Effect of Drying Conditions on the Collapse-prone Wood of *Eucalyptus urophylla*

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Collapse is considered one of the most severe defects that can occur during the drying of eucalyptus, resulting in drying degradation. Liquid tension is one of the reasons for the collapse. Some transient-collapse cells can be recovered upon the disappearance of liquid tension, when moisture content is reduced during the drying process. How to control collapse and help its recovery are key factors of drying technology. This supports the introduction of a kind of sequential drying technology to the drying process. Thus, several intermittent drying procedures were used in this study. Measurements of shrinkage and collapse were made on *Eucalyptus urophylla* under continuous drying as well as several kinds of intermittent drying. Key factors of the intermittent drying schedule, observed for their effect on collapse recovery, were the length of the drying periods and temperature during the intermittent periods. The microstructure of collapse under different drying schedules was examined at the cellular level using scanning electron microscopy (SEM). This confirmed that intermittent drying conditions can help collapsed cells recover more thoroughly than continuous drying conditions.

Keywords: Continuous drying; Intermittent drying; Collapse; Total shrinkage; Microstructure; Eucalyptus

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INTRODUCTION

Eucalyptus is well known as a fast-growing species and is planted in large tracts across southern China. However, until now, most eucalyptus plantations have been managed for pulpwood production only. The production potential of plantation-grown eucalyptus timber is often limited because drying costs become a major factor in determining the viability of establishing processing operations. Thus, determining the drying properties and appropriate drying procedure are important issues to be resolved (Terazawa and Hayashi 1972; Northway 2005).

The structural collapse of wood as a result of drying is a very severe but common problem during the drying of the eucalyptus (Tiemann 1941; Kauman 1964a,b; Hayashi and Terazawa 1977a,b; Chafe 1995a). Liquid surface tension is only one reason for the collapse (Tiemann 1941; Hayashi and Terazawa 1977a). Some transient-collapse cells can be recovered upon the disappearance of the surface tension, caused when the moisture content is reduced during the drying process (Kanagawa and Hattori 1978; Hattori *et al.* 1979; Chafe 1995b; Wu *et al.* 2005a,b; 2005; Yang *et al.* 2010). How to control a collapse that has already occurred and help its recovery are key factors of interest for the development of drying technology. Given the risk of collapse, a kind of sequential drying technology should be considered in the drying process. Thus, this study employed a modification of intermittent drying procedures used by other investigators (Hattori *et al.* 1979; Chafe 1995b; Wu *et al*. 2005a). Measurements of shrinkage and collapse were performed on samples of *Eucalyptus urophylla* after they were subjected to continuous drying as well as intermittent drying procedures in order to establish the key factors of the intermittent drying schedule that affect collapse recovery.

The main purpose of this study is to explore the influence of intermittent drying on total shrinkage and collapse while following different drying procedures, with the ultimate goal of generating some scientific parameters for the optimization of drying technologies to be applied towards the industrial utilization of eucalyptus. A morphological examination of the collapsed cells can enhance the understanding of the effects of intermittent drying on cell collapse and assist in the development of a refined drying process.

EXPERIMENTAL

Materials

Eucalyptus urophylla, eleven-year-old plantation-grown eucalypt planted in China, was selected for these experiments. The tree height was 27.5 m, and the diameter at breast height (DBH) was 22.8 cm. One 2-m-long billet at DBH upward was immediately removed from each tree stem after felling and sawn into a piece of 32 mm thick board. The initial moisture content (MC) was 88.6%, and the basic density was 0.48 g/cm^{-3}.

Sixty end-matched specimens, each measuring 30 mm (R) × 30 mm (T) × 30 (L) mm, were used in this experiment. As shown in Fig. 1, all the specimens were marked with a cross-line on the cross-section in order to measure the differences of the dimensions in tangential and radial directions before and after the drying treatment. The specimens were weighed and measured before they were used in the experiments. In order to investigate the fiber saturation point, ten 30 mm (R) × 30 mm (T) × 1 (L) mm wood slices were cut and the wood powder made before the drying test.

