COLLAPSE DEVELOPMENT OF *EUCALYPTUS SALIGNA* UNDER DIFFERENT DRYING TEMPERATURES

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YUNIARTI K, OZARSKA B, BRODIE G, HARRIS G & WAUGH G. 2015. Collapse development of *Eucalyptus saligna* under different drying temperatures. Collapse occurs in certain species such as in some members of the genus *Eucalyptus*. This study aimed to assess the degree of collapse developed during drying of *E. saligna* at different temperatures and determine its collapse threshold temperature range. The presence of internal checks and the number of samples with a washboarding effect on the surface of the board were used as indicators for collapse. Results showed boards dried at 30 °C had the highest percentage of cross-section loss due to internal checks. On the other hand, the highest number of samples with corrugated surface was found for boards dried at 35 °C. *Eucalytus saligna* had a collapse threshold temperature range below 20 °C.

Keywords: Collapse threshold temperature, collapse indicator, internal checks, washboarding effect, defect degree

INTRODUCTION

Collapse is a type of shrinkage which occurs above the fibre saturation point. Wood cells are flattened during the formation of collapse (Chafe 1985). The tendency for collapse occurs in most wood, including softwood species even though hardwood species will experience the most severe collapse (Kauman 1964). Collapse occurs in certain species such as some members of the genus *Eucalyptus* (Innes 1995a, 1996). Other collapse-prone timbers are radiata pine earlywood (Deyev & Keey 2001), oak (*Quercus* sp.), black walnut (*Juglans nigra*), western red cedar (*Thuja plicata*) and redwood (*Sequoia sempervirens*) (Langrish & Walker 2006).

The collapse phenomenon was first reported by drying expert, HD Tiemann from America, who proposed the theory of liquid tension to explain the formation of collapse during the drying of timber (Brown 1965). The theory explains that when free water moves out of a cell lumen, water vapour and air will fill up the empty spaces inside the lumen. This movement creates surface tension and capillary forces in capillaries of pits or gaps between cells. These tension and forces create stresses and further cause liquid tension to occur in the water of saturated, neighbouring cell lumens. When liquid tension exceeds strength properties of the cell walls, collapse occur and is manifested in the form of flattened or buckled cell walls. If there is non-uniformity in the actual thickness of fibre cell walls across the timber, collapse will likely occur at weak points in the timber, such as fibres near vessel or ray cells, which are less stiff than other parts in the timber (Innes 1995b).

In the Tiemann's liquid tension theory, two fundamental equations from mechanics and thermodynamics, Laplace's and Kelvin's equations, were proposed to estimate the degree of liquid tension that occurs in the saturated lumen (Chafe et al. 1992). While Laplace's equation uses merely the value of radius of the meniscus formed in the pit capillaries and/or gap between cells to estimate the degree of liquid tension, Kelvin's equation relates the degree of liquid tension that can occur with the temperature and relative humidity surrounding the meniscus. Thus, Kelvin's equation shows the influence of temperature

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on the formation of collapse (Brown 1965, Innes 1995b, Blakemore 2008, 2011). Temperature affects the relaxation process during drying process and the degree of restraint/stress (Lazarescu & Avramidis 2008). Cell walls soften at higher temperatures, their strength reduce and creep increases (Blakemore 2011). Raising temperature could possibly increase drying stresses and, therefore, increase the severity of collapse.

Due to the important role of temperature in affecting collapse intensity, a theory of collapse threshold temperature is postulated and defined as the maximum temperature where timber can still be dried without having collapse (Innes 1995a). A specific timber that is dried below its collapse threshold temperature should not collapse. Earlywood and latewood have different collapse threshold temperature (Innes 1996). Prior to the proposal of this theory, Brown (1965) stated that if initial dry bulb temperature exceeded the critical point of a prone-to-collapse species, then collapse would occur during the drying process of this timber.

Innes (1995a) found that 24–26 °C was the range for collapse threshold temperature for *Eucalyptus regnans*. Even though from the same genus, there is no evidence to show that *Eucalyptus saligna* will have similar collapse threshold temperature range to *E. regnans*. Furthermore, both species have different density values. *Eucalyptus saligna* has green and air-dry densities of about 1070 and 850 kg m^{-3} respectively (Bootle 2005). On the other hand, basic densities of *E. regnans* were 459–610 kg m^{-3} (Innes 1995a), depending on the location where it was taken from. Density and specific gravity affect the timber drying process (Simpson 1991).

