INTERRELATIONSHIPS BETWEEN SHRINKAGE PROPERTIES, MICROFIBRIL ANGLE, AND CELLULOSE CRYSTALLITE WIDTH IN 10-YEAR-OLD *EUCALYPTUS GLOBULUS*

JUN LI YANG, JUGO ILIC, ROBERT EVANS,

CSIRO Forestry and Forest Products
Private Bag 10, Clayton South, Victoria 3169, Australia

and DAVID FIFE

CSIRO Forestry and Forest Products
Airport Road, Mount Gambier, South Australia 5290, Australia

(Received for publication 8 August 2002; revision 31 March 2003)

ABSTRACT

Shrinkage properties, density, and moisture content of 59 trees from three provenances of 10-year-old plantation *Eucalyptus globulus* Labill. grown at two separate sites in the Mt Gambier region, South Australia, were determined from wood specimens of 20 × 20 × 90 mm. Microfibril angle (MFA) and cellulose crystallite width (W_{cryst}), typical routine measurements from SilviScan, were determined from strip specimens that were end-matched with the wood block specimens. Simple and multiple relationships between these properties were examined. The potential of using the SilviScan measurements to predict various shrinkage properties, in particular tangential collapse, was investigated. It was found that several shrinkage properties were significantly correlated with microfibril angle and W_{cryst}. However, microfibril angle had a direct effect (negative) only on tangential shrinkage and cross-sectional shrinkage, and W_{cryst} had a direct effect (positive) only on radial collapse. Density, microfibril angle, and W_{cryst}, either singly or collectively, accounted for a small to modest amount of variation in shrinkage and collapse in both the radial and tangential directions. Total tangential shrinkage was found to be the best single predictor for tangential collapse ($r^2 = 0.896$) and for total cross-sectional shrinkage ($r^2 = 0.924$). These strong relationships held for individual measurements as well as for tree means, and were not affected by positions along the radius.

Keywords: collapse; shrinkage; microfibril angle; cellulose crystallite width; plantation; *Eucalyptus globulus*.

INTRODUCTION

Eucalyptus globulus is one of the most widely planted hardwood species in the world, primarily because of its superb growth rate and high-quality pulpwood properties. It is the most extensively planted eucalypt species in Australia (approximately 311 600 ha to

September 2000 — Wood *et al.* 2001) and has been designated as a primary woodchip resource. Investigation of its potential for higher value products such as appearance-grade sawn timber is therefore a matter of high commercial significance, given the predicted fall in woodchip price in the near future.

Some commercially important eucalypt species, including *E. globulus*, are prone to checking during drying. Checking is the most serious form of drying degrade in the Australian hardwood timber industry as it severely affects the recovery of high-value sawn timber. Internal checking is often associated with cell collapse during drying and is common in many pale-coloured eucalypt species (Tiemann 1941; Bisset & Ellwood 1951; Kauman 1960, 1964; Pankevicius 1962; Cuevas 1969; Chafe 1985; Ilic & Hillis 1986; Wilkes 1988; Thomson 1989; Bekele 1995; Innes 1996; Yang & Waugh 1996a, b; Ilic 1999). The severity of internal checking generally increases with collapse (Innes 1996; Ilic 1999). Collapse in wood is caused by the collapse of cell lumens, whereas normal shrinkage results from the reduction in cell wall dimensions following moisture loss below the fibre saturation point. Therefore, total shrinkage from green to below the fibre saturation point equals normal shrinkage plus collapse. Surface checking is prevalent in high-density eucalypts and usually results from high levels of stress generated at the wood surface during the early stages of drying. Unlike internal checking, surface checking can be reduced by careful and gentle pre-drying.

Accurate measurement of collapse requires either reconditioning facilities or the use of thin sections, usually of the order of 1 mm thickness (Greenhill 1936). Methods that can easily, quickly, and reliably predict collapse are hence important for tree breeders. A number of wood properties have the potential to predict collapse because of their known intrinsic and/or generic relationships with collapse. These properties include permeability, extractives, initial moisture content, and density; poor permeability, high amounts of extractives, high initial moisture content, and low density directly contribute to the formation of collapse (Tiemann 1941; Bisset & Ellwood 1951; Kauman 1960, 1964; Pankevicius 1961, 1962; Cuevas 1969; Chafe 1985, 1986a, b, 1987, 1990a, b, 1992, 1993; Ilic & Hillis 1986; Wilkes & Wilkins 1987; Wilkes 1988; Thomson 1989; Chafe & Ilic 1992; Bekele 1995; Innes 1996; Chafe & Carr 1998; Ilic 1999). However, these properties are far from being ideal predictors. Measurements of permeability and extractives content are time consuming and require special equipment. Density and moisture content, although easy to determine, do not correlate closely enough with collapse either singly or in combination (Chafe 1985; Ilic 1999; Ilic & Chafe 1986). Severe tension wood results in severe collapse (Wardrop & Dadswell 1948, 1955; Dadswell & Wardrop 1955; Nicholson *et al.* 1972, 1975; Washusen & Ilic 2001), but slight to severe levels of collapse can occur independently of high-density tension wood, and internal checking can develop at these levels of collapse in low-density wood (Ilic 1999; Kauman 1964). In other words, tension wood formation can result in collapse and internal checking, but is not necessarily a precursor of the two.