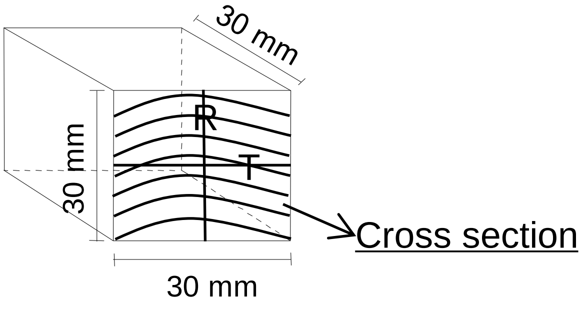

Fig. 1. Diagrammatic representation of sample

In general, shrinkage is calculated as the ratio of the dimensional difference values between green and various moisture content states to the dimension during the different drying process. In this study, total shrinkage (S_{total}/%) is the sum of the shrinkage in the tangential (S_t/%) and radial directions (S_r/%). The relationship is described by Eq. 1:

$$S_{total=} S_t + S_r \quad (1)$$

Methods

Fiber saturation point test

Generally, shrinkage occurs below the fiber saturation point (FSP). In view of the collapse vulnerability of the species, shrinkage below the FSP was considered normal shrinkage and shrinkage above the FSP was considered collapse shrinkage. Total shrinkage is the sum of the normal shrinkage and collapse. In order to discriminate between normal shrinkage and collapse, collapse-free shrinkage which is the shrinkage without collapse for the wood slices 1 mm in thickness in this test must be obtained. For this purpose, the fiber saturated point (FSP) was investigated. In order to determine the FSP of *Eucalyptus urophylla*, wood slices 1 mm in thickness and wood powder were used. For this purpose, the fiber saturated point (FSP) was investigated. In order to determine the FSP of *Eucalyptus urophylla,* wood slices 1 mm in thickness and wood powder were used.

Ten 1-mm-thick slices, along with wood powder (25 g), were placed into four different saturated sodium chloride solutions of concentrations 91%, 73%, 56%, and 22% at a constant temperature of 25 °C. The wood slices and wood powder were weighed at several intervals until the equilibrium moisture content (EMC) had reached 12%, and then they were oven-dried at 103 ± 2 °C to a moisture content of 0%. Additionally, the dimensions of the 1 mm-thick slices were measured in order to determine whether collapse-free shrinkage had occurred (Hattori *et al.* 1979; Wu *et al*. 2005a). The 1-mm-thickness slices, *i.e.*, collapse-free slices, do not collapse during the drying process, so the normal shrinkage is mean to the total shrinkage.

Continuous and intermittent drying condition

All of the green specimens were divided into 4 groups. Group 1 was subjected to continuous drying in an experimental chamber (PR-2FR, Tabai Espec Corp.; Japan), and the test conditions were arranged into 3 levels, *i.e.*, 25 °C, 60 °C, and 80 °C, with the corresponding relative humidities maintained at 66%, 76%, and 82%, respectively, in an attempt to maintain the EMC of 12%. Five specimens would be removed from the experimental chamber at several intervals corresponding to the different drying run, then weighed and measured, finally, the average value of the five specimens will be used in the data analysis. The drying schedule was repeated until each specimen had reached an EMC of 12%. Then, all of specimens were dried to 0% MC under oven drying (103 ± 2 °C）. The drying schedule is shown in Table 1.

Table 1. Summary of Continuous Drying Regime

Group Number	Number of Specimens	Parameters	Continuous drying		
			Run 1	Run 2	Run 3
1	15	T (℃)	25	60	80
		RH (%)	66	76	82

The other three groups were subjected to an intermittent drying process, as shown in Table 2. Each complete intermittent drying procedure was composed of a drying period followed by a time interval. Two drying periods made up one cycle, and this cycle was not complete until all the specimens reached 12% EMC. Finally, all specimens were dried to 0% MC under oven drying. The data analysis also used the average value of five specimens for each drying run.

