AN ATTEMPT TO REDUCE COLLAPSE THROUGH INTRODUCING CELL-WALL DEFORMATIONS

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ABSTRACT

The possibility of reducing collapse through the inducement of cell-wall deformations in the wood of 1939 regrowth *Eucalyptus regnans* F. Muell. prior to drying was investigated. Four groups of end-matched specimens from eleven logs were used. One group served as the control and the other three were subjected to predetermined loads in compression parallel-to-the-grain.

Cell-wall deformations (physical dislocation of the cell wall as a result of longitudinal compression) were induced in all treated groups, and the number of deformations was positively correlated with the compression load. However, the compression treatment had no significant effect on recoverable collapse, the total number of internal checks, nor the total area of checking before reconditioning. Physical alterations to cell walls, therefore, did not appear to have improved the way the wood dried. Additional results suggested that internal checks may be initiated by collapse in the early stages of drying, and that their later enlargement could be attributed to drying stresses.

Keywords: Cell-wall deformations, slip planes, collapse, internal checking, eucalypts.

INTRODUCTION

Collapse in wood during drying results from poor permeability, low wood density, water saturation of the cell lumen (Chafe et al. 1992), and drying temperatures that are too high. The heartwood of some eucalypts is highly susceptible to collapse because of its poor permeability: vessels are usually blocked by tyloses, and water pathways between cells via pits and cell-wall capillaries become increasingly narrowed following deposition of extractives in and on cell walls during sapwood-heartwood transformation. When such pathways are sufficiently small and the cell lumens are saturated, hydrostatic tensile forces formed in the water of the cell lumen during drying can become very high (Tiemann 1915). If this force exceeds their transverse compressive strength, the cells collapse.

Some eucalypts are also prone to brittleheart formation, which is a result of longitudinal compression associated with growth stresses and characterized by the presence of cell-wall deformations (Dadswell and Langlands 1934, 1938; Hillis et al. 1973; Yang 1990).

"Cell-wall deformation" is a general term to describe any physical dislocation of the cell wall which is a result of longitudinal compression; terms such as "slip planes" and "minute compression failures" (Wardrop and Dadswell 1947), "microscopic crease" (Dinwoodie 1968), and "microscopic compression lines" (Kisser and Steininger 1952; Yang 1990) appear in the literature. When a longitudinal section is viewed under polarized light, a slip plane appears as a simple crinkle in the cell wall and manifests a slight linear displacement of the cell-wall layers; it can be confined to a single fiber or extend to an adjacent fiber. A minute compression failure appears as a pair of either "X-shaped" or "V-shaped" crack-like lines crossing two adjoining cell walls (Wardrop and Dadswell 1947). "Microscopic crease" refers to multiple slip planes spreading along the cell axis (Dinwoodie 1968). "Microscopic compression lines" refers to the lining-up of slip planes and/or minute com-

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pression failures across several fibers (Kisser and Steininger 1952; Yang 1990). In most of the literature, mainly the physical changes in cell walls are represented by cell-wall deformations in the side walls of fibers. Figure 1 shows a few "complete" slip planes revealing deformations in both the side and back walls of fibers.

The shear effects of cell-wall deformations may create separations between adjacent cell-wall elements. It has been suspected that these separations can be sufficiently large to greatly mitigate the development of high liquid tension forces and thus the development of collapse (Chafe 1986). In addition to the shear effects, preferential staining reactions of cell-wall deformations have suggested rupture of the cellulose-lignin interface (Robinson 1920; Wardrop and Dadswell 1947) and increased micellar surfaces and intermicellar spaces in the region of deformation (Wardrop and Dadswell 1947).

Cell-wall deformations can be induced under parallel-to-the-grain compression well before the wood fails (Dinwoodie 1968; Keith 1971), and their amount and type depend on the load and the loading speed (Dinwoodie 1968). These deformations can markedly affect the impact strength (Hudson 1961) and the bending strength of timber (Kitahara et al. 1984).