The effect of microfibril angle (MFA) and cellulose crystallite width (W_{cryst}) on collapse in wood has seldom been studied because of difficulties in measuring these properties. However, microfibril angle and W_{cryst} can now be rapidly determined at CSIRO using SilviScan. SilivScan is an automated, fast, and cost-effective system that combines X-ray densitometry, diffractometry, and image analysis to measure a variety of wood properties including density, microfibril angle, and W_{cryst} (the average width of cellulose crystallites in the S2 layer of the cell wall) at high resolutions on samples prepared from increment cores (Evans 1999; Evans *et al.* 1999). Micrifibril angle in the S2 layer of cell walls is known to have a large and direct effect on shrinkages (Koehler 1930; Barber & Meylan 1964). The microfibrillar framework shrinks laterally with respect to the long axis of the microfibrils when molecules of liquid leave the cell wall. In general, longitudinal shrinkage increases and tangential shrinkage decreases with increasing microfibril angle (Koehler 1930; Harris & Meylan 1965; Meylan 1968). Fibres with large microfibril angle may resist collapse better but they often have lower density than low-microfibril-angle fibres in the same tree, as with earlywood *vs* latewood. This makes it difficult to obtain a clear view of the effect of microfibril angle on collapse. Cellulose crystallite width was chosen in this study to test if reduced W_{cryst} gives rise to higher shrinkage, the hypothesis being that smaller cellulose crystallites may exhibit greater specific surface area for hydrogen bonding and thereby higher shrinkage.

The objectives of this study were to examine the potential of using SilviScan density, microfibril angle, W_{cryst}, and other properties to predict key shrinkage properties, in particular tangential collapse and total tangential shrinkage. The study is a part of a project that includes several interrelated studies on the shrinkage and drying characteristics of wood from three provenances of 10-year-old *E. globulus*. The density, moisture content, shrinkage, and collapse data used in this study have been reported in a previous paper that dealt with their between-site and between-provenance differences (Yang *et al.* 2002). The new data comprise microfibril angle, W_{cryst}, and total cross-sectional shrinkage.

"Shrinkage property" is used as a general term in this paper to include linear shrinkage properties (shrinkage, collapse, and total shrinkage in radial and tangential directions) and cross-sectional shrinkage properties (cross-sectional shrinkage and total cross-sectional shrinkage) without being specific. Total shrinkage equals shrinkage plus collapse. Total cross-sectional shrinkage equals cross-sectional shrinkage plus cross-sectional collapse. The longitudinal shrinkage was not measured because it was difficult to obtain reliable measurements for technical reasons.

MATERIAL AND METHODS

Source of Material

The material was from 59, 10-year-old *Eucalyptus globulus* trees that were sampled from three provenances (Jeeralang, King Island, and South-eastern Tasmania) grown at two separate sites (Heath Block and Johnstons Block) in the Mt Gambier region of South Australia. A detailed description of these trees has been given by Yang *et al.* (2001). These trees were originally chosen for a large project that was to investigate between-site and provenance differences in various wood properties. However, sites and provenance were not factors in our study and had no bearing on data analysis and results.

Preparation of Shrinkage Block Specimens

One 1.2-m-long billet at a height of 1.3 m was removed from each tree stem after felling. From each billet were cut two end-matched pith-to-cambium strips (20 × 90-mm, tangential × longitudinal), free from visible defects. As many 20 × 20 × 90-mm specimens as possible were cut from each strip, starting from the pith. This gave two sets of 20 × 20 × 90-mm specimens for each billet. The 20 × 20 × 90-mm dimensions were close to those of samples used by Kingston & Risdon (1961) to ensure reliable comparisons between shrinkage data. Our earlier work had shown that the difference in cross-section size between 20 × 20 mm and 25 × 25 mm had little effect on shrinkages and collapse. The specimen ends were immediately sealed with silicone gel and covered with aluminium foil to prevent moisture loss.

Determining Moisture Content, Density, and Shrinkage Properties

One set of specimens* was dried to 12% moisture content (m.c.) to determine linear shrinkage properties (Kingston & Risdon 1961) and density. Details of the measurements and calculation of the shrinkage properties have been given by Yang *et al.* (2002). Density at 12% m.c. was determined from the weight and linear dimensions of each specimen after reconditioning. Moisture content was determined from block specimens of 20×20×30 mm that were also prepared from the billets and end-matched with the shrinkage specimens.

An imaging routine (Ilic 1999) was used to determine cross-sectional shrinkage from a 2-mm-thick cross-section removed from each block specimen after reconditioning.

Total cross-sectional shrinkage (TCS) — that is, the sum of normal shrinkage and collapse — was calculated from linear measurements using Equation 1. It is expected to be very close to total volumetric shrinkage since longitudinal shrinkage is usually very small and can be ignored except when severe reaction wood is present.

$$TCS = 100 \times (A_{Green} - A'_{12\%m.c.}) / A_{Green} \quad (1)$$

where:

A_{Green} = Green cross-sectional area ($D_{R,Green} \times D_{T,Green}$) (mm^2)

$A'_{12\%m.c.}$ = Cross-sectional area at 12% m.c. before reconditioning ($D'_{R,12\%m.c.} \times D'_{T,12\%m.c.}$) (mm^2)

$D_{R,Green}$ and $D_{T,Green}$ are respectively the radial and tangential green dimensions measured, and $D'_{R,12\%m.c.}$ and $D'_{T,12\%m.c.}$ respectively the radial and tangential dimensions at 12% m.c. before reconditioning.

Obtaining Microfibril Angle and Cellulose Crystallite Width using SilviScan

One pith-to-cambium SilviScan strip with final dimensions of 2 × 6 mm (tangential × longitudinal), at 12% m.c., was prepared from each billet along the same radius as the shrinkage block specimens. Each strip was scanned using SilviScan to determine the radial profile of microfibril angle and W_{cryst}. For each of microfibril angle and W_{cryst} the data were integrated over 5-mm intervals to produce the average values in each 5-mm radial segment of the specimen. Evans (1999) and Evans *et al.* (1999) have given the details for the estimation of microfibril angle using SilviScan. Cellulose crystallite width was determined from the X-ray diffraction patterns using the formula of Scherrer (Cullity 1977). The values

* The other set was used in other experiments for effect of drying temperature on shrinkage properties, the results of which will be reported in a separate paper.

of W_{cryst} reported in this paper are not corrected for instrumental broadening effects. Such corrections would give larger and more accurate cellulose crystallite widths. However, corrections may not be necessary when the purpose is to examine relationships as in this study.

