of collapse, the control of collapse, amongst other criteria. Because the surface tension of water results in wood cell collapse, the shape of collapsed cells should be recovered after the liquid tension disappears. Therefore, pretreating green timber (such as pre-heating, pre-steaming, microwave treatment, pre-freezing, or boiling) prior to drying results in the modification of wood cell tissue and inhibits the conditions for collapse. Thus, there is improved wood permeability, drying rate, shortened drying time, as well as reduced collapse during the drying process. In addition, applying process control in regards to a suitable drying schedule (especially the drying temperature), relative humidity, drying time, intermittent drying process, combined drying technology, *etc.*, tends to reduce the amount of collapse and improve drying quality. Reconditioning, such as steaming during the drying process, can aid collapse recovery. Generally, reconditioning or other treatment can help recover 50% of the collapse.

Keywords: Eucalyptus wood; Drying defects; Pre-treatment; Process control; Reconditioning

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INTRODUCTION

The genus *Eucalyptus* is widely planted across the southern hemisphere and China. Some of the faster growing eucalyptus species have properties that are well-suited for higher value wood products, *e.g.* furniture, doors, joinery, flooring, veneer, plywood, and laminated lumber, although it is well known that eucalyptus with their high shrinkage are difficult to dry without degrading (Chafe 1995; Vermaas 1995; McKenzie *et al.* 2003a, 2003b). Wood collapse is a drying defect that occurs during wood drying, especially above the fiber saturation point (FSP). The tendency for collapse occurs in most wood species, including softwood species, although hardwood species will experience the most severe collapse (Kauman 1964a, 1964b). Collapse is especially notable in certain species, such as *Eucalyptus urophylla*, *Eucalyptus urophylla* × *E. grandis*, and *Eucalyptus grandis* × *E. urophylla*. Other collapse-prone timbers are radiate pine earlywood (Deyev and Keey 2001), oak, black walnut, western red cedar, and redwood (Langrish and Walker 2006). Therefore, there have been a number of studies on drying characteristics, including collapse and shrinkage (Chafe 1985, 1986a, 1986b, 1987, 1990a). Furthermore, studies on checking and drying technologies that mainly concern various pretreatments (Chafe 1990b, 1992, 1993, 1994a, 1994b), conventional kiln drying process, as well as continuous and intermittent drying methods (Chafe 1995a, 1995b) have been conducted by many researchers. The objective of this paper is to comprehensively review the published literature and discuss the research work related to microstructural collapse, including the mechanism of collapse, control of the drying process, and reconditioning. By discussing relevant research findings, this review should help promote improved drying processes that will result in faster drying times and raw material with better quality and technical support for the accelerated eucalyptus utilization process as solid wood.

COLLAPSE

Historical Review

Peter Cunningham (1827) reported that the contractibility of the woods in Australia has been widely studied and pointed out that excessive shrinkage existed in Australian timber. Warren (1892) later published data showing the high shrinkage of some Australian timbers. Dunlap (1906) first photographed the collapsed wood in America through capturing images of case hardening.

Harry D. Tiemann, the American timber expert, was the first to examine in detail the excessive shrinkage in eucalyptus and point out its distinction from normal shrinkage (Tiemann 1913, 1915). He gave the term ‘collapse’ to the phenomenon and published his liquid-tension theory. George Grant later found that the excessive loss in dimensions could be largely recovered by a steaming treatment that has since become known as ‘reconditioning’ (Anonymous 1953). Walter G. Kauman showed that both liquid tension acting in individual cell cavities and drying stresses involving large numbers of cells contribute to the production of collapse (Kauman 1960a, 1960b, 1964a, 1964b).

Systematic studies on the cell-collapse of water-saturated balsa wood have been performed based on the relationship of the shrinkage process and moisture distribution to the cell-collapse mechanism, the effect of pre-freezing upon the reduction of cell-collapse, the effect of the tensile stress on the collapse intensity, the increase in collapse intensity produced by steaming, and the estimation of the magnitude of liquid tension produced by drying (Hayashi and Terazawa 1974, 1975, 1977a, 1977b; Hayashi 1992). The progress of shrinkage accompanied with collapse has also been examined in detail by some researchers (Kanagawa and Hattori 1978, 1979; Hattori *et al.* 1979).