This study sought to investigate the effect of varying degrees of cell-wall deformations on the development of collapse and internal checking. The cell-wall deformations can be induced by applying different loads in parallel-to-the-grain compression to green wood. Freedom from drying defects is a primary requirement of wood for high-value end-use such as furniture manufacture, and a gain in drying quality through the introduction of cell-wall deformations could be worth the subsequent loss in wood strength.

MATERIALS AND METHODS

Eleven logs from a 1939 *Eucalyptus regnans* F. Muell. regrowth forest in the Toolangi area of Victoria were selected from a log yard of the Healesville sawmill of Thomas P. Clark Pty., Ltd. Two boards freshly sawn from each log, one from the inner heartwood zone and the other from the sapwood zone, were collected from the green chain. Each board measured approximately 60 × 100 × 1,400 mm. Due to the narrow width of sapwood (approximately 30–50 mm), the sapwood boards unavoidably contained various amounts of outer heartwood material, up to 30%. Two inner heartwood boards were later discarded because of excessive defects.

Four end-matched green specimens of identical dimension (40 × 40 × 100 mm) were cut from each board, end-sealed using a silicon sealing compound immediately after their removal from the boards, and wrapped with plastic.

Two blocks, each measuring 40 × 40 × 50 mm and positioned at least 200 mm from the ends, were also obtained from each board. Their average moisture content and basic density were used to represent those of the original board.

The green specimens were divided into four groups as follows. Of the four end-matching specimens within each board, one was randomly assigned to Group 1, one to Group 2, one to Group 3, and the last to Group 4. Each group had 20 specimens.

Group 1 served as the control. Group 2 specimens were subjected to maximum parallel-to-the-grain compression at 0.3 mm/min, using an Instron Model 1185 testing machine. The values for maximum load thus obtained ($L_{(max,i)}$, $i = 1, 2, \ldots, 20$) were used to calculate 30% and 60% of maximum load values, which were applied to matched Group 3 and Group 4 specimens, respectively. After mechanical testing, the sealed ends of all specimens were trimmed by 20 mm. The specimens were then dried in a 12% EMC room at 30°C.

When moisture content of the specimens dropped to approximately 20%, one 2-mm-thick cross section was removed from one end of each specimen and returned to the 12% EMC room to be equilibrated. These equilibrated 12% MC sections would later be referred to as the "before-reconditioning 2-mm sections," and measurements made on these sections would be referred to as "before-reconditioning measurements." One broken section was discarded.

The remaining wood blocks were reconditioned in saturated steam for 2 hours, then equilibrated in the 12% EMC room (To recondition eucalypt wood after initial drying to recover collapse is a standard industry practice in Australia. Collapse can be recovered to a large extent). After that, a 2-mm-thick cross section was removed from the same end of each block as previously. These sections would later be referred to as "after-reconditioning 2-mm sections," and measurements made on these sections would be referred to as "after reconditioning measurements."

An imaging method for quantitative assessment of collapse-checking degrade was developed in-house, which is explained as follows. A 2-mm section is positioned on a light box under a video camera. The image of this section is captured. Brighter areas in this image correspond to checks in the 2-mm section. By utilizing OPTIMAS® 5 image analysis program (Optimas Corporation), each single brighter area (each check) can be readily identified and its boarder readily defined; the area of the 2-mm section and the area of each single check can be readily measured. The entire procedure of image processing and analysis, and data acquisition, is routinized and controlled by a macro.

Using this imagining method, the total number of checks, the total checked area, and the net wood area were measured for each of the before and after reconditioning 2-mm sections. The total checked area is the total area of the checks measured in a 2-mm section. The net wood area is the area of a 2-mm section minus the total checked area in the section.

Recoverable collapse was calculated as the difference in net wood area between measurements made before and after reconditioning expressed as a percentage of the cross-sectional area of the green specimen (40 × 40 mm).

Nonrecoverable collapse can be calculated from the following formulae.