The first four microfibril angle data points corresponding to the 20-mm radial segment of the specimen were arithmetically averaged to represent the microfibril angle of the 20 × 20 × 90-mm shrinkage specimen located next to the pith. The average of the next four microfibril angle data points represented the microfibril angle of the shrinkage specimen second from the pith, and so forth. This same averaging process was also carried out for W_{cryst}.

Data Analysis

The hypothesised causal effect of various selected properties on key shrinkage properties was examined using PATH analysis (*EQS 5 for Windows* software package by Multivariate Software Inc., USA). PATH analysis is a special approach of multiple regression to help assess the hypothetical direct and indirect causal effects of independent variables. The best regression model can be formed by elimination of variables that contribute little to the equation. PATH coefficients are standardised regression coefficients. In PATH analysis output diagrams, single-headed arrows point from independent variables towards a dependent variable and imply direct cause. Curved double-headed arrows connect independent variables and represent correlations. The diagrams show PATH coefficients next to the single-headed arrows, correlation coefficients between independent variables next to the curved double-headed arrows, coefficient of determination from the multiple regression, and the residual variance. For clarity, correlation coefficients and the associated curved double-headed arrows between any two independent variables are usually not shown in the output diagrams in this paper if one of the variables did not have significant direct effect on the dependent variable.

Simple correlations between shrinkage properties, density, moisture content, microfibril angle, and W_{cryst} were examined. Multiple regression analysis was used specifically to investigate the potential of predicting various shrinkage properties from density, microfibril angle, and W_{cryst}, which were the routine SilviScan measurements.

RESULTS

Mean values of shrinkage properties, microfibril angle and W_{cryst}, are summarised in Table 1. PATH analysis output diagrams are shown only for tangential collapse, radial collapse, and total cross-sectional shrinkage as dependent variables in Fig. 1, 2, and 3 because of their significance in the development of internal checking. A simple correlation matrix between shrinkage properties, density, moisture content, microfibril angle, and W_{cryst} is presented in Table 2. The sample size was 236. The correlation coefficients that were not shown in the PATH analysis diagrams (when one variable did not have significant direct effect on the dependent variable) can be found in Table 2. Relationship between total tangential shrinkage and tangential collapse is illustrated in Fig. 4 based on individual values and in Fig. 5 based on tree means at 1.3 m height. Multiple regression equations that were intended to predict linear and cross-sectional shrinkage properties from only three independent variables (density, microfibril angle, and W_{cryst}) are summarised in Table 3.

TABLE 1–Mean values of shrinkage properties, MFA, and W_{cryst}. Values in brackets are standard errors.

Properties	Means
Number of trees	59
Age of trees (years)	10
Radial shrinkage, S_R (%)	2.48 (0.11)
Radial collapse, C_R (%)	0.97 (0.10)
Total radial shrinkage, TS_R (%)	3.45 (0.16)
Tangential shrinkage, S_T (%)	5.73 (0.12)
Tangential collapse, C_T (%)	4.69 (0.31)
Total tangential shrinkage, TS_T (%)	10.42 (0.37)
Cross-sectional shrinkage, CS (%)	8.05 (0.19)
Total cross-sectional shrinkage, TCS (%)	13.46 (0.45)
Ratio of tangential to radial shrinkage	2.48 (0.09)
Microfibril angle, MFA (degrees)	14.92 (0.35)
Cellulose crystallite width, W_{cryst} (nm)	2.88 (0.01)

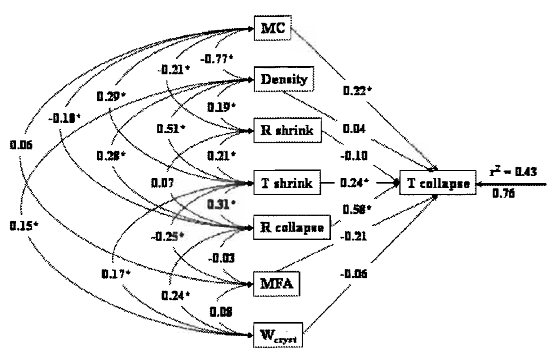

FIG. 1–PATH analysis output diagram of the hypothesised effect of various variables on tangential collapse. "T collapse" = tangential collapse, "MC" = moisture content, "Density" = density, "R shrinkage" = radial shrinkage, "T shrinkage" = tangential shrinkage, "R collapse" = radial collapse, "MFA" = microfibril angle, and "W_{cryst}" = cellulose crystallite width. Sample size is 236 and Chi-square = 0.

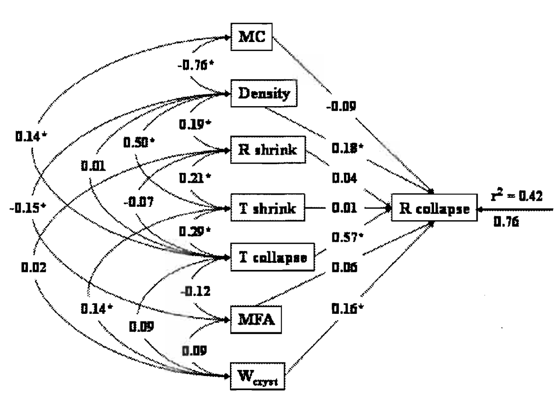

FIG. 2–PATH analysis output diagram of the hypothesised effect of various variables on radial collapse. *See* Fig. 1 for full name of each variable. Sample size is 236 and Chi-square = 2.26.