The objectives of this study were to assess the degree of collapse developed during drying of *E. saligna* at different temperatures and to determine its collapse threshold temperature range. The hypotheses used were:

(1) different drying temperatures would cause different degrees of collapse formation and
(2) the collapse threshold temperature level or range for *E. saligna* would be different from that suggested by Innes (1995) for *E. regnans*.

MATERIALS AND METHODS

Source and storage

The main material used for the project, *E. saligna*, was obtained from north-east Victoria, near Rutherglen. The provenance was obtained from Kangaroo Valley. All trees were located in single line check-bank plantings lining irrigated lucerne paddocks. The total number of trees in the planting site was more than 100 per row with spacing of 4 m within the row and 35 m between the rows. The total site area was 30 ha.

Seven 12-year-old *E. saligna* trees were randomly sampled and selected from the stand. The range of diameter at breast height of the trees was 30–48 cm. All trees had been pruned up to 8—10 m at the age of 5 years. Depending on the previous standing height of the tree, each tree was divided into two or three logs, with length of the logs ranging from 2.5–5.2 m. Each log was sawn into several backsawn (tangential) boards. The width and thickness of each board were around 100 and 40 mm respectively. Logs were cut at the Timber Training Centre, Creswick. Sourcing and log-cutting processes were executed in May till June 2012.

Each board was further resawn into two smaller boards of 1000 mm each at the University of Melbourne. These small boards were end-sealed with silicone sealant and aluminum foil. Every four to six boards were wrapped tightly with plastic and coded. These small boards were stored in the cooling room at 4 °C until use.

Sampling preparation

A total of 25 to 30 boards of *E. saligna* were randomly taken out from the cooling room. Each board was further sawn into two drying samples at length of 320 mm each as shown in Figure 1. This process gave 50–60 drying samples. Three pieces of 20-mm width biscuits were taken from between and the two edges of the two samples. These biscuits were used to determine initial moisture contents of the boards using the oven-dry method. The biscuits were weighed prior to being dried in an oven at 103 ± 2 °C. After the biscuits reached constant weight, they were reweighed. The initial moisture content of each

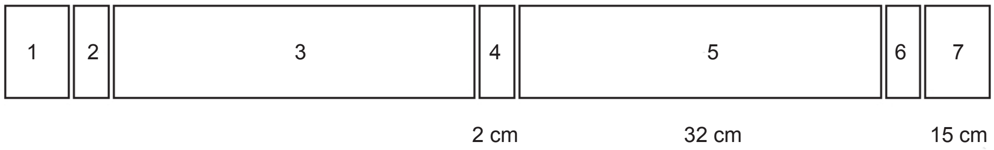


Figure 1 Sampling pattern for the drying experiment: 1 and 7 are the starting points to collect the two 2-cm biscuit joiners, i.e. at 15 cm distance from each end of the board, 2, 4, and 6 are the 2-cm biscuits to determine initial moisture contents of the drying samples, 3 and 5 are the 32-cm drying samples

drying sample was calculated using equation 1 below:

$$M = \frac{W_D - W_O}{W_O} \times 100\% \qquad (1)$$

where M = moisture content of the board (%), W_D = initial weight of biscuit (g) and W_O = final weight of biscuit (after being dried) (g).

Methods

The experiment for this study followed one of the procedures introduced by Innes (1995a), with some modifications. These modifications were necessary because (1) *Eucalyptus* species used in this study was different from that used by Innes (1995a), (2) sample thickness used in this experiment was higher, being almost twice of that used by Innes (1995a), (3) initial green moisture content of samples in this study was different from that used by Innes (1995a) and (4) there was very little information available on the exact level of moisture content when internal checks started developing in *E. saligna.* Innes (1995a) recommended using samples in the form of boards rather than slices in order to include the less sensitive parts of the boards in determinating collapse threshold temperature.

The experiment to assess the effect of different drying temperatures on collapse development and collapse threshold temperature used several drying temperatures. The first trial used 40 °C as starting temperature as recommended by Innes (1995a) when he determined the collapse threshold temperature for *E. regnans.* Stöhr (1977) suggested decreasing the dry- and wet-bulb temperatures by 5 °C if collapse developed during drying of *E. saligna.* Therefore, in this study, when the results obtained during drying at 40 °C showed signs of collapse, the next trials used lower temperatures at a decrease of 5 °C. The trials continued until the temperature of 20 °C. At this temperature, the trials had to be stopped due to limited features of the kilns and climate condition which did not allow further trials to be run below 20 °C.