Nonrecoverable collapse =

$$S_R - S_N \approx A'_R - S_N \qquad (1)$$

$$A'_R = \left(\frac{A_G - A_R}{A_G}\right) \times 100\ (\%) \qquad (2)$$

$$S_N = \frac{D_{basic}}{D_{water}}(MC_{FSP} - MC_X) \qquad (3)$$

where:

S_R = Volumetric shrinkage after reconditioning

S_N = Normal volumetric shrinkage

A'_R = Cross-sectional shrinkage after reconditioning

A_G = Cross-sectional area in green condition

A_R = Cross-sectional area after reconditioning

D_{basic} = Basic density of specimen (kg/m³)

D_{water} = Density of liquid water (100 kg/m³)

MC_{FSP} = Moisture content at fiber saturation point; chosen to be 28% in this study

MC_X = Moisture content at which S_N takes place; nominated as 12% in this study.

Multiple analysis of variance was conducted separately on the before and after reconditioning data. The total number of internal checks, the total checked area, and the net wood area were dependant variables; compression treatment, location of specimens (heartwood vs. sapwood), and specimen number (logs) were factors. Multiple analysis of variance on recoverable collapse was similarly conducted. The variability between logs was graphically examined.

Radial sections (20 μm) were prepared from

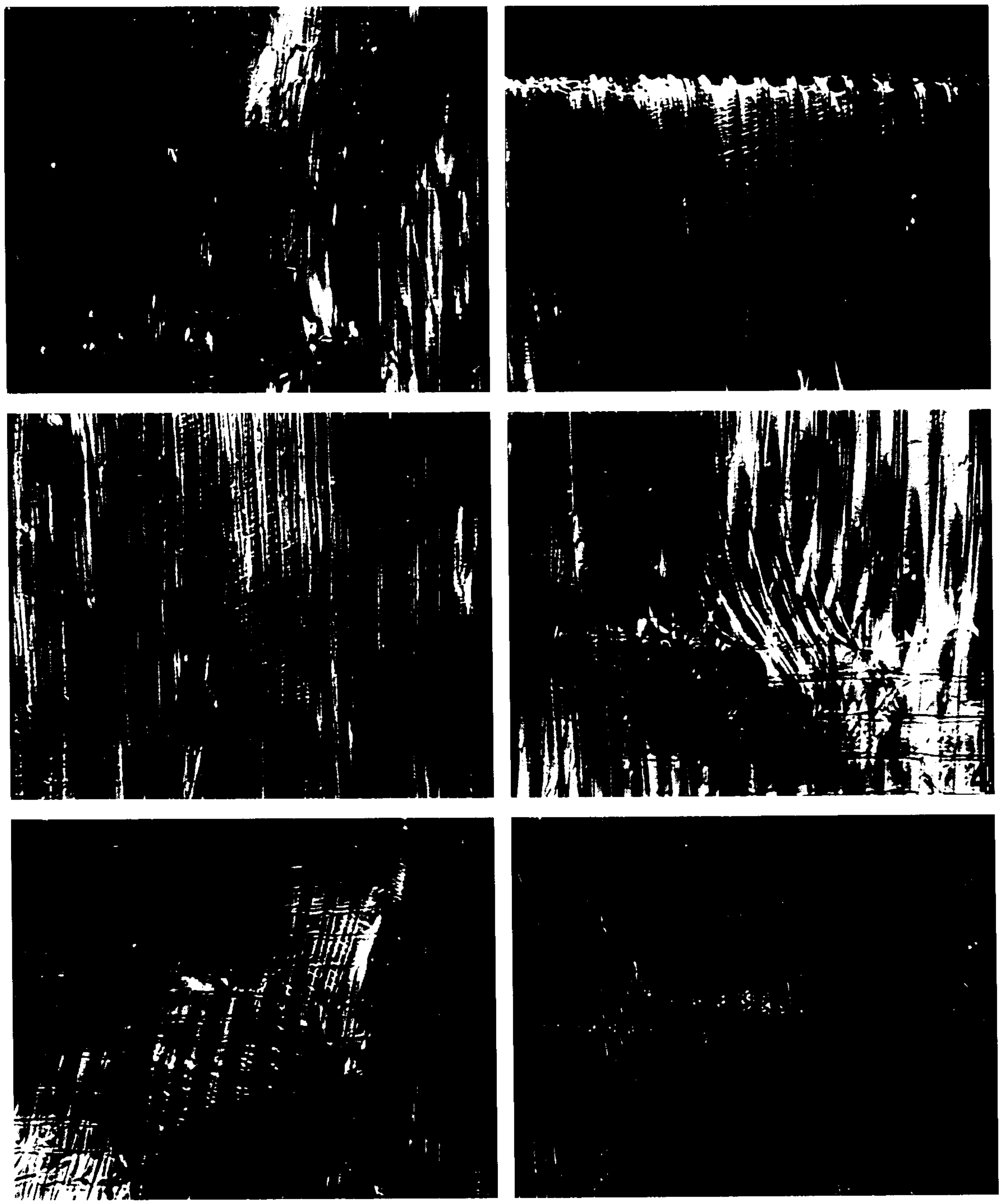

FIG. 1. A few slip planes (arrow) in a Group 4 sapwood specimen reveal cell-wall deformations in both side and back walls of the fibers. ×230

FIG. 2. Slip planes (arrow) induced during microtome sectioning at the edge of a Group 1 sapwood specimen where the microtome knife made first contact with the wood. ×230

FIG. 3. Highly localized dense cluster of slip planes (arrow) or gross microscopic crease in a Group 4 sapwood specimen. ×190

two heartwood and two sapwood specimens of each group. The 16 specimens were end-matched between the four groups. Recommendations on microtome orientation by Keith and Côté (1968) were followed to avoid inducement of cell-wall deformations during sectioning. The sections were examined using polarized light microscopy for physical changes in the cell walls.

RESULTS AND DISCUSSION

General observations

