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ORIGINAL ARTICLE

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Relationships of anatomical characteristics versus shrinkage and collapse properties in plantation-grown eucalypt wood from China

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Abstract To explore the influence of the basic density on collapse-type shrinkage properties and to quantify the relationships of the main anatomical features with shrinkage and collapse properties, all above-mentioned parameters were determined and analyzed for three species of collapse-susceptible eucalypts, *Eucalyptus urophylla, Eucalyptus grandis*, and *E. urophylla* × *E. grandis*, planted in South China. The correlation coefficients were also determined and the corresponding regression equations were established with the anatomical parameters measured by using multiple linear regression. The results indicated that: (1) basic density was strongly positively linearly related to both unit tangential shrinkage ($r = 0.970$) and unit radial shrinkage ($r = 0.959$), weakly positively related to total shrinkage ($r = 0.656$ and 0.640 for tangential and radial, respectively), and weakly negatively related to residual collapse ($r = 0.632$ and 0.616 for tangential and radial, respectively). (2) The main factors affecting unit shrinkage were cell wall proportion (WP), microfibril angle (MFA), and double fiber cell wall thickness (DWT); factors playing an important role in total shrinkage were WP, ray parenchyma proportion (RP), and MFA, while RP had the highest effect on residual collapse ($r = 0.949$ and 0.860 for tangential and radial, respectively). (3) All corresponding regression models obtained were very suitable for the evaluation of relationships between the anatomical parameters and unit shrinkage, total shrinkage, and residual collapse, as measured using a moisture content of 28% as the fiber saturation point for all specimens.

Key words Anatomical characteristics · Unit shrinkage · Total shrinkage · Residual collapse · Plantation-grown eucalypt

Introduction

Eucalypt is the most important plantation tree species extensively planted in temperate, subtropical, and tropical regions outside Australia, and ranks first in terms of cultivated forest areas in the world.[1–3] Of the introduced eucalypt tree species, *Eucalyptus urophylla, Eucalyptus grandis*, and their hybrids have been widely popularized and preferred in countries planting eucalypt, such as China, Brazil, India, and South Africa, owing to their superb growth rate, high productivity, and their ability to produce a range of useful forest products such as pulp and paper, round timber, and sawn products.[3–6] Previous studies have been largely focused on wood properties as a resource for wood fiber,[1,2,4,5] while there have been few studies involving the processing characteristics when used as solid products. In recent years, there has been considerable interest in growing trees for solid wood products and some preliminary investigation has been performed regarding their potential for higher value products such as appearance-grade sawn timber. However, it is well known that some commercially important eucalypt species, like the eucalypts mentioned above, are prone to collapse and honeycomb during drying. Collapse is an abnormal shrinkage encountered in wood of certain tree species during drying and quite a few studies have already been conducted on the mechanisms of collapse,[8–16] methods of prevention and relief of collapse,[17,18]

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Part of this article was presented at the 54th Annual Meeting of the Japan Wood Research Society, Sapporo, August 2004, and at the 7th Pacific Rim Bio-based Composites Symposium in Nanjing, P.R. China prediction of collapse,[19,20] and wood properties closely related to both collapse and shrinkage.[6,7,21–28] Little information, however, was reported on the relationship between some anatomical parameters and the shrinkage process, including collapse, in eucalypt wood. The few studies on these aspects[22,29] were only qualitative or were carried out quantitatively between either one or several species of anatomical parameters and shrinkage and collapse.[6,7,15] Thus, it is necessary to systematically investigate the relationship between anatomical characteristics and shrinkage properties in collapse-susceptible plantation-grown eucalypt wood.

Therefore, the objectives of this study were to quantify the correlation of systematic anatomical parameters with shrinkage properties and to provide quantified mathematical models predicting drying qualities in standing trees or green wood in plantation eucalypt. Moreover, the relationship between shrinkage properties and basic density, the main anatomical factors contributing to shrinkage and collapse, and radial variation in shrinkage and collapse are also discussed.

