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Shrinkage-related degrade and its association with some physical properties in *Eucalyptus regnans* F. Muell

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Summary Assessments of internal checking and the physical properties of 124 trees of *Eucalyptus regnans* F. Muell. have shown that for material dried under relatively mild predryer conditions (30 °C, 65% RH) internal checking was highly positively correlated with each of collapse, moisture content and normal shrinkage, and weakly negatively correlated with total external shrinkage. Collapse alone explained 47% of the variation in internal checking. Incidence of internal checking in sample boards could be estimated with moderate success by each of the following properties measured on board ends: collapse, the number of internal checks and initial moisture content. Material with high mean basic density above 530 kg/m^3 was associated with low levels of internal checking and collapse. However, the maximum naturally occurring density of *E. regnans* was not high enough to obviate collapse and internal checking. It was observed that growth rings in 100 × 50 mm backsawn boards in which the earlywood air-dry density was below 450 kg/m^3 showed internal checking. The size and number of internal checks increased with a decrease in earlywood density. It was shown that drying *E. regnans* below temperatures of 24–30 °C does not eliminate collapse, thus raising doubt about the validity of a temperature threshold concept in that range.

Introduction

High levels of shrinkage due to 'collapse' are particularly evident in low to medium density *Eucalyptus* species of the ash-group (Ilic 1995, 1997). Collapse occurs during drying as water is removed from highly impermeable wood fibres which become distorted because of the high tensile forces generated in the lumen water. Internal checking, which cannot be alleviated by the steam reconditioning process associated with collapse recovery, is usually not evident until after the wood is further processed. Such processing thus constitutes considerable waste of the timber resource and conversion time.

In *E. regnans,* relationships between shrinkage, collapse and properties including basic density, green density, moisture content and derived quantities have been investigated and clarified by Chafe (1985, 1986a) using 5 mm diameter increment cores, and further confirmed for sample boards by Ilic and Hillis (1986), Chafe (1994) and Ilic (1995). Both total shrinkage and collapse are usually

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negatively related to basic density and positively related to moisture content; moisture content is negatively related to basic density for reasonably saturated material. In contrast, Vermaas and Bariska (1994) obtained a positive relationship between collapse and basic density over a narrow density range (330–440 kg/m^3) in *E. grandis* W. Hill ex Maid. from South Africa. Internal checking showed a significant positive relationship with each of collapse, total shrinkage and moisture content in sample boards from 12 trees of *E. regnans*, and a negative relationship with basic density but only at p = 10% (Ilic and Hillis 1986). Chafe (1994) reported positive relationships by each of internal checking with shrinkage and green density and saturation level; the relationship with basic density for oven dried samples was not significant at p = 20%. However, a positive relationship was observed with basic density for heat-treated material, thus indicating that the disposition and width of earlywood and latewood bands (Ilic and Hillis 1984) was not as important in anticipating this defect. Furthermore, Chafe (1994) obtained a positive relationship between the number of checks, checking shrinkage (check area/green section area) and external shrinkage. Using a 'shape factor', Ilic and Hillis (1986) also obtained this result between the number of checks, their area and total shrinkage, but external shrinkage was not related to such an extent. Chafe (1994) noted that this positive association between the three variables suggested that honeycomb checking would not necessarily occur at the expense of external shrinkage as has sometimes been supposed.

As significant variation is known to exist between shrinkage, collapse, internal checking and basic properties (Ilic and Hillis 1985; Chafe 1985, 1986a, b), the following study was intended to clarify such associations. Means of indicating specific physical properties useful for assessing check susceptibility of green timber were also considered.

Materials and methods

Test samples of 1939 regrowth *Eucalyptus regnans* F. Muell. were obtained from East Gippsland, Victoria. The material consisted of 124 backsawn boards from ongoing experimental work at CSIRO. Each board was cut from a different butt log and taken from outer heartwood with the aim of obtaining maximum shrinkage degrade. The boards were green-dressed to 100 × 50 and 650 mm long. A 25 mm end-section (hereto referred as 'board-end') was cut from the end of each board for the determination of moisture content, basic density and shrinkage. One-millimetre-thick sections were cut from each end between the 25 mm board-end and the board. These sections were used for the determination of collapse-free shrinkage, first applied by Greenhill (1936), to obviate the need for reconditioning. The remaining boards (referred hereto as 'sample boards') were trimmed to 600 mm in length.