Of these three intermittent groups, for Group 2 and Group 3, the influence of the length of drying period was the experimental focus, while for Group 3 and Group 4, the effect of drying temperature was the experimental focus.

Scanning electron microscopy (SEM)

To understand cell collapse and recovery during the different drying processes, the morphology of the samples were examined by SEM (JSM-5610LV, JEOL; Japan). Thin slices (less than 0.1 mm thick) were cut from small samples taken from the final stage of the drying process and fixed to a holder with double-sided tape. The samples were coated with a gold alloy and examined on an SEM operating at an accelerating voltage of 10 kV.

Table 2. Summary of Intermittent Drying Regimes

Group Number	Number of Specimens	Parameters	Intermittent drying					
			Drying period			Intermittent period		
			Run 4	Run 5	Run 6	Run 4	Run 5	Run 6
2	15	T (℃)	25	60	80	25	25	25
		RH (%)	66	76	82	96	96	96
		Time Interval (min)	120	120	120	120	120	120
3	15	T (℃)	25	60	80	25	25	25
		RH (%)	66	76	82	96	96	96
		Time Interval (min)	120	90	50	120	120	120
4	15	T (℃)	25	60	80	25	60	80
		RH (%)	66	76	82	96	96	96
		Time Interval (min)	120	90	50	120	120	120

RESULTS AND DISCUSSION

Determination of the FSP and Residual Collapse

Figure 2 shows the regression line for the relationship between moisture content and shrinkage of the wood slices. From this regression equation, the FSP of *Europhylla* was found to be 29.5%. Figure 3 shows the regression curve for the relationship between relative humidity and EMC of the *Europhylla* wood powder. The FSP of *Europhylla* was calculated as 28.4% based on this regression curve. Finally, the average value of the FSP, obtained from the wood slices and the wood powder, was found to be 29.0%. This FSP value was used in this study.

Below a moisture content of 20%, the shrinkage curve in any drying condition was almost straight line, as shown in Fig. 2. The relationship is described by Eq. 2,

$$y = -\alpha x+\beta \tag{2}$$

where y represents normal shrinkage, x equals MC, α is the slope of the straight line, and β is the intersection with the y-axis. The equation expresses the greatest amount of normal shrinkage when MC is equal to 0%.

According to Eq. 2, the normal shrinkage can be determined using a straight regression line. Therefore, when x=FSP (29.0%), y=8.7%; *i.e.*, the normal shrinkage of *Europhylla* was 8.7%. As mentioned, normal shrinkage can be calculated using the difference between total shrinkage and collapse during the drying process. Therefore, in the following test, collapse was determined by the difference between total shrinkage and normal shrinkage below FSP during the drying process; above FSP, the total shrinkage was considered equivalent to collapse.