Materials and methods

Collection of sample woods

Five 11-year-old trees from each of three species of eucalypts (*Eucalyptus urophylla, Eucalyptus grandis*, and *E. urophylla* × *E. grandis*) grown in the same clonal gene pool, established through a China–Australia cooperation program, in Dong-Men Forest Farm located at 22°30′19″N, 107°30′25″E, at 200 m altitude in Guangxi Autonomous Region, China, were sampled in this study. The climatic conditions in the gene pool are as follows: 1213 mm mean annual precipitation, 1448 mm annual evaporation, 21.3°C annual mean temperature, 39.2°C maximum temperature in the hottest month, 1.2°C minimum temperature in the coldest month, and an average of 3 days per year of frost.

Preparation of specimens

One 1.3-m-long billet was removed upward of breast height from each tree stem after felling. From each billet, one pith-to-cambium radial board [21 × 120 mm, tangential (t) × longitudinal (l)] free from visible defects was cut from south to north and labeled. One 21 × 21 × 120-mm (t × r × l) sample stick was cut from each of three positions of 10% (innerwood, I), 50% (middlewood, M), and 90% (outerwood, O) for all these boards from pith to bark. Finally, 30 sample sticks for every species of eucalypt were taken. At first, two end-matched specimens (5 × 21 × 10 mm, t × r × l) were cut on each stick, of which one was used as the determination of microfibrilangle (MFA) and the other for other designated anatomical properties. Then as many 21 × 21 × 5-mm (t × r × l) specimens as possible were cut from the remaining part of the same stick for the measurement of basic density and shrinkage properties.

Determination of unit shrinkage, total shrinkage, and residual collapse

Five end-matched specimens at each of three positions of I, M, and O for each of five trees in each of three species of eucalypt were cut, and all specimens were dried sequentially in a conditioning experimental drying kiln at dry-bulb temperature (DBT) 25°C from green to nominal equilibrium moisture contents (EMC) of 24%, 18%, 12%, 6%, and, finally, 0% at 103° ± 2°C for 24 h to constant weight. The dimensions at various stages of moisture content were measured with an electronic caliper with a precision of 0.01 mm. The total shrinkage, consisting of normal shrinkage below the fiber saturation point (FSP), which is defined as the moisture content where only cell walls are saturated with bound water while no free water exists in cell cavities, and abnormal shrinkage due to collapse above FSP, was represented as the ratio of the dimensional change at various moisture content (MC) states to the dimension in the green condition. The mean value of the 25 specimens from same positions of each eucalypt species was represented as the shrinkage at a certain position for the given species. Collapse (we refer to residual collapse here), was extrapolated by the following method. Because the shrinkage curves in this work are almost straight below about 24% MC, the regression equation of a straight line can be expressed as:

$$y_1 = -\alpha x + \beta_1 \tag{1}$$

where y_1 represents total shrinkage, including residual collapse, x equals MC, α denotes the slope of the line and is described as unit shrinkage, and β_1 is the intersection with the y-axis and expresses the largest total shrinkage at 0% MC. In order to obtain the normal shrinkage without collapse, a straight line that coincides with FSP and parallel to that of Eq. 1 was obtained as follows:

$$y_2 = -\alpha x + \beta_2 \tag{2}$$

where y_2 is normal shrinkage at the any MC below FSP, β_2 is the intersection with the y-axis and the highest normal shrinkage at 0% MC, and x and α are the same as in Eq. 1. Let x be 28% as FSP, then $y_2 = 0$; therefore, β_2 can be determined. The residual collapse was calculated by the difference between β_1 and β_2, that is, $(\beta_1 - \beta_2)$.

Measurement of basic density

Basic densities (BD) of all green specimens that were end-matched with those used for measurement of shrinkage were determined by using the water displacement method.