The sample boards were endcoated with 'Silastic 1080' silicon RTV adhesive sealant and aluminium foil to prevent end-grain drying and thus to simulate full length boards. They were placed in a 12% EMC room set for 30 °C and 65% RH and allowed to dry to equilibrium.

Determination of shrinkage, collapse and internal checking

The 25 mm board-ends were dried in an oven at 102 °C. Each one millimetre thick section was placed between two strips of 0.5 mm thick chromatography paper 60 mm × 120 mm, loosely held between glass plates to prevent warping (Fig. 1a), and allowed to dry with the sample boards. The initial green dimensions

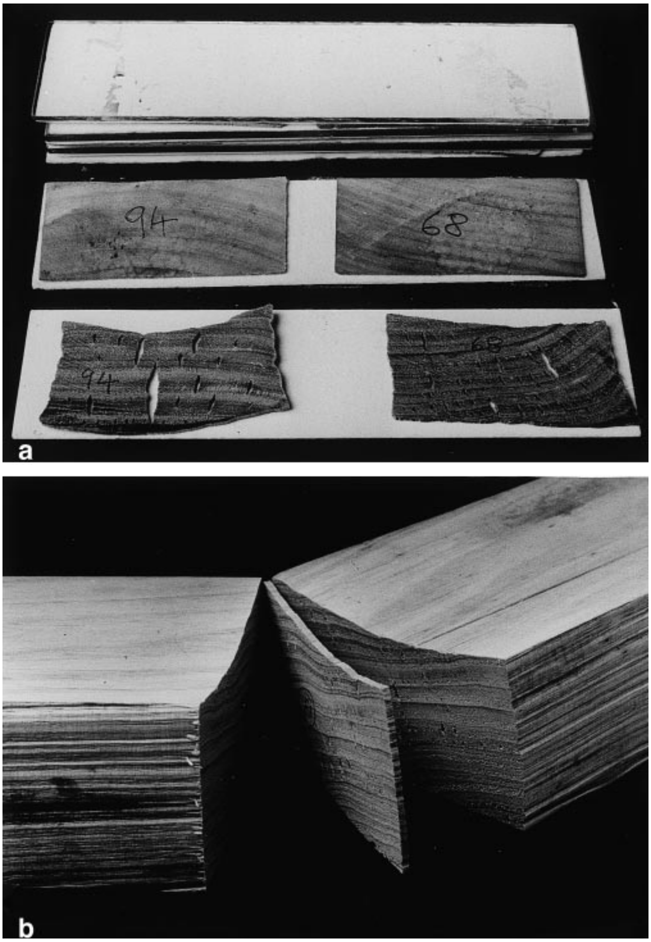

Fig. 1. **a** Typical one and two mm thick sections used for normal and total shrinkage determinations placed between sheets of chromatography paper and glass plates. Note the marked difference in shrinkage between sections labelled with the same number. **b** Dry board with a two mm thick excised section, used for collapse and check determinations, showing collapse as irregular shrinkage and internal checks

of the sample boards were measured with an electronic calliper, and the area of thin sections was measured using an image processor.

After equilibration, sample boards were cross-cut at half their length and a two-millimetre-thick section (along the grain) was removed (Fig. 1b). The one and two millimetre sections were oven dried and their transverse areas measured on a light box using the image processor. The equipment for image digitisation consisted of a closed circuit TV camera (Sony, AVC-D5CE) and a video frame grabber (Imaging Technologies, PC-Vision Plus). Custom software (CHECK ANALYSIS) was prepared for determinating the cross-sectional area, and number and area of checks were obtained using OPTIMAS, a commercial image processing package.