To avoid the occurrence of collapse, quite a few investigations have been performed, such as those of chemical treatment by zinc chloride solutions (Chudnoff 1953, 1955), the impregnation of wood *via* wetting agents or replacement of water by other liquids of lower surface tension, and so forth. In addition, some researchers have focused on the drying process. Vermass (2000) reported that good results were obtained with an intermittent drying schedule in the drying of *Eucalyptus grandis*, at the cost of a longer drying time. Chafe (1992a, 1995b) discovered the reduction of surface and inner checks of *E. regnan*s through using intermittent drying combined with the collapse-type shrinkage processes. Wu *et al.* (2004, 2005a, 2005b) conducted further investigations on the feasibility of intermittent drying of seven species of young fast-grown eucalyptus from China. Wu *et al.* researched theoretical analyses on both transient collapse and maximum transient collapse developments and their conclusions on intermittent drying were likely suitable for collapse-prone plantation-grown eucalypts. Based on Wu *et al.*’s research achievements, Yang *et al.* (2014) further investigated the effect on total shrinkage and collapse under different drying schedules and the morphological change for collapsed cells, especially during intermittent drying.

Morphological Characteristics of Collapse

Meyer and Barton (1971) found that the collapse of western redcedar wood was related to its high extractives content, and that the pit chambers and membranes of heartwood tracheids were heavily deposited with extractives. The microscopic nature of collapsed wood has not been extensively studied, mainly because of the difficulty in preparing specimens for observation. Collapsed material is usually very dense, so that microscopic sections are difficult to obtain without softening and embedding procedures. However, the normal methods of softening and embedding samples involve swelling agents that would certainly change the configuration of collapsed cells due to swelling. With a special method, Tiemann (1941) was able to prepare a smooth transverse surface of collapsed wood for microscopic observation using vertical illumination. Micrographs provided by Tiemann show the general outline of collapse in wood but lack detailed information at the cellular level. Terazawa and Hayashi (1972, 1974) used thin sections to observe the collapsed cells in balsa wood. Yang *et al.* (2014) applied this method for observing the collapse and its recovery in the same position during the drying process of *E. urophylla* (Fig.1). They concluded that a scanning electron microscopic examination is a good way to observe the morphological characteristics of collapse and its recovery using the mirror surface and the collapsed surface of the same sample.

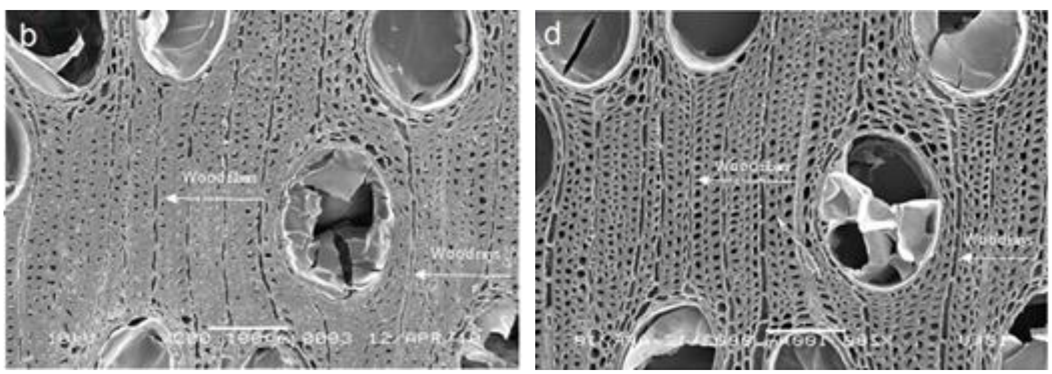

Fig. 1. The collapse (b) and its recovery (d) of *E. urophylla* in the continuous drying at temperature 60 °C.

The Theory of Collapse

Essentially, the liquid tension theory of collapse formation relies on two equations from mechanics and thermodynamics, *viz*.,

$$\triangle p = 2\sigma/a \quad \text{(Laplace 1806)} \quad (1)$$

and

$$\triangle p = -\rho RT.\ln r \quad \text{(Kelvin's equation; Thompson 1871)} \quad (2)$$

where $\triangle p$ is the pressure difference across a meniscus (Pa), in this case, that of water; effectively, this is the tensile stress during drying undergone by water in a cell lumen saturated with water; σ is the surface tension of water (N/m), a is the radius (m) of curvature of the meniscus and, effectively, radius of the opening (capillary) through which water must pass; R is the gas constant for water, ρ is the density of liquid water

(g/cm^{-3}), T is the temperature (Kelvin), ln is the natural logarithm, and r is the relative humidity (%).

From Eq. 1, it can be seen that the smaller the capillary, the greater the tension in the water in the cell lumen (Δp). Equation 2 shows how Δp is related to temperature and relative humidity in the immediate vicinity of the meniscus.