Determination of microfibril angle

All end-matched blocks selected were softened by boiling in a solution of 90% alcohol glycerin (1 : 1, v/v). Twenty-five to 30 tangential sections of 10–12 μm in thickness were cut

Table 1. Mean values of anatomical properties and basic density in three positions of three species of eucalypt

Properties	*Eucalyptus urophylla*			*Eucalyptus grandis*			*E. urophylla* × *E. grandis*		
	I	M	O	I	M	O	I	M	O
MFA (°)	18.17	15.26	13.16	19.56	15.61	14.28	16.54	13.49	11.36
FCD (μm)	10.83	10.62	11.25	11.18	11.09	11.24	10.80	10.64	10.90
DWT (μm)	6.27	6.55	7.52	5.12	5.59	6.05	6.01	6.15	6.87
WP (%)	68.36	72.41	74.55	65.54	68.97	71.50	65.62	69.46	72.45
FP (%)	65.20	59.34	65.62	67.34	65.91	62.15	60.31	58.05	64.25
VP (%)	12.52	13.66	17.70	10.50	14.15	17.15	13.22	15.21	17.20
RP (%)	18.02	17.09	14.20	17.20	15.43	13.10	17.34	16.03	12.70
PP (%)	4.60	3.86	3.64	4.96	4.68	4.35	6.65	6.37	4.79
BD (g/cm^3)	0.42	0.48	0.52	0.38	0.46	0.48	0.39	0.46	0.49

I, Innerwood; M, middlewood; O, outerwood; MFA, microfibril angle; FCD, fiber lumen diameter; DWT, double fiber cell wall thickness; WP, proportion of all cell wall; FP, proportion of fiber; VP, proportion of vessel; RP, proportion of ray parenchyma; PP, proportion of axial parenchyma; BD, basic density

Table 2. Mean values of unit shrinkage, total shrinkage, and residual collapse in three positions of three species of eucalypt

Properties	*E. urophylla*			*E. grandis*			*E. urophylla* × *E. grandis*		
	I	M	O	I	M	O	I	M	O
α_T (%)	0.25	0.28	0.29	0.24	0.26	0.27	0.24	0.26	0.28
α_R (%)	0.20	0.21	0.23	0.19	0.21	0.22	0.19	0.21	0.22
S_T (%)	9.26	10.25	10.21	8.44	8.88	8.78	8.46	9.24	9.12
S_R (%)	6.08	6.78	6.81	4.91	5.56	5.47	4.89	5.64	5.61
C_T (%)	1.67	1.81	1.12	1.56	1.69	0.95	1.47	1.51	0.87
C_R (%)	0.70	0.74	0.38	0.35	0.65	0.11	0.47	0.59	0.21

α_T, unit tangential shrinkage; α_R, unit radial shrinkage; S_T, total tangential shrinkage; S_R, total radial shrinkage; C_T, tangential residual collapse; C_R, radial residual collapse

with a sliding microtome (Model AO-860, AO) and placed in a test tube and immersed with Jeffrey's solution (10% nitric acid/10% chromic acid/water, 1:1:18) for 14–18 h at 40°C until they were entirely macerated into single half-wall fibers. These were then transferred to a glass slide using a clean stainless steel needle and spread evenly. Thirty half-wall fibers were observed and determined randomly by polarized light microscopy for each sample block, and all measurements from the same locations of five trees of each eucalypt species were averaged to represent the magnitude of a certain location of the given eucalypt species.

Determination of fiber morphology and various tissue proportions

Transverse 25-μm-thick microsections were cut using a sliding microtome from block matched with that used for measurement of MFA. Temporary sections were made on glass slides with glycerine. Microscopic images from the wood cross sections were collected using a Quantimat-750 Image Analyzer with image analysis software. Consecutive images were captured from the start to the end of each cross section in the radial direction. In each measured frame, fiber cavity diameter (FCD), double fiber cell wall thickness (DWT), and the proportions of various tissues including cell wall (WP), fiber (FP), vessel (VP), ray parenchyma (RP), and axial parenchyma (PP), which are defined as the fraction of the total cross-sectional area covered by their respective tissue, were measured and calculated.