Total shrinkage of sample boards was calculated as the difference between the green and oven dry area per green area. Similarly, the total shrinkage calculated from the one-millimetre-thick sections was used to provide a measure of normal or collapse-free shrinkage. Total shrinkage and the number of internal checks from the two-millimetre-thick sections were used to indicate those quantities in sample boards. Collapse was calculated as the difference between the total shrinkage of the two- and one-millimetre-thick sections.

Results and discussion

The mean values of the physical properties are indicated in Table 1. Collapse checks were present in the earlywood of all material. On occasion some checks, originating in the earlywood, traversed single latewood bands (Fig. 1). In many cases, large surface checks developed during the initial stages of drying. These checks closed tightly after stress reversal towards the end of drying. With the exception of tensionwood, collapse checks were not exclusive to the latewood although very small splits were often visible on or near the end surfaces of boards after steam reconditioning. On occasion, the darker latewood showed some degree of collapse, but never to the exclusion of the earlywood as reported by Innes (1996b). It should be noted that highly collapsed zones of low density can give the appearance of latewood (Davis et al. 1993), particularly in species like *E. regnans* where the growth rings may be less well defined. Inspection of Table 1 shows that the ranges for basic density and shrinkage are almost identical to those given in Kingston and Risdon (1962) thus indicating that the sample was representative.

Collapse as a function of physical properties

Basic density is an important indicator of collapse. Bisset and Ellwood (1951), Chudnoff (1961) for *E. camaldulensis*, Chafe (1985) and Chafe and Ilic (1992a, b) reported that each of the total volumetric shrinkage and collapse decreased with an increase in density, a result confirmed in this study (Table 2) and contrary to that reported by Vermaas and Bariska (1994) for *E. grandis*. Collapse showed a very weak positive relationship (R^2 = 3%) with green density in sample boards, and a stronger, highly significant relationship (R^2 = 20%) in board-ends (Table 2), a result in keeping with that of Chafe (1994). In both cases the stronger association with green density was obtained only from material dried at 100 °C.

Collapse and initial moisture content were highly correlated in sample boards as well as in board-ends (Table 2). This result is consistent with that of Chafe (1985, 1994), Ilic and Chafe (1986), Ilic and Hillis (1985, 1986) and Ilic (1998). Initial moisture content and basic density were also highly negatively correlated (R^2 = 72%) as in Chafe (1985) and Ilic and Hillis (1985), however, when collapse was regressed against both variables simultaneously, the relationship with initial moisture content was in agreement with Chafe (1985), i.e. more highly significant, thus indicating that this variable was superior in defining collapse.

In line with the reports cited above, relationships between collapse and total shrinkage were characteristically very strong. It was this strong relationship that formed the basis of the predication method described by Chafe (1985, 1986a) and Ilic and Hillis (1985, 1986).

Internal checking as a function of physical properties

The main relationships between internal checking and the other properties in sample boards are shown in Table 3. The relationship with collapse was strongest (positive, R^2 = 46%), with those for initial moisture content and total shrinkage (also positive) less strong. As with collapse, the relationship between internal checking and basic density was negative and highly significant, but was weaker

Table 1. Mean values of basic properties measured from sample boards from 124 trees of 1939 regrowth *Eucalyptus regnans*. (Total range given in brackets)

Internal check count	Collapse (%)	Oven dry density (kg/m^3)	Total shrinkage (%)	Basic density (kg/m^3)	Green density (kg/m^3)	Normal shrinkage (%)	Saturation level (%)	Initial moisture content (%)
22 (0–159)	5.1 (1.0–18.5)	648 (553–763)	20.7 (14.1–33)	511 (431–583)	1079 (982–1151)	15.6 (10.5–20.6)	82.5 (67.8–95.3)	108 (77.8–145)

Table 2. Relationships between collapse and the basic physical characteristics in sample boards and board ends (C_b = Collapse in board samples; C_e = Collapse in 25 mm board ends; p = probability; R^2 = coefficient of determination (%); and n.s. = not significant)