The average moisture content and standard deviation were 135.2% and 14.9(%) for the heartwood specimens, and 123.1% and 14.3(%) for the sapwood specimens. The average basic density (oven-dry weight divided by green volume) and standard deviation were 452.2 kg/m^3 and 48.2 kg/m^3 for the heartwood specimens, and 483.3 kg/m^3 and 45.6 kg/m^3 for the sapwood specimens. Basic density and moisture content were highly correlated ($P < 0.01$), with $R = -0.95$ for the heartwood specimens, and $R = -0.92$ for the sapwood specimens.

Gross failures in Group 2 specimens, which had been subjected to maximum load, were either barely noticeable or appeared V-shaped near the specimen ends closer to the loading head.

Internal checks did not seem to occur completely randomly. Certain growth rings seemed "doomed" to internal checking, or to have more or larger checks.

Darkening occurred in almost all the specimens after reconditioning.

Cell-wall deformations

Slip planes were little observed in microscopic sections of three of the control specimens, except at the edge where the microtome knife made first contact with the wood (Fig. 2). However, this showed that the knife had been properly oriented in relation to the wood grain during sectioning. A small number of slip planes were observed in the fourth control specimen. However, due to their sporadic distribution, it is probable that these already existed in the standing tree and were not induced during microtome sectioning.

Slip planes in sections of Group 2, 3, and 4 specimens (respectively subjected to maximum load, 30% and 60% of maximum load) tended to occur in clusters and the "density" of these clusters depended on the number of the slip planes. The distribution of slip planes was far from uniform when in small numbers, but became less uneven as the numbers increased. Figure 3 gives a perfect example of a highly localized dense cluster of slip planes or gross microscopic crease (Dinwoodie 1968).

The uneven distribution of cell-wall deformations made their quantification difficult. Therefore, only qualitative assessment was attempted in this study. In addition to the clustering tendency, cell-wall deformations seemed to occur more often in nonlinear fibers (Fig. 4) adjacent to rays, and/or in the cross field (Fig. 5).