Statistical analysis

Pearson correlation coefficients were calculated among the unit shrinkage, total shrinkage, residual collapse, and anatomical characteristics. Model equations of the relationships among unit cell wall shrinkage, total shrinkage, and residual collapse to anatomical parameters were constructed on a microcomputer using multiple linear regression analysis with SPSS 12.0 software. The main factors contributing to the regression model equations were evaluated by the magnitude of the standardized regression coefficients.

Results

Statistics for various indices

The mean values of anatomical characteristics, unit shrinkage, total shrinkage, and residual collapse properties in *Eucalyptus urophylla, Eucalyptus grandis* and *E. urophylla* × *E. grandis* are summarized in Tables 1 and 2. For the anatomical features, it can be seen that BD, DWT, WP, and

Table 3. Correlation coefficients between anatomical properties, unit shrinkage, total shrinkage, and residual collapse in eucalypt wood

Variables	MFA	FCD	DWT	WP	FP	VP	RP	PP	α_T	α_R	S_T	S_R	C_T	C_R
MFA	1.00	ns	*	*	ns	**	**	ns	**	**	*	*	ns	ns
FCD	0.06	1.00	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
DWT	–0.70	–0.07	1.00	**	ns	*	ns	ns	**	**	*	*	ns	ns
WP	–0.78	0.12	0.84	1.00	ns	**	ns	*	**	**	*	*	ns	ns
FP	–0.33	0.43	0.33	0.48	1.00	ns	ns	ns	ns	ns	ns	ns	ns	ns
VP	–0.92	–0.23	0.73	0.82	–0.16	1.00	**	ns	*	*	ns	ns	ns	ns
RP	0.80	–0.48	–0.43	–0.67	–0.11	–0.88	1.00	ns	*	*	*	*	**	**
PP	0.12	–0.44	–0.42	–0.68	–0.46	–0.29	0.32	1.00	*	*	ns	ns	ns	ns
α_T	–0.84	0.57	0.82	0.99	0.43	0.65	–0.75	–0.69	1.00	**	*	*	ns	ns
α_R	–0.81	0.53	0.82	0.99	0.31	0.64	–0.73	–0.66	0.99	1.00	*	*	ns	ns
S_T	–0.71	–0.22	0.78	0.81	0.39	0.39	0.68	0.52	0.74	0.75	1.00	**	ns	ns
S_R	–0.65	–0.14	0.76	0.79	0.38	0.38	0.66	0.40	0.73	0.73	0.98	1.00	ns	ns
C_T	0.51	0.44	–0.48	–0.55	–0.24	–0.60	0.90	0.28	–0.60	–0.61	0.42	0.42	1.00	**
C_R	0.44	0.50	–0.48	–0.58	–0.23	–0.49	0.74	0.25	–0.24	–0.27	0.36	0.37	0.89	1.00

ns, No significance at 0.05 level
* $P < 0.05$ (two-tailed); ** $P < 0.01$ (two-tailed)

Table 4. Standardized regression coefficients (r_{std}) of independent variables in regression model equations

Variables	MFA	FCD	DWT	WP	FP	VP	RP	PP
α_T	–0.60	0.20	0.32	0.74	–0.01	–0.31	0.11	–0.11
α_R	–0.33	0.23	0.28	0.71	–0.05	–0.14	0.07	–0.12
S_T	–0.68	0.14	0.44	1.58	–0.01	–0.51	1.01	0.21
S_R	–0.56	0.24	0.47	1.26	0.22	–0.44	1.15	–0.06
C_T	1.48	0.08	–1.12	–1.24	0.47	1.13	3.47	0.78
C_R	1.30	0.25	–1.05	–1.14	0.52	1.12	3.14	0.85

VP increase and MFA, RP, and PP decrease from the pith toward the bark (Table 1). While as far as shrinkage and collapse properties are concerned, a parabolic radial variation pattern, i.e. low value (I)-peak value (M)-low value (O), was observed for both total shrinkage and residual collapse except for the increase in basic density and unit shrinkage from the pith toward the bark (Tables 1 and 2).