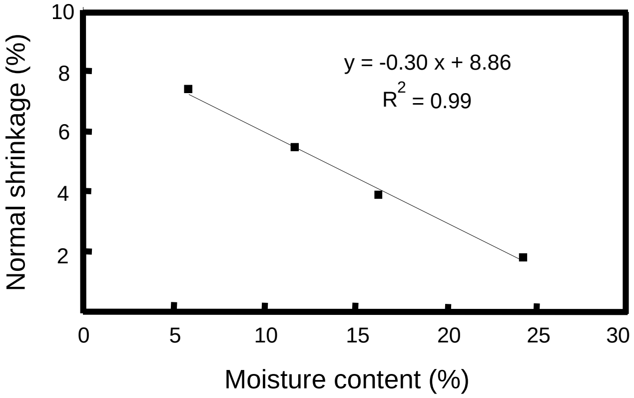

Fig. 2. Regression equation for 1-mm-thick *Europhylla* wood slices

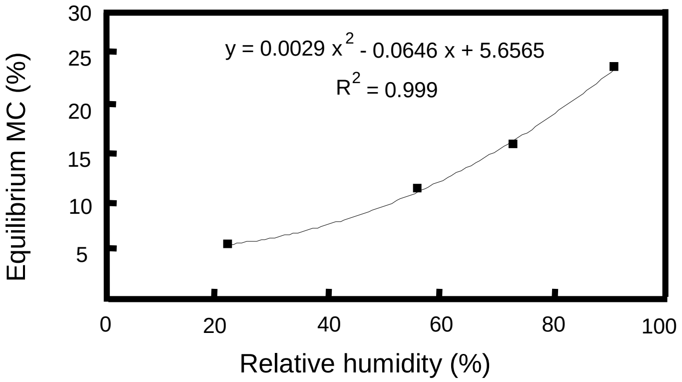

Fig. 3. Regression equation for wood powder derived from *Europhylla*

Effect of Length of Drying Period on Total Shrinkage and Collapse

Figure 4 shows the total shrinkage and collapse for both continuous and intermittent drying procedures. It can be seen that the total shrinkage and collapse was greater for the continuous drying procedure than for either of the intermittent drying procedures. During the continuous drying, as drying temperature increased, the total shrinkage and collapse increased. Generally speaking, the higher the drying temperature, the faster the drying rate and the greater the gradient of the moisture content, which can cause high capillary tension as the liquid menisci retreat into cells filled with liquid. This kind of high liquid tension led to more severe collapses.

In contrast, the periodic interruption that occurs during the intermittent process can provide an opportunity for equilibration of the moisture contents in different regions of the specimen; furthermore, it can provide enough time to facilitate collapse recovery. Because the recovery from a collapse is an elastic lag process, that is, a process that cannot occur instantaneously, this process needs time. The different intermittent drying schedules had different effects, as shown in Fig. 4. The general trend was that the intermittent drying produced better effects than did the continuous drying. However, when drying temperature was 80 °C, the total shrinkage was lower than it had been at 60 °C. It is known that it takes some time to transfer from a drying period to an intermittent period during the intermittent drying process. Hence, the reason for this procedure is that more time is needed when the drying temperature is decreased from 80 °C to 25 °C than when it is decreased from 60 °C to 25 °C. Thus, due to the process of adjusting the temperature of the chamber, greater recovery from collapse occurred at the 80 °C drying temperature than at 60 °C.

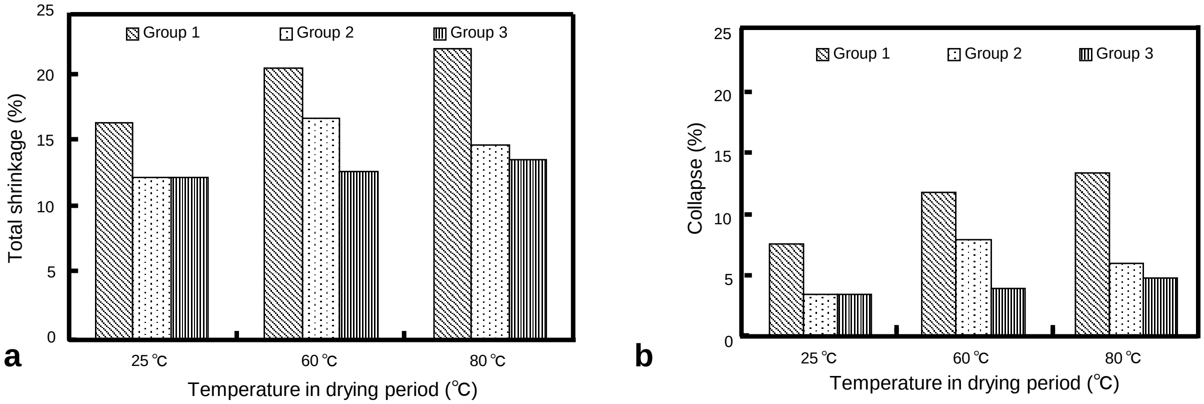

Fig. 4. Effect of drying length in drying period on (a) total shrinkage and (b) collapse in *Europhylla*. Group 1: 25 °C，Group 1: 60 °C, and Group 1: 80 °C represent continuous drying temperatures of 25 °C, 60 °C, and 80 °C, respectively. Group 2 and Group 3: 25 °C, Group 2 and Group 3: 60 °C, and Group 2 and Group 3: 80 °C represent drying temperatures of 25 °C, 60 °C, and 80 °C, respectively, during intermittent drying periods