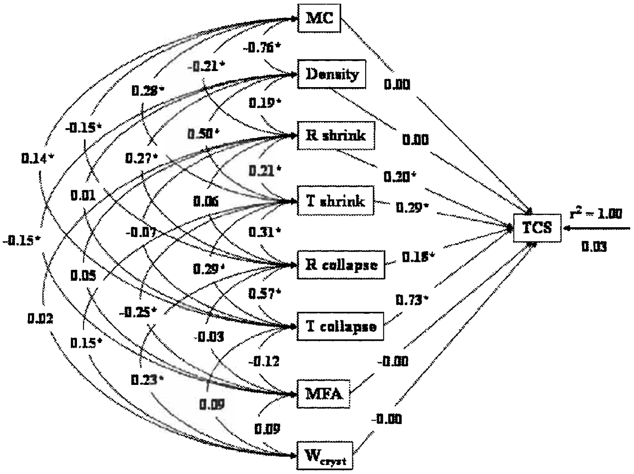

FIG. 3–PATH analysis output diagram of the hypothesised effect of various variables on cross-sectional shrinkage. "TCS" = total cross-sectional shrinkage, *see* Fig. 1 for full names of other variables. Sample size is 236 and Chi-square = 2.19.

TABLE 2–Correlation coefficients between shrinkage properties, density, MFA, and W_{cryst} (n=236).

Property	S_R (%)	S_T (%)	TS_R (%)	TS_T (%)	C_R (%)	C_T (%)	CS (%)	TCS (%)
S_T (%)	0.22**							
TS_R (%)	0.75**	0.36***						
TS_T (%)	0.03	0.60***	0.41***					
C_R (%)	0.08	0.31***	0.72***	0.60***				
C_T (%)	–0.06	0.32***	0.35***	**0.95*****	0.58***			
CS (%)	0.66***	0.74***	0.63***	0.36***	0.26***	0.14*		
TCS (%)	0.23**	0.61***	0.63***	**0.97*****	0.70***	**0.91*****	0.49***	
Moisture content	–0.22**	0.27***	–0.26***	0.01	–0.16*	0.11	–0.31***	0.05
Density	0.19**	0.50***	0.31***	0.19**	0.27***	0.03	0.39***	0.25***
MFA	0.06	–0.24**	0.02	–0.18*	–0.03	–0.12	–0.19**	–0.15*
Density/MFA	0.04	0.50***	0.16*	0.26***	0.21**	0.12	0.38***	0.27***
W_{cryst}	0.07	0.16*	0.23**	0.15*	0.27***	0.12	0.11	0.19**

S_R = radial shrinkage (normal shrinkage)
S_T = tangential shrinkage (normal shrinkage)
TS_R = total radial shrinkage (shrinkage before reconditioning)
TS_T = total tangential shrinkage (shrinkage before reconditioning)
C_R = radial collapse
C_T = tangential collapse
CS = cross-sectional shrinkage
TCS = total cross-sectional shrinkage (shrinkage before reconditioning)
* = $p < 0.05$
** = $p < 0.01$
*** = $p < 0.001$

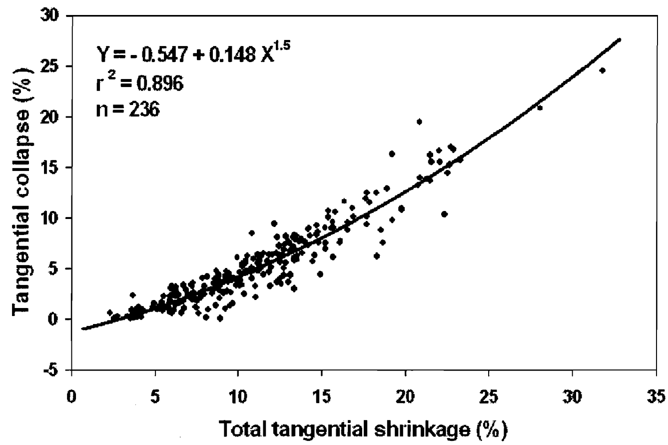

FIG. 4–Relationship between total tangential shrinkage and tangential collapse of individual shrinkage specimens of 10-year-old *E. globulus* ($p<0.001$).

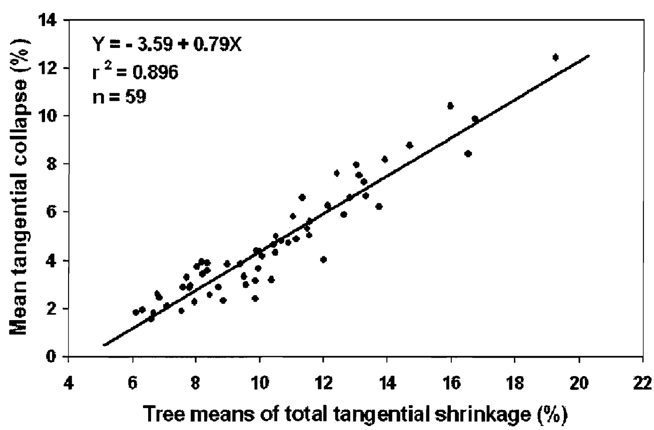

FIG. 5–Relationship between tree means of total tangential shrinkage and tangential collapse ($p<0.001$).

DISCUSSION

PATH Analysis

For tangential collapse, the PATH coefficients (Fig. 1) were significant for the path of "MC" (moisture content, 0.22), "T shrink" (tangential shrinkage, 0.24), and "R collapse" (radial collapse, 0.58), implying significant direct effect of these properties on "T collapse" (tangential collapse). The PATH coefficients for the path of other independent variables were not significant, implying they were unlikely to have direct effect on tangential collapse. Microfibril angle had an indirect effect on "T collapse" through its significant correlation with tangential shrinkage ($r = -0.25$). It can be quantified by multiplying the

TABLE 3–Summary of coefficients of multiple regression equations for predicting four linear shrinkage properties and two cross-sectional shrinkage properties from density, MFA, and W_{cryst}. Sample size = 236.