Observation and weighing of samples were carried out every two days until all samples reached fibre saturation point (25–30%). When fibre saturation point was reached, the sample was sawn into four equal parts as shown in Figure 2. Parameters used to indicate the presence of collapse at various drying temperatures were internal checking and washboarding effect on board surfaces (Innes 1995a).

Presence of internal checks

The technique used to observe the presence of internal checks was another modification applied to the procedure developed by Innes (1995a). Internal checks usually start to develop above fibre saturation point and close gradually as moisture content of the timber decreased. However, the checks may still be present when the fibre saturation point is reached. Therefore, any presence of internal checks at fibre saturation point should not be ignored since it may still signal the occurrence of, or tendency to, collapse. Considering these assumptions, while Innes (1995a) dried samples at each temperature level for only 24 hours, in this experiment, drying process was carried out until each sample reached the top range of fibre saturation point(moisture content range of 25–30%) or 30%, whichever came first.

In this experiment, the sample was cut into four equal sections. The modification was applied to anticipate the occurrence of internal checks on other interior parts of the sample. The presence

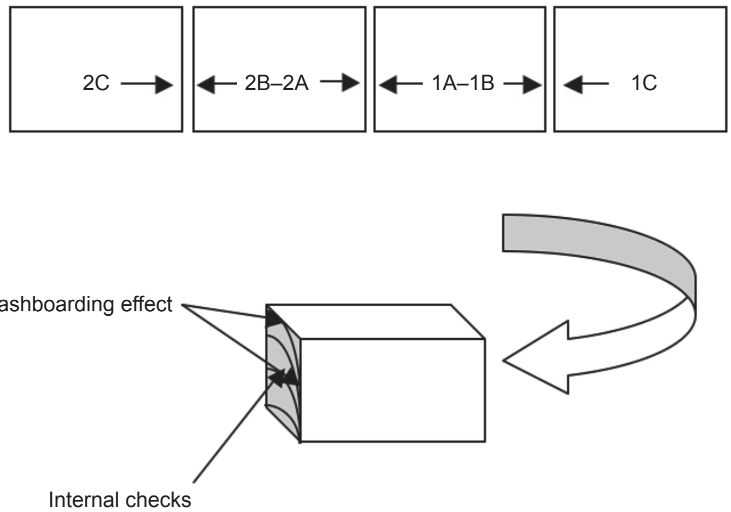


Figure 2 Internal checks and washboarding effect on dried samples; 2C to 1C are the observation positions for washboarding effects and internal checks

or absence of internal checks was observed on freshly-cut surface. Width and length of internal check were measured and its area determined. The presence or absence of internal checks was considered to affect the percentage loss of cross-section. The amount of internal checks found on each freshly-cut surface was determined using equation 2 and the percentage loss of cross-section was measured using equation 3 below:

Amount of internal checks on freshly-cut surface $(D_j, \%) = [(C_1 + \ldots + C_i)/A] \times 100\%$ (2)

Percentage loss of cross-section $(L, \%) = \Sigma D_j$ (3)

where $C_1 \ldots C_i$ = area of internal checks (i × (width × length of the check)); j = surface number, i.e 1, 2, ..., 6 (with 1 and 6 representing the ends of board); i = check number 1, 2,...etc; and A = cross-section area (width × thickness of cross section of the sample). The results were also classified according to the Australian Standard for drying quality (AS/NZS 2001) as shown in Table 1.

Presence of washboarding

Observation of washboarding effect was carried out prior to the investigation of internal checking. The whole board was examined closely for the presence of washboarding effect resulting from the drying process. Washboarding on a tangential board appears in the form of concave surface on some or all of its surface where the growth ring deviates to some degree of angle from the regular position (Keey & Nijdam 2002). The formation of washboarding on *Pinus radiata* sapwood occurred within only 1 min after drying commenced at dry-bulb temperature of 105 °C, wet-bulb temperature of 72.5 °C and airflow velocity of 4–4.5 m s^{-1} (Keey & Nijdam 2002). The ripple will usually occur on the radial face of backsawn board (G Harris, personal communication 2012). His statement confirms the information about the general presence of fibre collapse in radially oriented zone (Chafe et al. 1992). The presence of collapse occurs in the form of corrugated surface on the radial direction of the board and usually on its early wood fraction (Langrish & Walker 2006). Therefore, qualitative observation of washboarding effect and/or corrugated surface was also carried out on the radial face of the timber samples. When rippled/corrugated surface occurs at any surface (tangential or radial direction), the affected sample was numbered. However, up to now, there is no standard in Australia for classifying the washboarding effect (corrugated surface).