	Basic density	Green density	Oven dry density	Initial moisture content	Saturation level	Normal shrinkage	Total shrinkage	Internal check number
C_b	$p = -0.000$ $R^2 = 18.7$	$p = 0.039$ $R^2 = 3.4$	$p = 0.13$ n.s.	$p = 0.000$ $R^2 = 25.4$	$p = 0.000$ $R^2 = 11.1$	$p = -0.007$ $R^2 = 5.9$	$p = 0.000$ $R^2 = 72.5$	$p = 0.000$ $R^2 = 46$
C_e	$p = -0.003$ $R^2 = 18.9$	$p = 0.000$ $R^2 = 20.1$	$p = 0.965$ n.s.	$p = 0.000$ $R^2 = 28.0$	$p = 0.000$ $R^2 = 36.0$	$p = -0.000$ $R^2 = 14.1$	$p = 0.000$ $R^2 = 87.5$	$p = 0.000$ $R^2 = 24.6$

Table 3. Relationships between the number of checks and basic physical characteristics of sample boards. (IC_b = Internal check number in board samples, IC_e = internal check number in board ends; p = probability; and R^2 = coefficient of determination (%))

	Green density	Oven dry density	Basic density	Saturation level	Initial moisture content	Collapse	Normal shrinkage	Total shrinkage
IC_b	$p = 0.042$ $R^2 = 3.3$	$p = 0.130$ n.s.	$p = -0.000$ $R^2 = 23.6$	$p = 0.000$ $R^2 = 15.0$	$p = 0.000$ $R^2 = 32.6$	$p = 0.000$ $R^2 = 46$	$p = -0.001$ $R^2 = 8.7$	$p = 0.000$ $R^2 = 25.0$
IC_e	$p = 0.001$ $R^2 = 11.0$	$p = 0.02$ $R^2 = 5.7$	$p = -0.001$ $R^2 = 11.5$	$p = 0.000$ $R^2 = 18.5$	$p = 0.000$ $R^2 = 21.6$	$p = 0.000$ $R^2 = 24.6$	$p = -0.001$ $R^2 = 14.0$	$p = 0.000$ $R^2 = 15.2$

than that with moisture content. The relationship with green density was positive and significant at the 4% level (R^2 = 3%), but that for oven dried board ends was more highly significant at 0.1% with R^2 = 11%, a result more in keeping with that of Chafe (1994). These results are also consistent with those obtained by Ilic and Hillis (1986) and Ilic (1998).

Considering the relationship between internal checking and collapse, it can be seen that just over half the variation is affected by other factors. It may be noted that sample thickness as well as drying stresses arising from normal shrinkage can affect collapse and check formation (Kauman 1958; Chafe and Ilic 1992b).

Internal checking was also positively related to initial moisture content (IMC), the association being little stronger than that for collapse and IMC (Table 2); it was also positively related to collapse, but to a lesser extent than previously reported by Chafe (1985), and Ilic and Chafe (1986). When internal checking was regressed against the properties in Table 3 by stepwise regression, the combination represented by model 2 in Table 4 shows an increase in R^2 of some 20% over that obtained when collapse was the single predictor. This shows that internal checking increases when collapse, IMC, and normal shrinkage increase and when total external shrinkage decreases, a result consistent with Table 3 and general observations. For example, with thick samples there is a greater likelihood of set being induced which would tend to reduce the total external shrinkage, such reduction then being compensated to some extent by increased internal checking. Additional stresses arising from normal collapse-free shrinkage (positively correlated with internal checking, Table 3), could also be contributory.

Ilic (1998) originally conjectured that fewer checks would develop if collapse could be reduced through lowering differential tensile stresses by prefreezing. However, in spite of collapse reductions of between 36–50% in all samples, a reduction in checking occurred in only a few of the samples, particularly in those with a low collapse propensity. It would thus appear that such material is more likely to be free of internal checking. To test this proposal, the number of internal checks was plotted against each of collapse (Fig. 2) and basic density (Fig. 3). In addition, collapse was plotted against basic density (Fig. 4). In Figure 2 the regression line for internal checking intersects the collapse axis at about 2%, thus suggesting that low checking should be expected when collapse is low. Although Fig. 2 also shows that a low number of checks can be associated with high levels of collapse (up to 12%), low levels of collapse are always associated with low check counts.