The small number of slip planes in the Group 3 specimens rendered them barely noticeable. In the Group 4 specimens, slip planes were much more evident and some compression lines were found. In the Group 2 specimens, slip planes were highly conspicuous and microscopic compression lines, which appeared as a more or less horizontal alignment of "creases" across several but usually fewer than 20 fibers (Fig. 6), were easily detected. Microscopic compression lines had a far rarer occurrence than slip planes and seemed to increase in specimens that had been subjected to greater compression. Whereas there was a def-

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FIG. 4. Slip planes (arrow) in nonstraight fibers of a Group 4 sapwood specimen. ×230

FIG. 5. Slip planes (arrow) in fiber walls within a cross field of a Group 4 sapwood specimen. ×190

FIG. 6. A microscopic compression line (arrow) in a Group 2 heartwood specimen. ×230

TABLE 1. *Averages of measurement on the 2-mm sections for each group.*

	Averages	Compression treatment			
		Control	30% loading	60% loading	Max loading
Before reconditioning	Total No of checks	4.00	3.85	3.31	3.80
	Total checked area (mm^2)	3.46	2.83	3.15	4.22
	Net wood area (mm^2)	1,349.30	1,354.52	1,353.23	1,349.63
	Total specimen area (mm^2)	1,352.76	1,357.34	1,356.37	1,353.85
After reconditioning	Total No of checks	0.15	0.20	0.10	0.25
	Total checked area (mm^2)	0.02	0.03	0.02	0.12
	Net wood area (mm^2)	1,410.69	1,413.08	1,415.75	1,412.38
	Total specimen area (mm^2)	1,410.71	1,413.11	1,415.76	1,412.51
	Recoverable collapse (%)	3.84	3.66	4.00	3.92
	Nonrecoverable collapse (%)	2.46	2.27	2.07	2.27
	Total collapse (%)	6.30	5.93	6.07	6.19

inite between-group variation in the number of cell-wall deformations, variation between specimens within the same group was also evident.

The effect of compression treatment

Before reconditioning.—Table 1 summarizes averages of the measurement made on the before and after reconditioning 2-mm sections, and the recoverable and nonrecoverable collapse calculated from these measurements, for each group.

Table 2 summarizes the results of multiple analysis of variance on the total number of checks, the total checked area, the net wood area, the total specimen area (total checked area plus net wood area), and the recoverable collapse. The factors were "compression treatment", "heartwood vs. sapwood", and "logs." Figures in the table are probability values showing the significance level of the analysis. Values smaller than 0.05 are highlighted.

The total number of checks and the total checked area before reconditioning are a direct measurement of drying degrade. The more checks and the larger the checked area, the more severe the drying degrade.

No significant difference was found between compression treatments for the total number of checks, the total checked area, the net wood area, or the total specimen area (Table 2). Nevertheless, Group 3 showed the least total checked area, and Group 4 showed the smallest total number of internal checks.

Although, by inspection, the number of slip planes differed between groups, this difference did not result in a between-group difference for the drying properties measured. There are three possible reasons for this: (1) Artificial compression may not have physically altered cell walls in the induced cell-wall deformation regions in the same way and/or to the same extent as growth stresses do to the wood in standing trees during the formation of brittleheart. Natural cell-wall deformations in standing trees are formed and modified over a long period of increasing compressive stresses during tree growth. The cell-wall deformations induced in this study were formed during a much shorter loading process, usually about 20 minutes. It would be interesting to investigate any differences that might exist between natural and artificially induced cell-wall deformations. (2) Slip planes tended to be distributed unevenly. This might affect the level of improvement on drying, even if the induced cell-wall deformations were able to reduce liquid tension forces. (3) The contribution of induced cell-wall deformations to the reduction of liquid tension forces, assuming any existed, was counteracted by the weakening of the cell walls due to the presence of the deformations.