Dependent variable	Inter.	Regression coefficients			r^2	Residual variance
		Density	MFA	W_{cryst}		
Radial shrinkage	ns	0.23	ns	ns	0.042	1.25
Radial collapse	–6.22	0.25	ns	0.19	0.103	1.07
Tangential shrinkage	ns	0.39	–0.29	ns	0.261	1.59
Tangential collapse	ns	ns	–0.12	ns	0.035	4.21
Cross-sectional shrinkage	ns	0.321	–0.24	ns	0.182	2.21
Total cross-sectional shrinkage	ns	0.26	–0.26	ns	0.159	5.49

ns = p>0.05

PATH coefficient of "T shrink" (0.24) with the correlation coefficient between "T shrink" and "MFA" (–0.25). The negative relationship between MFA and tangential shrinkage (r = –0.25) was as expected. This weak relationship reflects the complexity of shrinkage in which other structural and chemical properties of the cell wall also play a role, as illustrated by Kelsey (1963) and Megraw *et al.* (1997). The negative relationship between MFA and tangential collapse (r = –0.21) appeared to support the hypothesis that fibres with larger microfibril angle have more resistance to collapse. On the other hand, collapse-prone fibres often have large microfibril angle and thin walls, as typically observed in earlywood. Hence, a positive relation of microfibril angle with collapse could happen if there was a lack of other cell wall layers (S1 and/or S3) that provide restraint. Cellulose crystallite width had an indirect effect on tangential collapse through its significant correlations with "T shrink" (r = 0.17) and with "R collapse" (r = 0.24), which can be quantified in the same way as described for microfibril angle. However, it is not apparent whether W_{cryst} and collapse are fundamentally connected. Tension wood fibres have larger W_{cryst} and are check-prone. But larger W_{cryst} is not the cause for their susceptibility to collapse. It is the lower lignin content in tension wood cells, hence reduced rigidity to resist inward collapse, that makes tension wood fibres prone to collapse. The macro behaviour of wood such as collapse is more likely dependent on several properties at higher structural levels. The coefficient of multiple determination (r^2) from the multiple regression model is 0.43.

For radial collapse, the PATH coefficients (Fig. 2) were significant for the path of "T collapse" (0.57), density (0.18), and "W_{cryst}" (0.16), implying their significant direct effect on radial collapse. Tangential collapse had the most direct effect on radial collapse (Fig. 2) and vice versa (Fig. 1). This demonstrates the intrinsic relationship between the two properties. Moisture content, microfibril angle, and radial and tangential shrinkages had little direct effect but had indirect effect through their significant correlations with each of tangential collapse, density, and W_{cryst} as shown by their correlation coefficients (Fig. 2). The indirect effect of these properties on radial collapse was very small. The significant path of W_{cryst} for radial collapse is interesting, in contrast with the insignificant path of W_{cryst} for tangential collapse. No explanations are available for this difference.

For tangential shrinkage, the PATH coefficients were significant for the path of density (0.56), "R shrink" (0.16), "T collapse" (0.23), and MFA (–0.17). Other independent variables had an indirect effect on tangential shrinkage through their significant relationships with radial shrinkage, tangential collapse, and microfibril angle.

For radial shrinkage, the PATH coefficients were significant only for the path of "T shrink" (tangential shrinkage, 0.57). Other independent variables had indirect effect on radial shrinkage through their significant correlations with tangential shrinkage (*see* their correlation coefficients in Table 2).

For cross-sectional shrinkage, the PATH coefficients were significant for the path of all variables except "T collapse" (–0.07) and "W_{cryst}" (–0.02). The variables that had the highest direct effect on cross-sectional shrinkage were radial and tangential shrinkages, as expected.

For total cross-sectional shrinkage, the PATH coefficients (Fig. 3) were significant only for the paths of linear shrinkage properties, which is an obvious relationship. Moisture content, density, microfibril angle, and W_{cryst} had indirect effects through their significant correlations with these linear shrinkage properties (Fig. 3), but these effects were small overall. The main variable accounting for the variation of total cross-sectional shrinkage was tangential collapse ($r = 0.73$). Microfibril angle and W_{cryst} had no effect on total cross-sectional shrinkage ($r = 0$) because they were not related to tangential collapse (Table 2).

Simple Correlations

Most correlations among shrinkage properties, and between shrinkage properties and microfibril angle and W_{cryst} were highly significant ($p<0.001$, Table 2). However, many of the correlation coefficients were well below 0.7. Strong correlations were found only among tangential collapse, total tangential shrinkage, and total cross-sectional shrinkage. Their correlation coefficients were greater than 0.9 (Table 2). The positive correlation between W_{cryst} and tangential shrinkage ($r = 0.16$, Table 2) did not necessarily disprove the hypothesis that wood with smaller cellulose crystallite width would shrink more due to increased specific surface area for hydrogen bonding and thereby higher shrinkage. The PATH analysis suggested (output diagram is not shown) that W_{cryst} did not have a direct effect on tangential shrinkage. Cellulose crystallite width was positively correlated with tangential shrinkage because it was also positively correlated with density, which itself had a significant direct effect on tangential shrinkage.

Radial collapse and radial shrinkage both were best correlated with total radial shrinkage (respectively, $r = 0.72$ and $r = 0.75$, Table 2). Hence, total radial shrinkage is the best single predictor for either of these two properties and a useful predictor because it is easy to measure.