Correlation analysis

The correlation coefficients between anatomical characteristics and shrinkage properties such as unit shrinkage, total shrinkage, and residual collapse are presented in Table 3. In order to simplify the data analysis, three species of eucalypts that had no significant difference in basic density and most anatomical properties[1,2,30] were dealt with as the same species during the correlation analysis and the following regression analysis.

Regression analysis

The standardized regression coefficients (Table 4) were applied to evaluate the main anatomical factors that influence unit shrinkage, total shrinkage, and residual collapse. The larger the absolute values of the standardized regression coefficients (r_{std}), the greater their influence on the dependent variables in regression model equations.[31,32] Linear multiple regression model equations that were intended to quantify the relationships between anatomical features and collapse-shrinkage properties are summarized in Table 5.

Discussion

Relationship between basic density and unit shrinkage and total shrinkage

Density is widely acknowledged to reflect shrinkage properties. However, it appears that it would not be an entirely satisfactory indicator for low to medium density eucalypt species. As demonstrated in Figs.1 and 2, a simple linear regression showed that basic density was a better indicator for unit shrinkage than total shrinkage. That is, the variation in unit tangential shrinkage and unit radial shrinkage to BD are 97.0% and 95.9%, respectively. While the variation in total tangential shrinkage (S_T) and radial tangential shrinkage (S_R) only accounted for 65.6 % and 64.0%, respectively. A very strong linear association between BD and unit shrinkage indicates that volumetric changes in cell wall substances play the most important role in unit shrinkage below FSP, while total shrinkage from green to 0% MC reflects the combined varieties in both cell cavity and cell wall volumes. In other words, as long as the shape of cell lumen changes above the FSP, collapse should theoretically

Table 5. Multiple regression summary for variables of unit shrinkage, total shrinkage, and residual collapse versus anatomical characteristics in planted eucalypt wood

Regression equations	*r*	*P*
$\alpha_T = -0.0881 - 0.00409\mathrm{MFA} + 0.00140\mathrm{FCD} + 0.00451\mathrm{DWT} + 0.00470\mathrm{WP} - 0.00100\mathrm{FP} - 0.00219\mathrm{VP} + 0.00101\mathrm{RP} - 0.00191\mathrm{PP}$	0.995	<0.05
$\alpha_R = -0.0572 - 0.00148\mathrm{MFA} + 0.00107\mathrm{FCD} + 0.00125\mathrm{DWT} + 0.00261\mathrm{WP} - 0.000182\mathrm{FP} - 0.000642\mathrm{VP} + 0.000414\mathrm{RP} - 0.00135\mathrm{PP}$	0.990	<0.05
$S_T = -25.9 - 0.126\mathrm{MFA} + 0.0844\mathrm{FCD} + 0.323\mathrm{DWT} + 0.337\mathrm{WP} - 0.00139\mathrm{FP} - 0.138\mathrm{VP} + 0.314\mathrm{RP} + 0.136\mathrm{PP}$	0.980	<0.05
$S_R = -22.4 - 0.195\mathrm{MFA} + 0.102\mathrm{FCD} + 0.170\mathrm{DWT} + 0.283\mathrm{WP} - 0.0455\mathrm{FP} + 0.124\mathrm{VP} + 0.310\mathrm{RP} + 0.0419\mathrm{PP}$	0.975	<0.05
$C_T = -0.645 + 0.168\mathrm{MFA} + 0.112\mathrm{FCD} - 0.334\mathrm{DWT} - 0.0261\mathrm{WP} + 0.0474\mathrm{FP} + 0.155\mathrm{VP} + 0.424\mathrm{RP} + 0.189\mathrm{PP}$	0.979	<0.05
$C_R = 4.94 + 0.195\mathrm{MFA} + 0.215\mathrm{FCD} - 0.327\mathrm{DWT} - 0.0791\mathrm{WP} + 0.0344\mathrm{FP} + 0.145\mathrm{VP} + 0.350\mathrm{RP} + 0.173\mathrm{PP}$	0.970	<0.05

r, Correlation coefficients in multiple regression models; *P*, significance of regression coefficients in regression models