RESULTS AND DISCUSSION

Internal checks occurred on *E. saligna* boards exposed to different drying temperatures (Table 2). The lowest number of samples having internal checks, the lowest total amount of internal checks and the lowest degree of internal checks were found in samples dried at 20 °C. Thus, it was suggested that the collapse threshold temperature for this species might occur below 20 °C. This value is lower than the temperature for *E. regnans* as reported by Innes (1995a), which ranged from 24 to 26 °C.

Different parts along the board responded differently when they were exposed to different drying temperatures (Figure 3). The middle parts of *E. saligna* boards experienced more internal checks than its ends when exposed to temperatures of 25–35 °C. However, when it was dried at 40 and/or 20 °C, a higher percentage of internal checks was found on the parts of the board that were close to the end.

Figure 4 shows the shape of internal checks formed at the end (marked 3) and middle (marked 1 or 2) parts of the board dried at 20 and 40 °C respectively. The appearance of internal checks formed at the end and middle parts of the board was slightly different. They occurred on ray cells of both end and middle parts of the boards. However, bigger checks/cracks were found at the ends of the boards (marked 3) compared with the middle parts (marked 1 or 2). Most checks at the middle part of the boards were more like thin strips (Figures 4a and c, marked 1 or 2).

The highest cross-section loss due to internal checks occurred when boards were dried at 30 °C, and not at 40 °C as expected even though this was the highest drying temperature applied. Internal checks that occurred at 40 °C was almost as low as that found on samples dried at 20 °C. This contradicted the work carried out by Innes (1995a) which suggested that higher drying temperature should produce more internal checks.

Average percentage loss of cross-section on the boards ranged from 0.03 to 6.62% (Table 2). Based on this evaluation and Table 2, the quality class of dried boards from this experiment ranged from class A/B to C/D. Boards dried at 30 and 35 °C were classified as C/D as they had the highest percentage loss of cross-section and the highest number of samples having internal checks.

Table 1 Specifying internal checking by quality class (AS/NZS 2001)

Quality class	Maximum percentage loss of cross-section of 90% of sample pieces (%)
A/B	0
C	5
D	10
E	15

Table 2 The presence of internal checks and washboarding effect on *Eucalyptus saligna* boards dried at different drying temperatures

Temperature (°C)	Internal check			Number of samples with washboarding effect on the surface
	Number of samples with internal checks	Total number of internal checks	Average cross-section loss due to internal checks (%)	
20	2	3	0.03	6
25	5	26	0.52	7
30	6	33	6.62	9
35	8	43	2.36	10
40	5	22	0.92	8