To solve this problem, drying length was decreased during the drying period for Group 3. Even by decreasing the drying length in the drying period, it was found that total shrinkage and collapse were lower for Group 3 than for Groups 1 or 2. However, Group 3 needed more total drying time compared to Group 2 from the beginning to the end of the each run drying process, as shown in Table 3.

Table 3. Summary of Total Drying Time during Different Drying Procedures

Total Drying Time (day)	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Group 1	7	3	2			
Group 2				9	5	3
Group 3				11	8	5
Group 4				11	6	3

This is perhaps due to a similar lag time between drying period and the intermittent period, indicating that some adjustment time, when switching from the drying period to the intermittent period, may also have been needed. In addition, the differences in total shrinkage and residual collapse for the different drying temperatures were barely evident in Group 3. Thus, the drying schedule used for Group 3 was not suitable for different drying temperature, even if it contributed to a decrease in the total shrinkage and collapse.

Effect of Drying Temperature during the Intermittent Period

To further optimize the drying process and decrease the drying time, the Group 4 drying temperature in each drying period was kept during the subsequent intermittent period. Figure 5 shows that when the drying temperature in the intermittent period was increased, the total shrinkage and collapse still declined in comparison to that of Group 3. But compared to Group 3, the total shrinkage and collapse had increased markedly by 80 °C. It can be further explained that during the high drying temperature, increasing the relative humidity from the drying period to the intermittent period led to the disappearance of the bubbles in the wood cells and an increased effect of liquid surface tension. This surface tension caused more transient collapse to develop into residual collapse and increased the total shrinkage. However, under 60 °C, Group 4 had a smaller increase in total shrinkage and collapse compared to Group 3. Group 4 can economize total drying time, as shown in Table 3, and was thus considered a preferable drying schedule for middle temperature drying. For the high-temperature drying, the procedure used on Group 3 may have been more effective at decreasing total shrinkage and collapse.

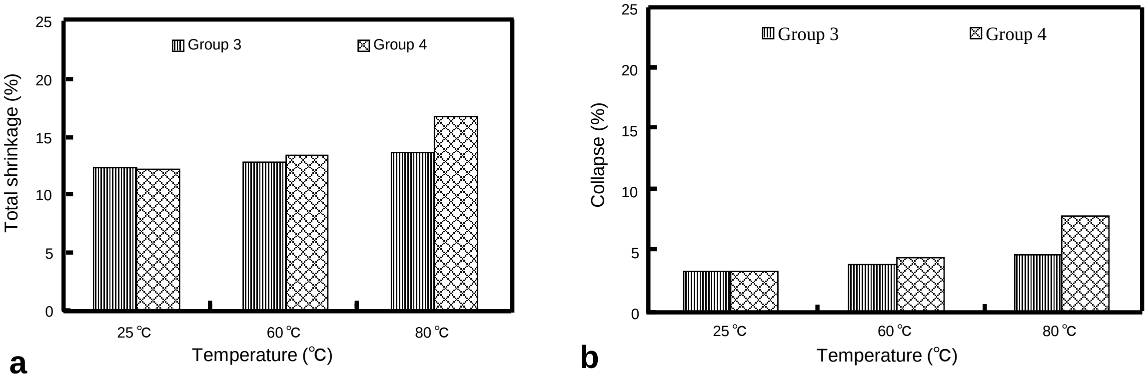

Fig. 5. The effect of drying temperature in the intermittent period on (a) total shrinkage and (b) collapse in *Europhylla*. Group 3 and Group 4: 25 °C, Group 3 and Group 4: 60 °C, and Group 3 and Group 4: 80 °C represent drying temperatures of 25 °C, 60 °C, and 80 °C, respectively, during the intermittent drying period