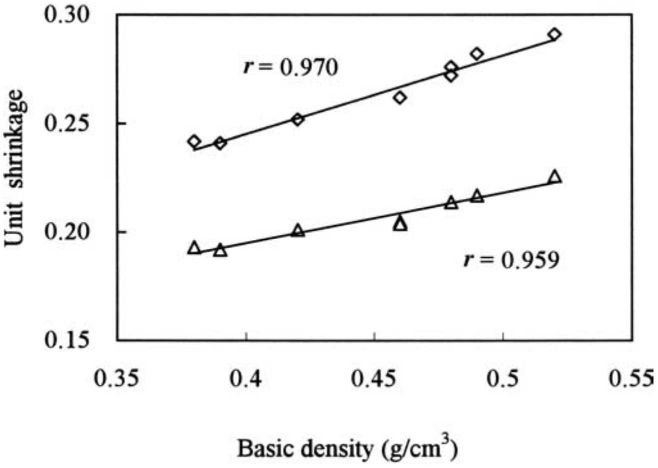

Fig. 1. Unit shrinkage plotted against basic density for planted eucalypt. *Diamonds*, unit tangential shrinkage; *triangles*, unit radial shrinkage

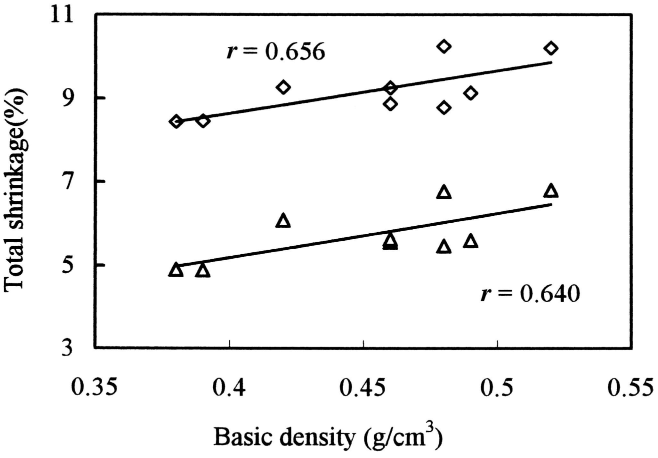

Fig. 2. Total shrinkage plotted against basic density for planted eucalypt. *Diamonds*, total tangential shrinkage; *triangles*, total radial shrinkage

occur. Therefore, collapse can lead to an increase of total shrinkage including residual collapse and normal shrinkage, while having no effect on unit shrinkage. This is the reason for inconsistent radial variation trends in unit shrinkage, which increased with increasing BD from the pith toward the bark, and total shrinkage, which increased in heartwood at first and then gradually decreased slightly near the outerwood with an increase of BD along the radial direction (Tables 1 and 2).