Tangential collapse and total tangential shrinkage were highly correlated ($r = 0.95$, Table 2) and the closeness of this relationship was independent of data composition. The r^2 was 0.896 whether the data were measurements on individual specimens (Fig. 4) or tree means (Fig. 5), or whether the specimens were inner-wood only (the first three shrinkage specimens from the pith) or outer-wood only, or whether tension wood was present or not (wide bands of several millimetres of severe tension wood may be an exception). This is in line with the results on *E. regnans* F. Mueller by Chafe (1985) and Ilic (1999) who observed collapse was highly correlated ($r > 0.90$) with volumetric shrinkage and total cross-sectional shrinkage respectively. Total tangential shrinkage therefore is the single property that can most reliably predict tangential collapse. The practical significance of this result is that total tangential shrinkage is much quicker and easier to determine than tangential collapse. The tangential collapse profile along the tree radius is an important wood quality indicator. It should be easily predicted through a series of measurements of total tangential shrinkage on trimmed increment cores (Fig. 6). To determine whether extra independent variables would improve the prediction of tangential collapse, a multiple regression analysis was run that included moisture content, density, and total radial shrinkage because of their easy measurement, in addition to total tangential shrinkage. It was found that only density significantly improved the prediction. However, the coefficient of multiple determination was 0.899 when total tangential shrinkage and density were used as independent variables, which was only slightly higher than when using total tangential shrinkage alone ($r^2 = 0.896$, Fig. 4).

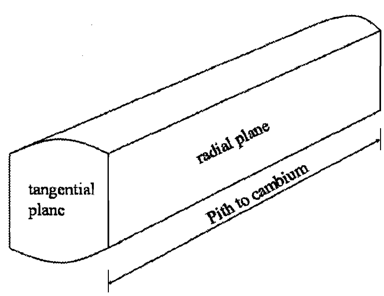

FIG. 6–Illustration of a trimmed increment core with two parallel radial surfaces for measurement of tangential dimensions.

For tangential shrinkage, the best single predictor was cross-sectional shrinkage, and vice versa ($r = 0.74$, Table 2). However, measurement of cross-sectional shrinkage is time consuming, and therefore its value as a predictor is practically limited. Total tangential shrinkage was the next best and a better predictor of tangential shrinkage from a practical point of view ($r = 0.60$).

Total cross-sectional shrinkage was best predicted by total tangential shrinkage alone ($r = 0.97$, Table 2). It was also well correlated with tangential shrinkage ($r = 0.61$) and tangential collapse ($r = 0.91$). In contrast, correlations between total cross-sectional shrinkage and any one of the linear radial shrinkage properties were considerably weaker (Table 2). Tangential shrinkage and tangential collapse were respectively twice and five times as high as radial shrinkage and radial collapse in young *E. globulus* (Table 1), and are therefore expected to dominate total cross-sectional shrinkage. Results of a similar nature have been reported on 43-year-old regrowth *E. regnans* (Chafe 1985). In that study, total volumetric shrinkage from green to oven dry was found to be highly correlated with volumetric collapse, and hence shown to be an accurate predictor of volumetric collapse.

Multiple Regressions

When density, microfibril angle, and W_{cryst} were entered in a multiple regression analysis as the only independent variables, density and microfibril angle showed more promise as predictors (Table 3).

Only density had a significant contribution to variation of radial shrinkage (Table 3). The coefficient of multiple determination was very low ($r^2 = 0.042$, Table 3) showing poor prospect of using density to predict radial shrinkage.

Only density and W_{cryst} had significant contributions to the variation of radial collapse (Table 3). The effect of these two properties was also direct, as suggested by the PATH analysis (Fig. 2). On the other hand, it was not clear whether there was a direct fundamental connection between W_{cryst} and collapse, as previously mentioned. The contribution of W_{cryst} could be from its association with other wood properties that have a direct effect on collapse. The coefficient of multiple determination was very low ($r^2 = 0.103$, Table 3), implying density and W_{cryst} had limited value in predicting radial collapse.

Only microfibril angle had a significant contribution to the variation of tangential collapse, but note that microfibril angle did not have a direct effect on tangential collapse (Fig. 1). Its significant contribution to the multiple regression came from its significant correlation with tangential shrinkage ($r = -0.25$, Fig. 1), a property that had a significant direct effect on tangential collapse (Fig. 1). As the coefficient of multiple determination is low ($r^2 = 0.035$, Table 3), the potential for using these three properties to predict tangential collapse is questionable.

Only density and microfibril angle had significant contributions to the variation of tangential shrinkage, cross-sectional shrinkage, and total cross-sectional shrinkage (Table 3). The coefficient of multiple determination was low or modest, ranging from 0.159 to 0.261 (Table 3). For total cross-sectional shrinkage, neither density nor microfibril angle had a direct effect. Density had an indirect effect through its significant correlations with the properties which had a direct effect — namely radial shrinkage, tangential shrinkage, and radial collapse (Fig. 3). Similarly, microfibril angle had an indirect effect through its significant correlations with tangential shrinkage (Fig. 3). Chafe (1985) and Ilic (1999) found total volumetric shrinkage was inversely related to density for regrowth *E. regnans*. Assuming longitudinal shrinkages can be ignored, total cross-sectional shrinkage can be compared with total volumetric shrinkage. The effect of density on total cross-sectional shrinkage in this study hence differs qualitatively from the studies of Chafe (1985) and Ilic (1999). Limited data from Yang & Evans (in press) showed that *E. regnans* had larger microfibril angle (14°) than *E. globulus* (11°), but this does not give much clue to microfibril angle of the *E. regnans* material used by Chafe (1985) and Ilic (1999) because of natural variability within species. Although microfibril angle is known to affect shrinkages, whether it had a role in the discrepancy in the effect of density between these three studies cannot be determined.