TABLE 2. *The significance level of multiple analysis of variance.*

	Dependant variables	Source of variation: Compression treatment	Heartwood vs. sapwood*	Logs
Before reconditioning	Total No of checks	0.9372	**0.0053**	**0.0007**
	Total checked area	0.8476	**0.0083**	**0.0005**
	Net wood area	0.9146	0.2709	**0.0000**
	Total specimen area	0.9339	0.4738	**0.0000**
After reconditioning	Total No of checks	0.9018	**0.0233**	**0.0461**
	Total checked area	0.5844	0.1145	0.2309
	Net wood area	0.5144	**0.0012**	**0.0000**
	Total specimen area	0.5221	**0.0011**	**0.0000**
	Recoverable collapse	0.9619	**0.0110**	**0.0211**
	Nonrecoverable collapse	0.6098	0.2002	**0.0001**
	Total collapse	0.9540	**0.0071**	**0.0005**

* These specimens contained up to 30% heartwood.

After reconditioning.—No significant difference was found between compression treatments (Table 2). Nevertheless, Group 4 showed the largest net wood area and total specimen area (an indication of final wood volume), followed by Group 3, Group 2, and, lastly, Group 1.

Collapse

There was no significant difference in the amount of recoverable collapse between compression treatments (Table 2). The average recoverable collapse was 4.19% for heartwood and 3.55% for sapwood, with the former being significantly higher than the latter (Table 2).

The average nonrecoverable collapse was found to be 4.13% for heartwood, and 4.22% for sapwood, and there was no significant difference between the two (Table 2). This means that the volume loss due to nonrecoverable collapse was almost the same for both heartwood and sapwood. Note that nonrecoverable collapse was almost as much as recoverable collapse for heartwood, but it was higher than the recoverable collapse for sapwood.

Tension wood in eucalypts collapses as normal wood and its collapse is not recoverable during the reconditioning process. No distinct gross characteristics of tension wood were observed in sapwood specimens. A cross section, 1 mm thick, was removed from each sapwood specimen of Group 1, and examined over a light box for a more translucent zone. Only one growth ring in one specimen appeared more translucent. No effort was made to microscopically confirm the occurrence of tension wood. Collapse in these sapwood specimens was caused by inclusion of heartwood in the specimens.

Results for total collapse (sum of recoverable and nonrecoverable collapse) were similar to those for recoverable collapse (Table 2).

Heartwood vs. sapwood

Before reconditioning.—As expected, the total number of checks and the total checked area were significantly higher in heartwood than in sapwood ($P < 0.001$). The total number of checks in heartwood was twice that of sapwood. The total checked area, expressed as a percentage of the cross section of the green wood specimens (40×40 mm), was on average 0.33% for heartwood and 0.12% for sapwood.

The net wood area and the total specimen area were not significantly different between heartwood and sapwood (Table 2), although the average was slightly higher for sapwood.

Sapwood specimens included up to 30% heartwood. However, internal checks more generally occurred in the center of the specimen rather than in the heartwood zone.

After reconditioning.—The total number of checks was again significantly higher in heartwood than in sapwood ($P < 0.05$, Table 2). On the other hand, the total checked area was not significantly different between heartwood and sapwood (Table 2), although the average was greater for heartwood. These results, together with the before-reconditioning observations, showed that internal checks in heartwood had closed up considerably upon reconditioning, although not as fully as those in sapwood.

The net wood area was significantly larger for heartwood than for sapwood after reconditioning ($P < 0.001$, Table 2), whereas it was not significantly different between heartwood and sapwood before reconditioning (Table 2). There are two possible causes: heartwood had a smaller component of normal shrinkage because it was less dense, and/or it had a similar amount of nonrecoverable collapse as sapwood but a larger amount of recoverable collapse (see previously *Collapse* section).

Relationship between variables

The total number of checks and the total checked area were highly correlated ($P < 0.01$), before and after reconditioning. A similar situation was found between the net wood area and the total specimen area ($P < 0.01$). Strong correlation between total number of checks and total checked area holds only if the checks are not substantially joined together, resulting in fewer number of checks. The correlation is poor when a specimen has numerous checks that are joined together. The total area of checks, therefore, is a far more reliable indicator of the magnitude of collapse-checking degrade.