Relationship between basic density and residual collapse

Collapse is a deformation of cells that occurs beyond FSP, that is, when free water saturated in air-tight cell lumina is removed, the cell walls are deformed by liquid tension. After the liquid tension disappears, the deformation of the cell will recover to some extent, and the shape of the cells after drying is different from the original shape.[33] It can be seen from Table 2 that radial variation in total shrinkage and residual collapse has a parabolic shape, that is, low values in the outerwood, in spite of high density, high values in the the middlewood, and a decline toward the pith. The lower values that occur near the pith when compared with the middlewood may be attributed to the combined interaction of both thinner-wall ray and axial parenchyma, which are prone to collapse by liquid tension forces, and, as compared with the other two positions, have larger MFA, which tends to prevent transversal shrinkage from increasing. Because the reduction of liquid tension by larger permeability mitigated collapse development, compared with the middlewood, the extremely low values in the outwood may be inferred to be closely related to its higher permeability in sapwood and low percentage of RP. As presented in Fig. 3, there is a weakly negative linear relationship between residual collapse and basic density; this finding is very similar to that reported by Chafe.[24] This shows that BD is not a good indicator for residual collapse because some more important anatomical characteristics, such as ray and axial parenchyma, very likely play a role in the formation of residual collapse so as to weaken greatly the effect of BD.

Relationship of anatomical characteristics with unit shrinkage and total shrinkage

Correlations between unit shrinkage and anatomical features were significant either or strongly significant, except

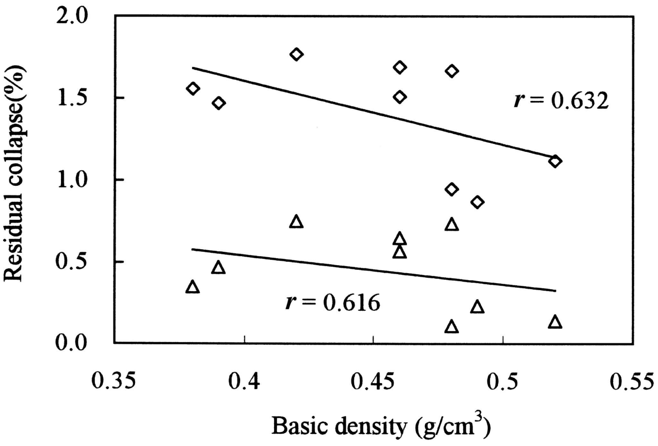

Fig. 3. Residual collapse plotted against basic density for planted eucalypt. *Diamonds*, tangential residual collapse; *triangles*, radial residual collapse

for FCD and FP (Table 3), implying significant immediate effects of MFA, DWT, WP, VP, RP, and PP. However, when all anatomical parameters were entered into a multiple regression, it was found that WP, MFA, and DWT were the main factors influencing unit shrinkage, apparently due to their standardized regression coefficients being greater than those of other anatomical indices (Table 4). In fact, significant correlations of both WP and DWT with unit shrinkage were consistent with BD and unit shrinkage, while MFA is known to affect linear shrinkage properties, especially transversal shrinkage of normal wood.[34,35] Total shrinkages, whether S_T or S_R, were significantly positively correlated with WP, DWT, and RP, significantly negatively correlated with MFA, and moderately positively correlated with PP (Table 3). It appears that shrinkage behavior in the collapse-prone eucalypt studied is complicated and even closely related to inferior anatomical elements such as RP and PP. When eight anatomical parameters were similarly regressed against both S_T and S_R, the standardized regression coefficients (r_{std}) of various independent variables showed that the absolute values of WP, MFA, and RP were greater than those of other anatomical features in the regression models (Table 4). Accordingly, it may be inferred that WP, MFA, and RP contribute greatly to total shrinkage. More interestingly, we also found that RP and PP that possess a larger cavity and thinner wall than others were significantly negatively correlated with unit shrinkage and moderately positively correlated with total shrinkage (Table 3). This relationship indicates that PP and RP may play different roles in the shrinkage process, i.e., an increase in total shrinkage including residual collapse and decrease in normal shrinkage of cell wall with the increases of RP and PP. This is because normal shrinkage is closely related to the contents of cell wall substances that decline with the increase of RP and PP. In addition, it was demonstrated that the established model equations based on multiple regression analysis were well suited for the assessment of unit shrinkage and total shrinkage (Table 5).