CONCLUSIONS

As suggested by PATH analysis, microfibril angle and W_{cryst} had a significant effect on several shrinkage properties but overall these relationships were moderate to weak. Microfibril angle had a hypothesized direct causal effect (negative) only on tangential shrinkage and cross-sectional shrinkage, and W_{cryst} had a hypothesised direct causal effect (positive) only on radial collapse. Microfibril angle was negatively correlated with all shrinkage properties except for radial shrinkage, which means that it is unrealistic to expect both small microfibril angle and low values of shrinkage properties in the same piece of wood. Microfibril angle and W_{cryst}, singly or jointly, were less able to predict shrinkage properties, in particular tangential collapse and total cross-sectional shrinkage.

Total tangential shrinkage was shown to be the best single predictor for tangential collapse ($r^2 = 0.896$) and for total cross-sectional shrinkage ($r^2 = 0.924$) because of their intrinsic relationships. Tangential collapse comprises much of the total tangential shrinkage which, in turn, comprises most of the total cross-sectional shrinkage. These relationships were strong for individual measurements and tree means, and for inner-wood and outer-wood. Tangential collapse was also highly correlated with total cross-sectional shrinkage ($r^2 = 0.865$). These findings are of practical significance since total tangential shrinkage can be easily measured from increment cores at low cost.

It appeared that reliable assessment of collapse and shrinkage properties requires direct measurement based on the data in this study. On the other hand, since the radial variability of wood properties in these specimens was high, the size of the specimens might have affected the strengths of the relationships when only average values were used in the data analysis. However, such effects could not be estimated very well from the present data even if the analysis involved pre-averaging information on microfibril angle and W_{cryst}. Further studies of different experimental plans are needed to discover the likely factors. In the mean time, the direct measurement of tangential shrinkage offers rapid and accurate assessment of important shrinkage properties of trees and boards for both wood processing and tree selection.

ACKNOWLEDGMENTS

The Natural Heritage Trust (Australia) provided funds to support this research. Thanks are also due to South Australia Forestry for providing the study trees and information relating to them; Mr P.Blakemore of CSIRO for assisting with statistical analysis; Mr P.Blackwell, Mrs S.Molenaar, and Mr G.Turville for contributing to shrinkage specimen preparation and measurement. The Victorian Timber Industry Training Centre at Creswick, Victoria, made a log yard available for the billet removal. Valuable comments and suggestions from Dr S.Chafe and Dr W.E.Hillis on this manuscript before its submission to the journal are greatly appreciated.

REFERENCES

BARBER, N.F.; MEYLAN, B.A. 1964: The anisotropic shrinkage of wood — a theoretical model. *Holzforschung 18(5)*: 145–156.

BEKELE, T. 1995: Degradation of boards of *Eucalyptus globulus* Labill. and *Eucalyptus camaldulensis* Dehnh. during air drying. *Holz als Roh- und Werkstoff 53*: 407–412.

BISSET, I.J.W.; ELLWOOD, E.L. 1951: The relation of differential collapse and shrinkage to wood anatomy in *Eucalyptus regnans* F.v.M. and *Eucalyptus gigantea* Hook. F. *Australian Journal of Applied Science 2*: 175–183.

CHAFE, S.C. 1985: The distribution and interrelationship of collapse, volumetric shrinkage, moisture content and density in trees of *Eucalyptus regnans* F. Muell. *Wood Science and Technology 19*: 329–345.

———1986a: Collapse, volumetric shrinkage, specific gravity and extractives in *Eucalyptus* and other species. Part 1: The shrinkage/specific gravity ratio. *Wood Science and Technology 20*: 293–307.

———1986b: Radial variation of collapse, volumetric shrinkage, moisture content and density in *Eucalyptus regnans* F. Muell. *Wood Science and Technology 20*: 253–262.

———1987: Collapse, volumetric shrinkage, specific gravity and extractives in *Eucalyptus* and other species. Part 2: The influence of wood extractives. *Wood Science and Technology 21*: 27–41.

———1990a: Changes in shrinkage and collapse in the wood of *Eucalyptus regnans* F. Muell. following extraction. *Holzforschung 44(4)*: 235–244.

———1990b: Effect of brief presteaming on shrinkage, collapse and other wood-water relationships in *Eucalyptus regnans* F. Muell. *Wood Science and Technology 24*: 311–326.

———1992: The effect of boiling time on the change in green wood volume in *Eucalyptus regnans* F. Muell. *Holzforschung 46*: 463–466.

———1993: The effect of boiling on shrinkage, collapse and other wood-water properties in core segments of *Eucalyptus regnans* F. Muell. *Wood Science and Technology 27*: 205–217.

CHAFE, S.C.; CARR, J.M. 1998: Effect of board dimensions and grain orientation on internal checking in *Eucalyptus regnans*. *Holzforschung 52*: 434–440.

CHAFE, S.C.; ILIC, J. 1992: Shrinkage and collapse in thin sections and blocks of Tasmanian mountain ash regrowth. Part 3: Collapse. *Wood Science and Technology 26*: 343–351.

CUEVAS, L.E. 1969: Shrinkage and collapse studies on *Eucalyptus viminalis*. *Journal of Institute of Wood Science 4(5)*: 29–38.

CULLITY, B.D. 1977: "Elements of X-ray Diffraction", 2nd ed. Addison-Wesley Publishing Co., London, U.K.

DADSWELL, H.E.; WARDROP, A.B. 1955: The structure and properties of tension wood. *Holzforschung 9(4)*: 97–104.

EVANS, R. 1999: A variance approach to the x-ray diffractometric estimation of microfibril angle in wood. *Appita Journal 52(4)*: 283–289, 294.

EVANS, R.; HUGHES, M.; MENZ, D. 1999: Microfibril angle variation by scanning x-ray diffractometry. *Appita Journal 52(5)*: 363–367.