The Microstructure of Collapsed Cells under Different Drying Conditions

Figures 6a, 6b, 6c, and 6d show the microstructure of the collapsed cells as observed using SEM following the final drying stage of the continuous and intermittent drying at 80 °C, along with the magnified area of the each collapsed sample. During the continuous drying condition at 80 °C, collapse occurred in all types of cells, including wood fibers, rays, and axial parenchyma; during the intermittent drying condition at the same drying temperature, however, the collapse only partially occurred in the wood fibers. Figures 7a, 7b, 7c, and 7d show the microstructure of collapsed cells following the final drying stage of the continuous and intermittent drying at 60 °C, along with the

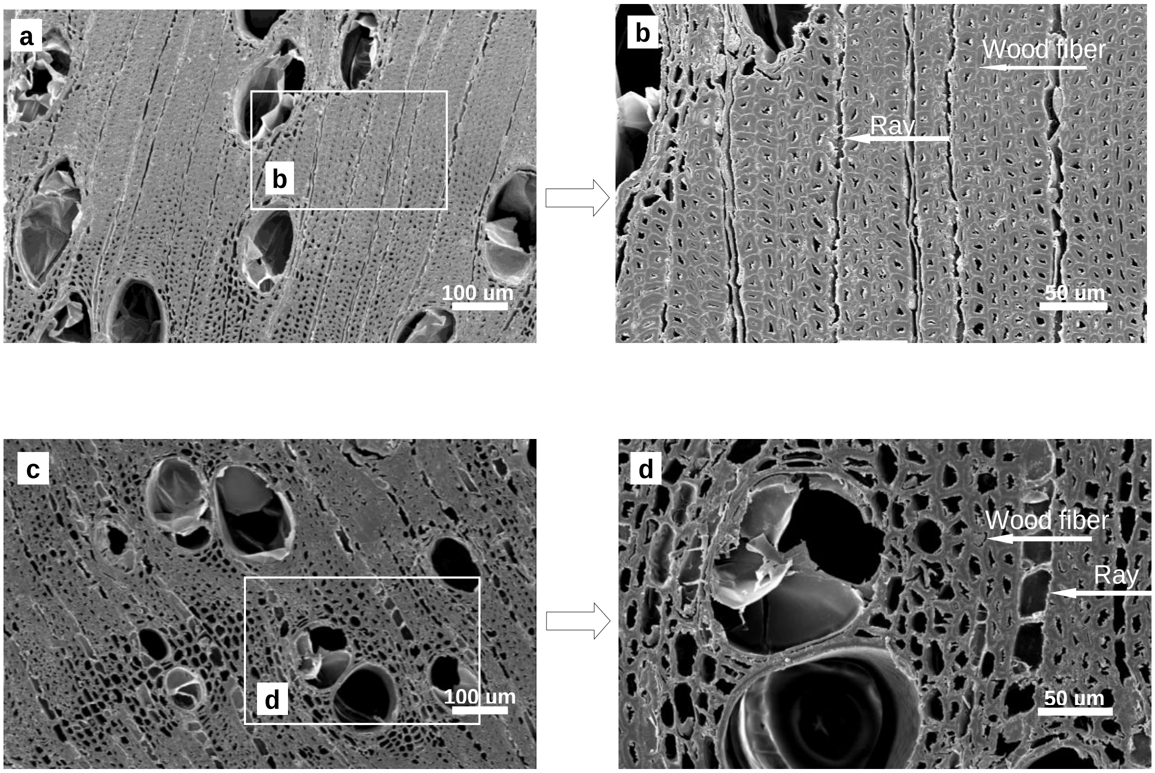

Fig. 6. Cell collapse at 80 °C in *Europhylla.* (a) continuous drying, (b) continuous drying (higher magnification), (c) intermittent drying, and (d) intermittent drying (higher magnification)