Relationship between anatomical characteristics and residual collapse

Until now, many studies on the collapse of eucalypt wood were concentrated on the two species of *Eucalyptus globulues* and *Eucalyptus regnans*. Although a few studies also involved in other *Eucalyptus* species such as *Eucalyptus grandis*,[18] these studies were focused on the qualitative relationships between anatomical features and collapse. Quantitative analyses have been performed in the present study. Multiple linear regression analysis between residual collapse and all anatomical parameters indicated that, as seen from Table 5, the model equations could be applied to the evaluation of the intensity of collapse in three species of eucalypts (minimum $r \geq 0.959$, $P \leq 0.05$). As shown in Table 3, correlation analysis demonstrated that the residual collapse was significantly positively correlated with RP, moderately positively correlated with PP, MFA, and FCD and moderately negatively correlated with WP, DWT, and VP. Hence, this shows that collapse is not only extremely complicated shrinkage phenomena, but is also greatly affected by RP when combined with the standardized regression coefficients (Table 4). This finding confirms the hypothesis made by Hart who advocated that RP could play an important role in the formation of collapse.[22] It is generally accepted that the three requirements of impermeability, water saturation of the cell lumen, and comparatively thin cell walls are necessary for collapse to occur. It seems that ray cells and axial parenchyma cells in the eucalypt wood investigated satisfy these requirements well, in particular meeting the impermeable condition. This is because of large quantities of phenolic extractives that are occluded in their cell lumens and pit cavities, which were observed by means of scanning electron microscopy (SEM). Collapse would be less likely to occur in relatively thick cell walls because the wood would be stronger in compression perpendicular to the grain. Kauman[36] found that the tendency for collapse was less in the radial direction than in the tangential direction and attributed this tendency to restraint offered by rays. This indication is consistent with the results shown in Table 2. It was reported by Hattori et al.[37] and Kanagawa and Hattori[38] that the increment in external shrinkage resulted from an increase in the number of collapsed ray cells within the high moisture content range above the FSP, and deformed cells in collapsed samples were observed mainly in ray parenchyma. These observations are consistent with further study by the authors (manuscript in preparation). It should be noted that the analysis of the relationship between residual collapse and ray parenchyma cells in this study is based on the collapse values obtained on the premise of 25°C drying. It seems to be postulated that, under low-temperature drying conditions, ray parenchyma in collapse-susceptible species may make a greater contribution to the generation of collapse than other anatomical features and would be regarded as one of main indicators of cell-collapse intensity. However, with high-temperature drying, especially above 80°C, fibers may play a major role in collapse occurring in eucalypt wood, although this needs to be further investigated in future work. In addition, it is still necessary to emphasize that when regression models are applied to assess the collapse susceptibility of eucalypt on the basis of anatomical features, not only ought the contribution of RP to collapse be specially paid attention to, but the effects of MFA, FCD, PP, WP, DWT, and VP on collapse should also be taken into account.

Conclusions

Based on correlation analysis, simple linear regression analysis between basic density and unit shrinkage, total shrinkage and residual collapse, and multiple linear regression analysis between anatomical parameters and unit shrinkage, the following conclusions were obtained for total shrinkage and residual collapse in plantation-grown eucalypt wood,

1. Basic density was the best single indicator for unit shrinkage, while it was only regarded as ordinary single indicators for total shrinkage and residual collapse properties.
2. The main factors affecting unit shrinkage in eucalypts were cell wall proportion, microfibril angle, and double fiber cell wall thickness. The factors contributing greatly to total shrinkage were cell wall proportion, ray parenchyma proportion, and microfibril angle, while ray parenchyma proportion (RP) had a great effect on residual collapse.
3. All regression models were able to be applied to quantify correlations of the anatomical parameters with their corresponding dependent variables in the regression equations.

However, the validity of the above-mentioned conclusions for high-temperature drying of the above three species of eucalypt wood and/or other collapse-prone eucalypt species should be investigated in future work.

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