GREENHILL, W.L. 1936: Shrinkage of Australian timbers. Part 1. — A new method for determining shrinkages and shrinkage figures of a number of Australian species. *CSIR, Australia, Division of Forest Products, Technological Paper No. 33*.

HARRIS, J.M.; MEYLAN, B.A. 1965: The influence of microfibril angle on longitudinal and tangential shrinkage in *Pinus radiata*. *Holzforschung 19(5)*: 144–153.

ILIC, J. 1999: Shrinkage-related degrade and its association with some physical properties in *Eucalyptus regnans* F. Muell. *Wood Science and Technology 33*: 425–437.

ILIC, J.; CHAFE, S.C. 1986: The relationship between collapse, pulp resistance and depth of electrode penetration in trees of *Eucalyptus regnans* F. Muell. *Australian Forest Research 16*: 291–299.

ILIC, J.; HILLIS, W.E. 1986: Prediction of collapse in dried eucalypt wood. *Holzforschung 40(2)*: 109–112.

INNES, T. 1996: Collapse and internal checking in the latewood of *Eucalyptus regnans* F. Muell. *Wood Science and Technology 30*: 373–383.

KAUMAN, W.G. 1960: Contributions to the theory of cell collapse in wood: Investigations with *Eucalyptus regnans*. *Australian of Journal of Applied Science 11(1)*: 122–145.

———1964: Cell collapse in wood. *Holz als Roh- und Werkstoff 22*: 183–196, 465–472 [CSIRO translation].

KELSEY, K.E. 1963: A critical review of the relationship between the shrinkage and structure of wood. Commonwealth Scientific and Industrial Research Organization, *Division of Forest Products Technological Paper* No.28.

KINGSTON, R.S.T.; RISDON, C.J.E. 1961: Shrinkage and density of Australian and other South-west Pacific Woods. *CSIRO Division of Forest Products Technological Paper No.13*.

KOEHLER, A. 1930: Longitudinal shrinkage of wood. *USDA Forest Service, Forest Products Laboratory Report 1093*. 10 p.

MEGRAW, R.A.; LEAF, G.; BREMER, D. 1997: Longitudinal shrinkage and microfibril angle in loblolly pine. Pp. 26–61 *in* Butterfield, B.G. (Ed.) "Microfibril Angle in Wood", Proceedings of the IAWA/IUFRO International Workshop on the Significance of Microfibril Angle to Wood Quality, Westport, New Zealand, November.

MEYLAN, B.A. 1968: Cause of high longitudinal shrinkage in wood. *Forest Products Journal 18(4)*: 75–78.

NICHOLSON, J.E.; CAMPBELL, G.S.; BLAND, D.E. 1972: Association between wood characteristics and growth stress level: A preliminary study. *Wood Science 5(2)*: 109–112.

NICHOLSON, J.E.; HILLIS, W.E.; DITCHBURNE, N. 1975: Some tree growth – wood property relationships of eucalypts. *Canadian Journal of Forest Research 5(3)*: 424–432.

PANKEVICIUS, E.R. 1961: Influence of position in tree on recoverable collapse in wood. *Forest Products Journal 11(3)*: 131–132.

——1962: Collapse intensity for two eucalypts after treatment with hydrochloric acid and sodium chloride solutions. *Forest Products Journal 12(1)*: 39–42.

THOMSON, A.B. 1989: Shrinkage, collapse and dimensional recovery of regrowth jarrah. *CALM Report No.13*. WA, Australia.

TIEMANN, H.D. 1941: Collapse in wood as shown by the microscope. *Journal of Forestry 39*: 271–283.

WARDROP, A.B.; DADSWELL, H.E. 1948: The nature of reaction wood. I. The structure and properties of tension wood fibres. *Australian Journal of Scientific Research B1*: 3–20.

——1955: The nature of reaction wood. IV. Variation in cell wall organization of tension wood fibres. *Australian Journal of Botany 3(2)*: 177–189.

WASHUSEN, R.; ILIC, J. 2001: Relationship between transverse shrinkage and tension wood from three provenances of *Eucalyptus globulus* Labill. *Holz als Roh- und Werkstoff 59*: 85–93.

WILKES, J. 1988: Collapse in billets of *Eucalyptus* spp. *Journal of Institute of Wood Science 11(3)*: 114–116.

WILKES, J.; WILKINS, A.P. 1987: Anatomy of collapse in *Eucalyptus* species. *IAWA Bulletin 8(3)*: 291–295.

WOOD, M.S.; STEPHENS, N.C.; ALLISON, B.K.; HOWELL, C.I. 2001: "Plantations of Australia — A Report from the National Plantation Inventory and the National Farm Forest Inventory" (abridged version). National Forest Inventory, Bureau of Rural Sciences, Canberra.

YANG, J.L.; EVANS, R.: Prediction of MOE of eucalypt wood from microfibril angle and density. *Holz als Roh- und Werkstoff* (in press).

YANG, J.L.; WAUGH, G. 1996a: Potential of plantation-grown eucalypts for structural sawn products. I. *Eucalyptus globulus* Labill. spp. *globulus*. *Australian Forestry 59(2)*: 90–98.

——1996b: Potential of plantation-grown eucalypts for structural sawn products. II. *Eucalyptus nitens* (Deane & Maiden) Maiden and *E. regnans* F. Muell. *Australian Forestry 59(2)*: 99–107.

YANG, J.L.; FIFE, D.; MATHESON, A.C. 2001: Growth strain in three provenances of plantation-grown *Eucalyptus globulus* Labill. *Australian Forestry 64(4)*: 248–256.

YANG, J.L.; FIFE, D.; ILIC, J.; BLAKEWELL, P. 2002: Between site and provenance differences in shrinkage properties of 10-year-old *Eucalyptus globulus* Labill. *Australian Forestry 65(4)*: 220–226.