Table 4. Relationship between internal checking in sample boards and physical variables: IC_b = number of checks in sample boards (dependent variable). Independent variables: collapse (C), total shrinkage (T), total external shrinkage – checks excluded (X), normal shrinkage (N), initial moisture content (M), basic density (D), oven dry density (O), green density (G), saturation level (S). (Subscripts 'b' and 'e' refer to sample board and board end respectively; R^2_{mult} adjusted multiple regression coefficient (%)). All variables but last remaining in model are significant at 0.00001 level, last variable in each group is significant at least at 0.006 level. The negative sign indicates a negative relationship

Model	Independent variables remaining	R^2_{mult}
1	IC_e C_e M	55
2	C_b M – X_b N	67

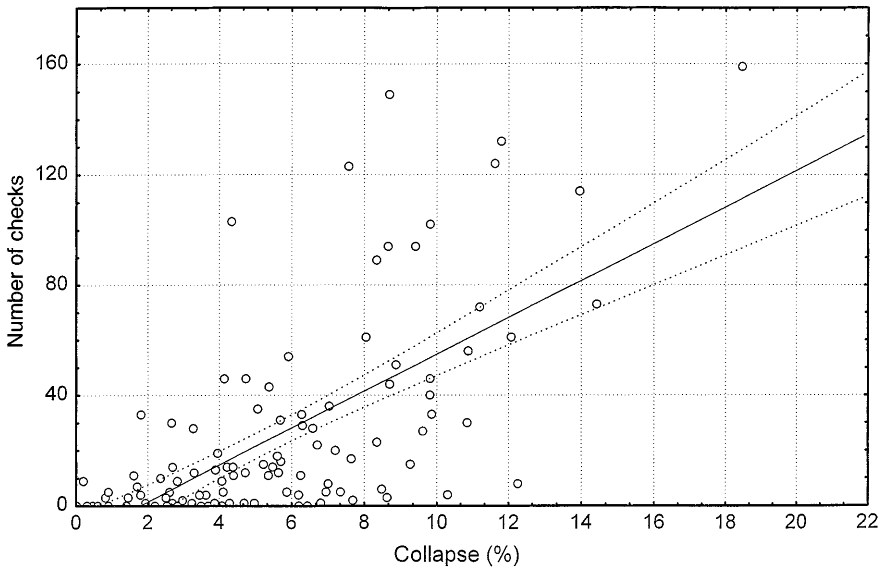

Fig. 2. Relationship between number of internal checks and collapse in sample boards

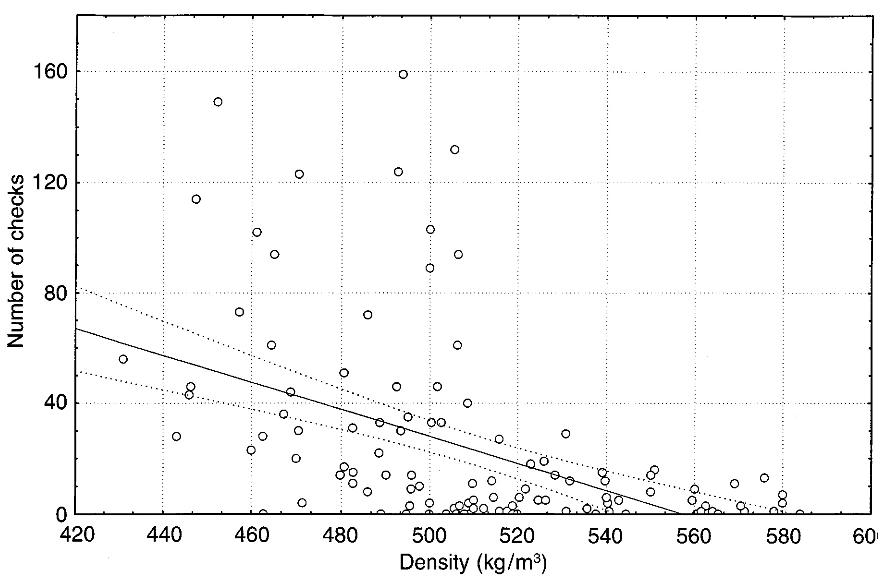

Fig. 3. Relationship between the number of checks and basic density in sample boards