On the other hand, there was no significant correlation between the net wood area and, respectively, the total number of checks and the total checked area, either before or after reconditioning. In addition, total collapse was only weakly, although significantly, correlated with the total number of checks ($R = 0.40$, $P < 0.001$) and the total checked area before reconditioning ($R = 0.32$, $P < 0.01$). These results tend to dispel the perhaps logical extension that the more internal checks and the greater total checked area, the smaller the net wood area. Rather, what may happen is that the wood cells, in addition to having collapsed, are also displaced by the enlargement of internal checks during drying. This process would result in greater specimen distortion but little change in net wood area. It is possible that the early formation of internal checks in drying is primarily caused by collapse, whereas later check enlargement is more attributable to drying stresses. If this were true, the amount of collapse could not reliably predict the degree of internal checking.

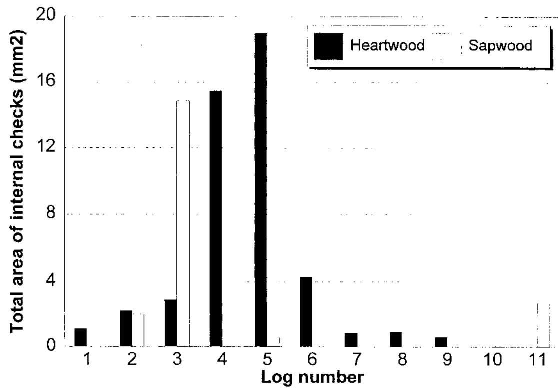

FIG. 7. Average total area of internal checks in heartwood and sapwood of different logs before reconditioning.

No correlation was found between basic density and recoverable collapse, either in heartwood or sapwood. The correlation between basic density and total collapse was significant for heartwood ($P < 0.05$, $R = -0.31$), but not significant for sapwood. The total checked area before reconditioning and the cross-sectional shrinkage after reconditioning were significantly correlated to basic density for sapwood ($R = -0.77$, and $R = 0.64$, respectively) but not for heartwood.

Variation between logs

Variation between logs in the total checked area before reconditioning is shown in Fig. 7. The heartwood data were separated from the sapwood data. Each data point is an average over four end-matched specimens. Except for logs 3, 4, and 5, the overall variability between logs is small for both heartwood and sapwood. Since sapwood of eucalypt trees has insignificant commercial value due to its small volume, logs 4 and 5 are therefore the "problem" logs in comparison to the rest. The initial moisture content and average basic density of logs 4 and 5 were near the overall average moisture content and basic density for all the logs. Therefore the higher amount of collapse internal checking in logs 4 and 5 did not appear to be associated with their initial moisture content and basic density. Large difference in the amount of internal checking between trees could be governed by the between-tree differences in anatomical properties. The ability to identify the "problem" logs and handle them accordingly has great practical importance. The ability to identify the "good" trees for breeding is equally, if not more, important.

There was a highly significant difference between logs for recoverable, nonrecoverable and total collapse (Table 2). However, among the 11 logs, logs 3, 4, and 5 had only modest amounts of such collapse. This suggests again that the degree of internal checking is not necessarily related to the amount of collapse.

CONCLUSIONS

Cell-wall deformations were successfully induced in specimens by means of various amounts of longitudinal compression, and their overall abundance increased with the degree of compression. No difference was found between compression treatments for collapse and internal checking, i.e., induced cell-wall deformations did not reduce drying degrade. It may be that artificial compression does not alter cell walls in the same way and/or to the same extent as growth stresses do in standing trees, e.g., in the formation of brittleheart. On the other hand, the contribution of induced cell-wall deformations to the reduction of liquid tension forces, if any existed, could have been hindered by uneven distribution of the deformations and/or consequent weakening of the cell walls.

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