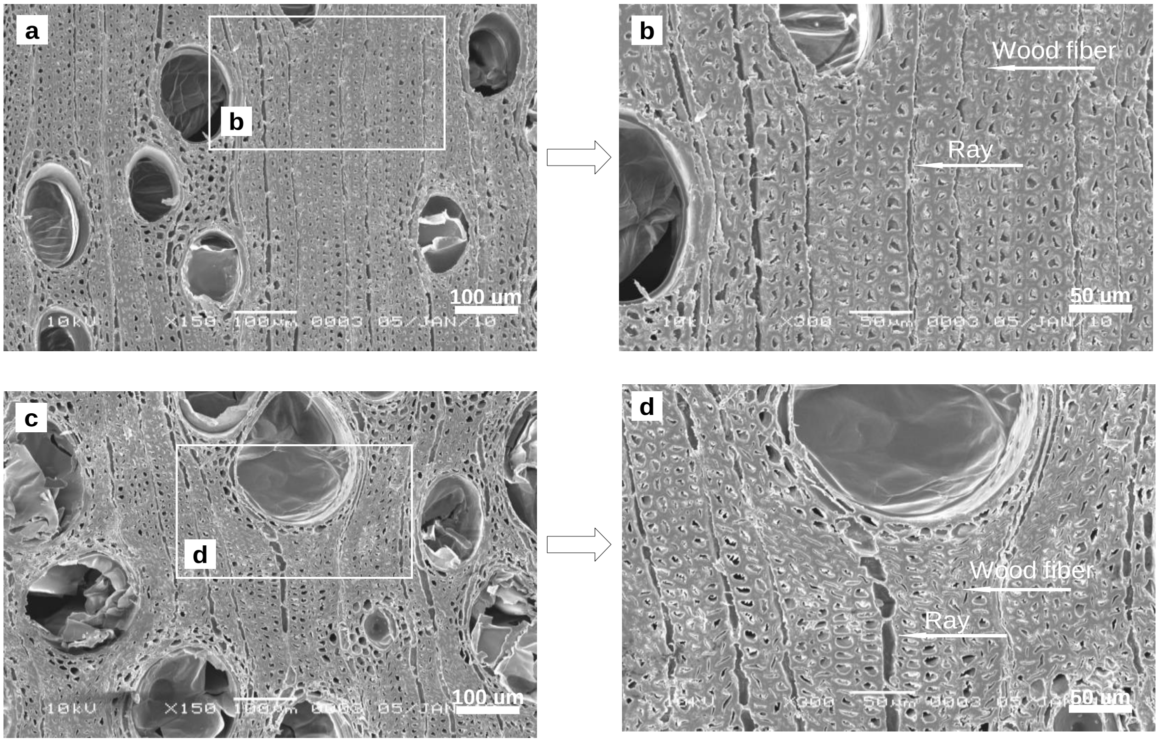

Fig. 7. Cell collapse at 60 °C in *Europhylla.* (a) continuous drying, (b) continuous drying (higher magnification), (c) intermittent drying, and (d) intermittent drying (higher magnification)

magnified area of the collapsed sample. This further confirmed that the number of cells involved in the collapse decreased with a decrease of the drying temperature regardless of whether the drying process was continuous or intermittent. It was inferred from these SEM micrographs that intermittent drying helped the wood rays and parenchyma to more thoroughly recover, while the procedure had little effect on the recovery of wood fibers.

CONCLUSIONS

1. An intermittent drying process decreases total shrinkage and collapse of the cellular structure of wood as compared to the continuous drying process.
2. Properly decreasing the drying length in the drying period has the effect of decreasing total shrinkage and collapse, but this requires a longer total drying time.
3. Drying temperature during the intermittent period has a greater effect on drying schedule than does drying length. For middle temperature drying, maintaining the same temperature between drying periods and intermittent periods can decrease total shrinkage and residual collapse and also economize drying time. At high drying temperatures, a temperature difference between the drying period and the intermittent period is helpful for aiding collapse recovery.