In Fig. 3, a dramatic reduction in the number of checks is evident above densities above ca. 520 kg/m^3. In low density wood it has been suggested by Bisset and Ellwood (1959), Ilic (1983) and Ilic and Hillis (1984) that collapse severity and internal checking tends to be greater in growth rings with thin earlywood cell walls; this is consistent with observation and results obtained here. Although such conclusions are difficult to infer from mean density, it is generally common for the density of earlywood zones to be lower than the lowest mean density.

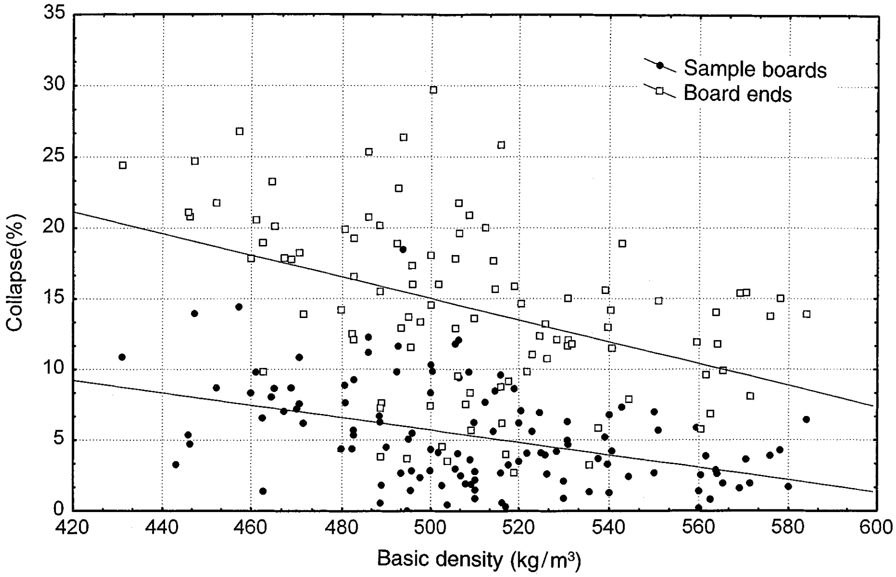

Fig. 4. Relationships between collapse and basic density in sample boards and board ends

To further test this proposal, about 30% of the test samples were reconditioned to substantially eliminate the effect of collapse. After equilibration to air-dry conditions, samples 50 mm along the grain were prepared and scanned radially with an X-ray densitometer (Davis et al. 1991) for microdensity variation. Although basic density cannot be measured directly from the X-ray trace, it can be estimated by dividing the reconditioned air-dry density by 1.21 (Greenhill and Dadswell 1940). Typical air-dry density traces of a checked and a non-checked sample are illustrated in Fig. 5. Based on inspection of such scans, checks were

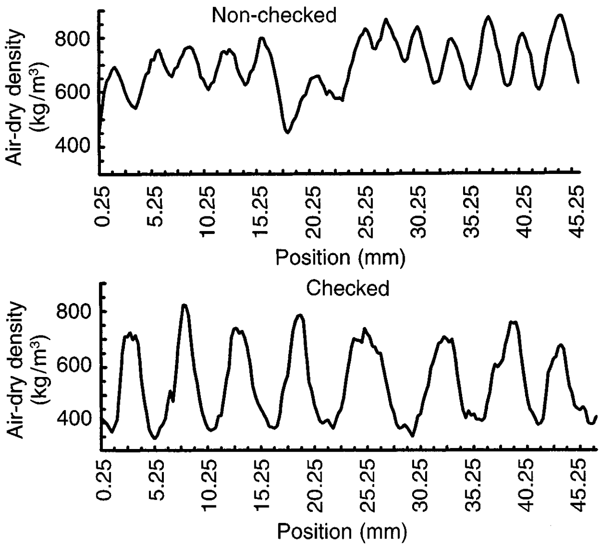

Fig. 5. Typical air-dry density variation in reconditioned material from a non-checked and a checked sample board showing growth rings with a markedly lower earlywood density in the checked sample