Total number of samples = 10

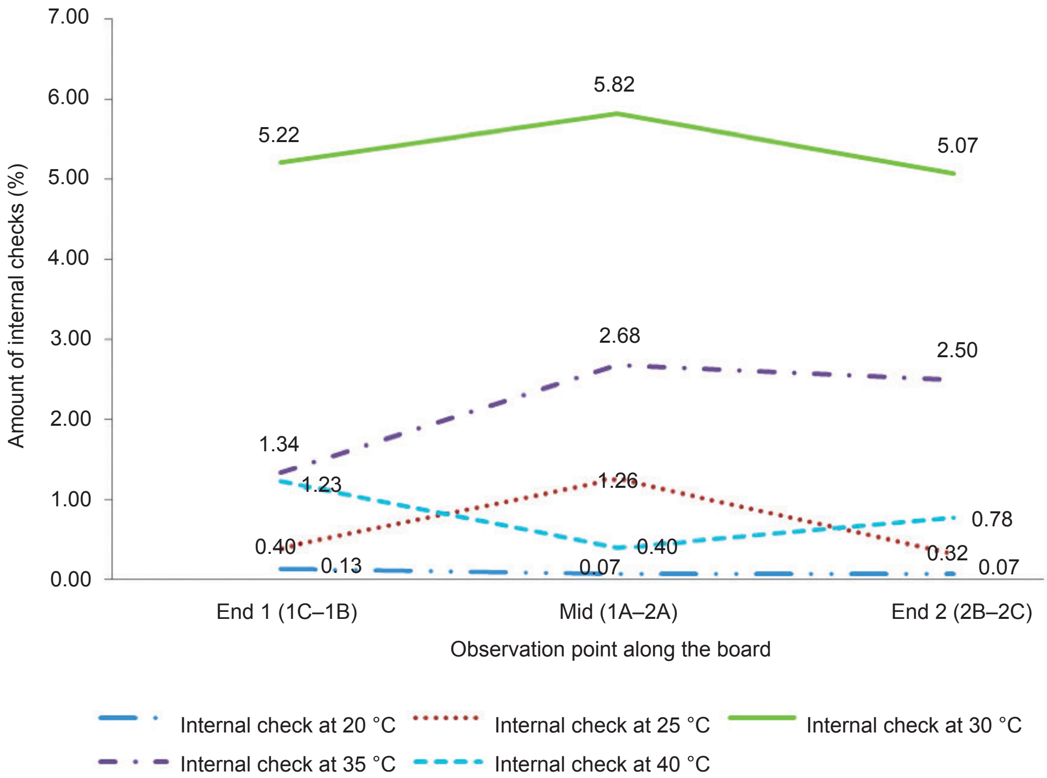


Figure 3 Occurrence of internal checks along *Eucalyptus saligna* boards dried using different drying temperatures; End 1, End 2 were at a distance of 80 mm from each end of board while Mid was at a distance of 160 mm from the end of the board

Figure 5 shows the shape of internal checks that occurr in boards dried at 30 °C. Severe internal checks occurred not only in the end parts but also in the middle parts of the boards. This result was assumed to be due to the presence of natural defects such as knots that were found on several boards dried at 30 °C.

Qualitative observation of washboarding effect on both radial and tangential surfaces showed that, at any drying temperature levels, the washboarding found on the surface of some boards was very slight, almost undetectable. Figures 6 and 7 show radial and tangential surfaces with washboarding on boards dried at different drying temperatures which were almost unseen if the boards were not resawn. The surface with washboarding could only be detected by running a hand across the surface to determine the presence of collapse or potential defects leading to collapse. Number of samples with washboarding surface at each drying temperature is given in Table 2. The presence of washboarding on the surface of the affected boards was observed at all temperatures tested. The highest and lowest number of samples with washboarding surfaces were found at drying temperatures 35 and 20 °C respectively.

Not every board with washboarding effect on its surface had internal checks. All boards were sourced from the same location and age. Therefore, it was assumed that there were still variations in the structure and properties of the boards that affected their performance during the drying process. These variations included natural defects that were present in the wood, sawing patterns and earlywood portions. While the initial condition of the samples used might contribute to this unexpected result, this peculiarity might also support the findings by Ilic (1999) who claimed that there was no collapse threshold temperature for eucalypts. His claim was based on observation of *E. regnans* samples which developed collapse under storage at 4 °C. On the other hand, the theory of collapse