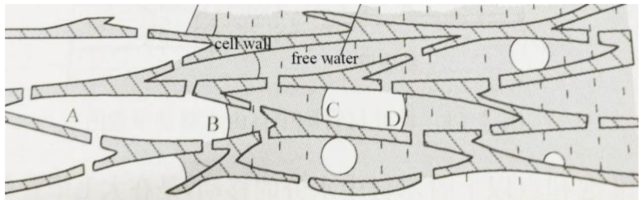

Fig. 2. Schematic diagram of liquid tension and cell collapse

During the drying of wood above the FSP, the virtually free capillary water in the cell cavities is withdrawn through small interstitial openings in the cell walls. A meniscus formed at the air-water interface in one of these openings will induce liquid tension in the water behind its convex face (Fig. 2). If this tension exceeds the compressive strength of the cell wall, the cell collapses.

In many tree species, the wood is relatively permeable, *i.e.* the pathways connecting cells (open pits in the cell wall or pores in the pit membrane) are sufficiently large to allow the movement of water to proceed relatively unhindered during drying. In such species, shrinkage is defined as that of the normal type described above. However, when the pathways are tiny, *i.e.* when pit membranes are densely packed or occluded with cytoplasmic debris or other extraneous materials, the first criterion for collapse formation is satisfied. In addition to impermeability, two other requirements are necessary for collapse, which are water saturation of the cell lumen and comparatively thin cell walls. If, in addition to water, the cell lumen contains air, it would be highly unlikely to collapse during drying regardless of the level of permeability. This is because liquid tension forces preferentially act on the meniscus of the largest radius of curvature. Hence, if an air bubble was present in the lumen, any tension in the water would be relieved by the expansion of the air bubble (Hayashi and Terazawa 1974), thus mitigating the potential for collapse of the cell. Again, if the cell walls were relatively thick, *i.e.* high-density wood, collapse would be less likely to occur because the wood would be stronger in compression perpendicular to the grain. This is the main reason why collapse and internal checking generally are greater in lower density wood than higher density wood from the same species. Chafe (1985, 1986) also found a positive correlation between collapse and moisture content of the wood and a negative correlation with density.

COLLAPSE CONTROL

Pretreatment

Preheating green timber prior to drying includes steaming (Lee and Jung 1985; Haslett and Kininmonth 1986; Zhang *et al.* 2011; Kong *et al.* 2017), microwave treatment and pre-freezing (Ellwood 1953), boiling (Vermaas and Bariska 1995), and other methods. Chafe (1994a) found that some reduction in the initial shrinkage was achieved when board sections of *E. regnans* were preheated at different temperatures. Such treatment results in an increased permeability and drying rate (Alexiou *et al.* 1990; Severo *et al.* 2013), while also resulting in a reduction of drying time (Campbell 1961) and drying defects (Calonego and Severo 2007). A reduced drying time was thought to be caused by conformational changes in wood extractives. During steaming, the growth stresses of wood are released easily by means of microstructural reorganization and thus improve the quality of the timber (Length and Kamke 2001; Severo *et al.* 2010; Kiemle *et al.* 2014). The woods are softened and growth stress is released as reaching its glass transition temperature during the drying process. The wood ductility is increased for its improved viscoelastic properties, and finally results in decreased drying cracks (Calonego *et al.* 2010).

The Influence of Process Control on Collapse during Drying

Temperature and relative humidity

Most researchers have found that collapse increases with temperature (Anonymous 1953). High temperature is now recognized as exerting both an irreversible and a reversible effect on wood. The reversible effect is due to transient plasticization of the cell walls that reduces their strength (Vermaas and Neville 1989) faster than the reduction of liquid tension with temperature, and the collapse-reducing force therefore increases. Due to frequently severe collapse and interior cracking occurring in higher drying temperature conditions for most eucalypts, low temperature drying is often used for the entire drying process (Kaumann *et al.* 1956; Langrish *et al.* 1992). Innes (1996) proposed the concept of a collapse threshold temperature for *E. regnans*. He suggested that collapse could be eliminated if wood were dried below 24 °C to 26 °C for Tasmanian material, and below 28 °C to 30 °C for Victorian material. These findings are of profound importance for the drying of *E. regnans*, particularly for the highly collapse- and check-prone Victorian material. Kauman found that the wood temperature of collapsing timber must be maintained below approximately 60 °C during drying until all portions of the boards are below FSP; thus excessive shrinkage and severe checking can be avoided (Kauman 1964a, 1964b). Yuniarti *et al.* (2015) found that the threshold temperature of the *E. saligna* boards was lower than 20 °C, which was different than that suggested by Innes (1995, 1996) for *E. regnans*. This testified that different species had different threshold temperatures, even if they were from the same genus.