found consistently in growth rings in which the earlywood density was below 450 kg/m^3. The checks in samples between 400 and 450 kg/m^3 were generally small and occasional, usually spanning only a narrow portion of the earlywood. However, in growth rings with earlywood below 400 kg/m^3 checks were numerous and usually spanned the whole earlywood zone, sometimes spreading into or across an adjacent latewood band. Thus it appears that there is a density transition zone between 400–450 kg/m^3 which seems to be associated with the development of checks. Such checking is, of course, also influenced by sample size, drying conditions, variation in residual collapse, scanner alignment accuracy and local wood permeability. Notwithstanding these, an indication of critical earlywood density is still likely to be useful for segregating material for particular end-use and possibly for the selection of trees for breeding. It may also be noted that it is extremely difficult to excise earlywood and latewood for separate analysis since, in *E. regnans*, latewood and earlywood are not always easily defined macroscopically. In such cases, X-ray densitometry may be particularly useful (Fig. 5).

As has been noted, internal checks can develop in low density wood in the presence of varying degrees of collapse. Typically, when internal checks occur, they are spaced at short tangential distances; high differential levels of tensile stress must be able to develop locally to initiate such checks. This development is consistent with collapse occurring in low strength (low density) earlywood bands in the presence of relatively high restraint from the denser latewood. Checks are known to form in wood due to high levels of differential shrinkage in local regions (Bisset and Ellwood 1951), and it is highly likely that they will be initiated in stress concentration zones of poorly lignified vessel and ray cell wall contact (Mackay 1972; Ilic 1998).

In some circumstances, e.g. in flooring and panel products, a low number of checks may be tolerated if they are small and close tightly upon reconditioning. As calculated from the regression line in Fig. 4, the basic density corresponding to zero collapse is ca. 640 kg/m^3. This suggests that material of higher density should be free from collapse and collapse-associated checks. Although this value lies outside the nominally highest density for *E. regnans* (580 kg/m^3) (Ilic 1997), it supports the proposition that other eucalypt species of greater average basic density and similar structure to *E. regnans* would be less likely to collapse, as illustrated by a negative correlation between total shrinkage and specific gravity (Chafe 1986b). This is generally the case for *E. obliqua* which exhibits greater density variation (487–720 kg/m^3) than *E. regnans* (Kingston and Risdon 1962; Ilic 1997); mature *E. obliqua* from Tasmania, in particular, exhibits little collapse and internal checking.

Similarly, Hillis and Brown (1984) state that eucalypts with basic density greater than 650 kg/m^3 do not collapse, this value being based on work reported by Chudnoff (1961) on Israeli grown trees of *E. camaldulensis* Dehn. However, this target density is not independent of drying temperature, as illustrated in Fig. 4. Here the higher target density for board ends dried at 100 °C was 695 kg/m^3. The same procedure carried out on 25 mm cubes dried at 20 °C (unpublished data) indicated such density to be 638 kg/m^3. The general usefulness of a target density of 650 kg/m^3, for example, is only meaningful for material of particular size and dried at low pre-dryer temperatures.

Collapse severity

Collapse severity is known to depend on drying temperature and relative humidity, particularly during the early stages of drying (Greenhill and Dadswell

1938; Ellwood 1952; Kauman 1959). In more recent work using computer modelling, Innes (1996a, b) proposed the concept of a 'collapse threshold temperature' for *E. regnans*. He suggested that collapse could be eliminated if wood were dried below 24–26 °C for Tasmanian material, and below 28–30 °C for material from Victoria. These findings are of profound importance for the drying of *E. regnans*, particularly for the highly collapse and check prone Victorian material. However, from Innes' papers it was not clear how many boards were tested or what method of collapse assessment was employed.