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REFERENCES CITED

Chafe, S. C. (1995a). "Preheating and continuous and intermittent drying in boards of *Eucalyptus regnans* F. Muell. I. Effect on internal checking, shrinkage and collapse," *Holzforschung* 49(3), 227-233. DOI: 10.1515/hfsg.1995.49.3.227

Chafe, S. C. (1995b). "Preheating and continuous and intermittent drying in boards of *Eucalyptus regnans* F. Muell. II. Changes in shrinkage and moisture content during drying," *Holzforschung* 49(3), 234-238. DOI: 10.1515/hfsg.1995.49.3.234

Hattori, Y., Kanagawa, Y., and Terazawa, S. (1979). "Progress of shrinkage in wood. III. An observation of the development of the cell-collapse by the freeze-drying method," (in Japanese) *Mokuzai Gakkaishi* 25(3), 191-196.

Hayashi, K., and Terazawa, S. (1977a). "Studies on cell-collapse of water-saturated balsa wood. IV. Increase in collapse intensity produced by steaming," (in Japanese) *Mokuzai Gakkaishi* 23(1), 25-29.

Hayashi, K., and Terazawa, S. (1977b). "Studies on cell-collapse of water-saturated balsa wood. V. Estimation of magnitude of liquid tension produced by drying," (in Japanese) *Mokuzai Gakkaishi* 23(1), 30-34.

Kanagawa, Y., and Hattori, Y. (1978). "Process of shrinkage in wood. I," (in Japanese) *Mokuzai Gakkaishi* 24(7), 441-446.

Kauman, W. G. (1964a). "Cell collapse in wood. Part I: Process variables and collapse recovery," (in German) *Holz Roh Werkst.* 22(5), 183-196. DOI: 10.1007/BF02613024

Kauman, W. G. (1964b). "Cell collapse in wood. Part II: Prevention, reduction and prediction of collapse-recent results," (in German) *Holz Roh Werkst.* 22(12), 465-472. DOI: 10.1007/BF02605572

Northway, R. (2005). "Determining drying characteristics of plantation-grown eucalyptus timber for resource assessment and improvement," *Proceedings of the International Conference on Plantation Eucalyptus*, Zhanjiang, Guangdong, China, pp. 103-109.

Terazawa, S., and Hayashi, K. (1972). "The collapse by wood drying," (in Japanese) *Mokuzai Kogyo* 27(11), 526-531.

Tiemann, H. D. (1941). "Collapse in wood as shown by the microscope," *J. For.* 39(3), 271-283.

Wu, Y. Q., Hayashi, K., Cai, Y. C., Sugimori, M., and Liu, Y. (2005a). "Effects of continuous and intermittent drying runs on shrinkage and collapse properties in plantation-grown eucalyptus wood from China," *The 55th Annual Meeting of the Japan Wood Research Society*, Kyoto, Japan, pp. 221-225.

Wu, Y. Q., Hayashi, K., Liu, Y., Cai, Y. C., and Sugimori, M. (2005b). "Collapse-type shrinkage characteristics in wood from plantation-grown eucalyptus in China subjected to the continuous and intermittent drying regimes," *Proceedings of the 9th International IUFRO Wood Drying Conference*, Nanjing, China, pp. 4441-4449.

Wu, Y. Q., Hayashi, K., Liu, Y., Luo, J. J., and Sugimori, M. (2005c). "Intermittent drying technologies suitable for plantation-grown eucalyptus timbers," *Proceedings of the International Conference on Plantation Eucalyptus Zhanjiang*, Guangdong, China, pp. 110-119.

Yang, L., Liu, H. H., Hayashi, K., and Sugimori, M. (2010). "The development of drying technology for collapse-prone eucalyptus wood as eco-material," *Proceedings of the 2010 International Conference on Environmental Science and Technology*, Bangkok, Thailand. DOI:10.3850/978-981-08-5716-5_T264

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