The influence of humidity is indirect: low humidity induces tension set and thus tends to reduce overall shrinkage in the width of rectangular specimens, but increases collapse in the thickness and promotes checking. High humidity maintains surface plasticity and minimizes checking, but permits freer collapse in the width. Relative humidity and drying temperature are two key factors affecting wood collapse, and their interaction is important to collapse and its recovery during the drying process. Kanagawa *et al.* (1979) found that increasing relative humidity during high drying temperature brings out high total shrinkage when drying some hardwoods. The bubbles in the wood cells disappeared and brought about greater liquid tension as relative humidity increased. The increased tension resulted in more transient collapse and increased total shrinkage.

Drying time

The drying time to reach the FSP is of negligible influence in sawn timber because the relaxation time of collapse is usually shorter than that of the drying process, except at temperatures of approximately 100 °C or higher. However, collapse is proportional to the time of drying from green to FSP in ash eucalypt veneer (Greenhill 1938). It is possible that the slight decrease of collapse observed in vacuum-dried timber at 105 °C is also due to the shorter drying time under reduced pressure. Wu *et al.* (2005b) found that the drying time had a great effect on the total shrinkage and collapse in continuous and intermittent drying for six eucalyptus wood species. However, if the drying time during the intermittent drying process was too long, the differences in shrinkage and collapse between both drying regimes were slight.

Intermittent drying

Intermittent drying can eliminate internal checking in red beech, as found by Langrish *et al*. (1992). Vermaas (2000) reported that good results could be obtained with an intermittent drying schedule in the drying of *E. grandis*, but a consequence is a longer drying time. The reductions of surface and inner checks of *E. regnans* by using intermittent drying were found by Chafe (1992, 1995), but he could not verify if it had a positive effect on decreasing total shrinkage and collapse. In recent years, intermittent drying procedures on seven species of young plantation-grown eucalyptus from China were developed by Wu *et al.* (2004, 2005a, 2005b), and they concluded that intermittent drying was likely suitable for collapse-prone eucalypts. The mechanism of intermittent drying is thought to achieve its success by reducing the stress gradient developed in wood with the progressive removal of water and consequent shrinkage, which induces stress in the material. Periodic interruption in the drying process allows partial equilibration of the moisture content and stress relaxation in different regions of the material, therefore reducing the predisposition of the wood to fail.

Reconditioning Treatment

If a collapse develops such that all shrinkage associated with the flattening of cell lumens is manifested externally, the collapse can be recovered. The generally accepted theory of reconditioning was found by Greenhill (1938). Ilic and Chafe (1986) noted that steam reconditioning after drying significantly reduces the effect of collapse, but not the degree of wood cracking. Cell lumen dimensions can be returned to near original form by steaming dried wood at 100 °C and then re-drying (Chafe 1992a,b). Collapse can be reversed, and the shape of cells begins to change when the liquid tension disappears. The deformation caused by the drying can be removed or recovered by a reconditioning procedure. Cracks or tiny internal separations will also be closed during this treatment but the strength loss is irreversible (Vermaas 1995). The recovery of collapse is negatively correlated with the drying temperature. Cuevas (1969) found that the recovery of collapse is related to the drying process and generally 50% collapse can be recovered during reconditioning or other treatment, while 50% collapse cannot be recovered.

CONCLUDING REMARKS

How to control microstructural collapse and help the collapsed cell recover more during the drying process is key for the drying of eucalyptus wood. Efforts to develop new methods for pretreating the eucalyptus wood before drying include microwave pretreatment, ultrasonic wave pretreatment, freeze drying, pre-steaming, boiling treatment, and pre-freezing treatment. All of the pretreatments can attain better quality and improve the drying rate.

Based on the trajectory of the research published over the past few decades and the current needs of eucalyptus wood modification, the authors predict that future research on collapse control will focus on new theory and technology for improving the quality of dried eucalyptus wood and on reducing the drying time. This current research can be further subdivided into three topics. The first topic is (a) research on the mechanisms of different pretreatments (*e.g.*, the ultrasonic wave pretreatment, freeze drying, and so forth) for collapse prevention or micro-modification of wood tissues, as well its application to different eucalyptus wood species. Even though the collapse control procedure will increase costs, it is a necessary approach to reduce collapse and improve drying quality for collapse-prone species. The second discussion would be (b) research on the control of the drying process of conventional, suitable drying technology for different eucalyptus wood species. Lastly (c) is research on the development of new technology for microstructural collapse control, such as combined drying technology. Each of these areas relates to each other as each will ultimately improve quality, reduce drying time, and reduce the microstructural collapse for eucalyptus wood drying.

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