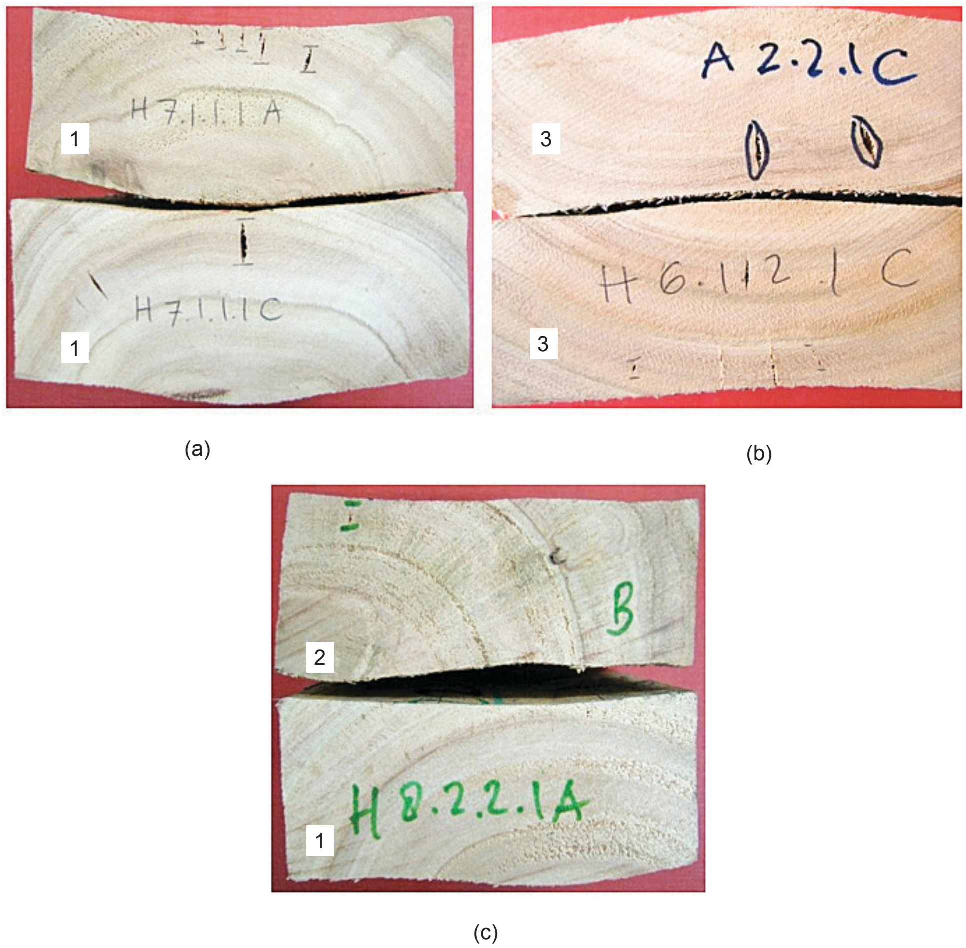


Figure 4 Internal checks on the middle parts (labelled 1 or 2) and end parts (labelled 3) of *Eucalyptus saligna* boards dried at (a) 20 °C, and (b) and (c) 40 °C