While there is no doubt that collapse severity is related to drying temperature, an analysis of data from six trees of *E. regnans* (Kauman 1959) does not indicate a threshold temperature. Collapse at 24 °C, the lowest temperature, was over 7% volumetric (4% tangential and 3% radial). Furthermore, extrapolation of the tangential collapse data indicates that collapse would be zero at −3.6 °C (25.5°F)! Ellwood (1952), investigating suitable drying conditions for veneer, also reported collapse of about 4% (gross shrinkage of 11.6%) tangentially in 1/16 inch veneer dried at 15.5 °C (EMC 15%). Pankevicius (1961) reported that total mean collapse in material from six mature *E. regnans* trees from Victoria, dried at 24 °C, was about 4% tangentially, and about 11% in two trees of Tasmanian *E. delegatensis* R.T. Bak. (Syn. *E. gigantea* Hook. f.). Cuevas (1969) reported mean collapse magnitudes of about 6.6% tangentially (total ca. 9%) in *E. viminalis,* a similar species to *E. regnans*, dried at 21 °C. Experimental work conducted by the author (unpublished data) on unsealed 25 mm cubes from ten trees of *E. regnans* dried at 20 °C and 65% RH showed total collapse ranging from 0.2% to 13.9% with a mean of 7.2%. Finally, the extensive work of Kingston and Risdon (1962) involving shrinkage measurements of hundreds of samples of young and mature *E. regnans* dried at 25 °C showed mean collapse levels between 16–18%.

In the light of this body of work, considerable doubt must be raised about the validity of a threshold temperature in the range of 24–30 °C for eliminating collapse and checking. In summary, the temperature threshold concept may require further definition.

Identification of check susceptible material

To consider the feasibility of improving the single relationships shown in Table 3, multiple regression analysis was carried out between the number of internal checks in sample boards (IC_b) and independent variables from sample boards and board-ends shown in Table 3. Two models are presented for relating internal checking (Table 4).

Model 1, provides the best useful indication of an internal check number using properties determined from rapidly dried board-ends, and Model 2, discussed earlier, indicates the best association of properties from the sample boards. Model 1 accounts for 55% of the variation in internal checking; variables included were collapse (C), total shrinkage (T), total external shrinkage (checks excluded) (X), normal shrinkage (N), initial moisture content (M), basic density (D), oven dry density (O), green density (G), saturation level (S). The three variables remaining in Model 1 account for the greatest proportion of the variation which constitutes a moderate indication of check susceptibility. Little improvement is gained by inclusion of additional variables, e.g. basic density, saturation level, etc., as many of these variables tend to be highly interrelated.

For an identification method to be useful, it must be accurate, simple to apply, present the least disruption in processing and, most of all, it must be rapid. While the procedure using board ends offers a moderately effective way of indicating checking susceptibility, it should be more useful for indicating extremes rather than providing specific determinations. It is necessarily slow because of the logistics of relating test specimens to sample boards and because of the need for oven drying. Ideally, a more rapid nondestructive approach should be developed. A subsequent communication will report on the suitability of dynamic elastic properties for this purpose.

Conclusions

Under relatively mild drying conditions, internal checking is highly positively correlated with each of collapse, moisture content, normal shrinkage and, to a lesser extent and negatively, with total external shrinkage. Collapse alone explains nearly 50% of the total variation in internal checking. Internal checking in sample boards can be indicated with moderate success from rapidly dried board ends by measuring collapse, number of internal checks and initial moisture content.

Regression analysis suggests that significant reduction or elimination of internal checks is dependent on minimal collapse. Material of high basic density has been shown to be associated with low levels of internal checking and collapse. However, the highest expected density corresponding to the complete elimination of collapse, and hence internal checking in *E. regnans*, is greater than the highest naturally occurring density of the species. This provides support for the proposition that other eucalypts of similar structure, but of higher density, are less collapse prone (see Chafe 1986b).

Growth rings with earlywood air-dry density above 450 kg/m^3 were check-free. However, the size and number of internal checks increased with a decrease in air-dry earlywood density below 400 kg/m^3.

Considerable doubt must be raised about the validity of a threshold temperature in the range of 24–30 °C for eliminating collapse and hence checking.

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