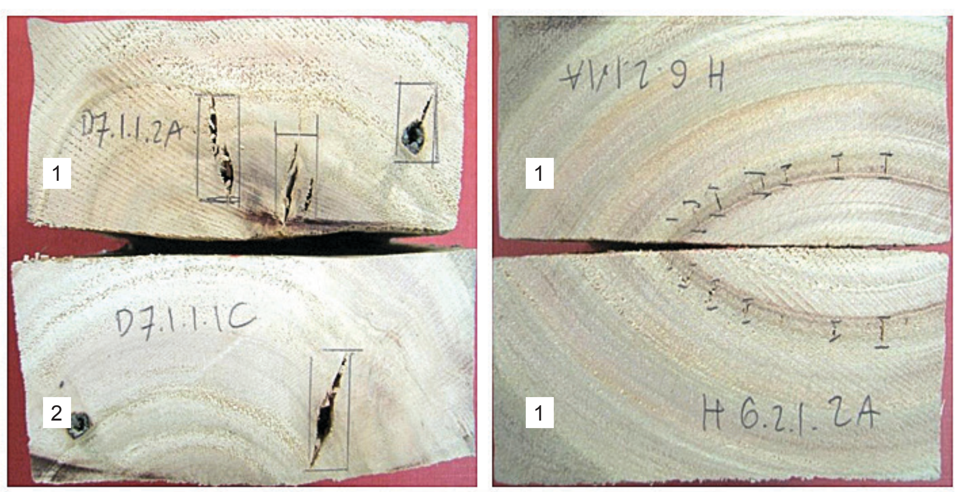


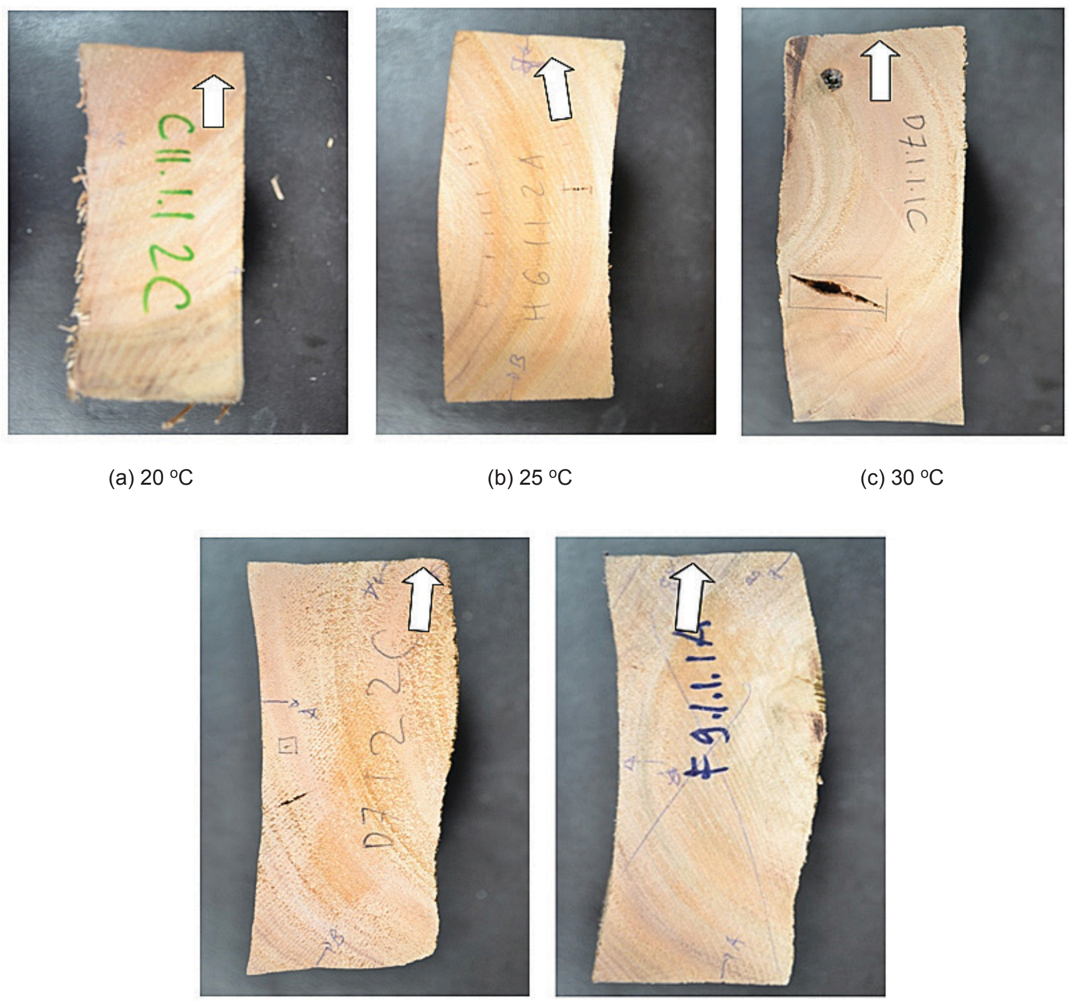
Figure 5 Internal checks on *Eucalyptus saligna* board dried at 30 °C; the ends of the boards are marked 2, while the middle parts of the boards are marked 1

Figure 6 Corrugation on tangential surface (marked with white arrow) of the boards dried at different temperatures

threshold temperature cannot be neglected as well. The liquid tension theory, which has been widely explained and accepted as the theory underlying the formation of collapse, has indicated that all species have collapse threshold temperatures. This indication was based on the Kelvin's equation, which was the formula used to explain collapse development. Based on this equation, as temperature increases, liquid tension will increase too. Thus, there should be a maximum temperature, which is termed as the collapse threshold temperature by Innes (1995a), that produces excessive tension exceeding the cell wall strength and causing collapse to occur.

CONCLUSIONS

Different drying temperatures influenced collapse development in *E. saligna* boards. The highest number of internal checks, one of the indicators of the occurrence of collapse, was found for boards dried at 30 °C. Based on the percentage loss of cross-section, the quality class of dry boards obtained from the different drying temperature levels ranged from class A/B to C/D. The highest number of samples with corrugated surface, i.e. the parameter used to indicate the formation of collapse, was at 35 °C. *Eucalyptus saligna* (lower than 20 °C) had



(a) 20 °C (b) 25 °C (c) 30 °C

(d) 35 °C (e) 40 °C

Figure 7 Washboarding on radial surface (marked with white arrow) of the board dried at different temperatures

different collapse threshold temperature from that of *E. regnans* (24–26 °C).

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