Cabardo, S. J.; Langrish, T. A. G.
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Maderas. Ciencia y Tecnología, vol. 8, núm. 1, 2006, pp. 15-24
Universidad del Bío Bío
Concepción, Chile

ISSN 0717-3644
ISSN online 0718-221X

Maderas. Ciencia y tecnología 8(1): 15-24, 2006

WITHIN-TREE VARIABILITY IN THE DRYING PROPERTIES FOR BLACKBUTT TIMBER IN NEW SOUTH WALES

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ABSTRACT

The within-tree variability of drying properties, including the green and final moisture conte the basic density, and the diffusion coefficient, has been investigated for regrowth blackbutt tim (*Eucalyptus pilularis* Sm).Timber boards from two regrowth trees were taken from Northern N South Wales in Australia, and dried in a lab scale kiln. The pattern of variation within the two trees similar, such that the diffusion coefficient was strongly correlated with the initial moisture content basic density. Principal components analysis suggested that the timber boards with low basic densi and high initial moisture contents had higher diffusion coefficients. A potential reason is that if ther less wood material per unit volume, then this leaves more space for water to occupy, and there is less resistance for the diffusive transport of moisture. In addition, this suggested correlation was evident in the analysis of variance (ANOVA).

A simulation study, using the timber data measured from the experiments in this paper, was conducted to estimate how different hardwood drying schedules are likely to affect the distributio the final moisture contents, and the time taken to reach an average stack moisture content of 0.15 kg. A revised version of the drying schedule used for the experiments in this paper, i.e. adding 5ºC the dry and wet-bulb temperatures, has been predicted to be a better drying schedule out of the drying schedules studied, due to it drying the timber quicker as well as having a small dispersio final moisture contents.

Keywords: diffusion, drying schedules, density, moisture content

INTRODUCTION

Australia produces close to 1 million cubic metres of sawn hardwood timber each year and imp another 142,000 cubic metres, of which more than 90% comes from Indonesia and Malaysia (Casw 2005). It is predicted that 9.2 million cubic metres of logs per year will be harvested in the latter hal the present decade (Ferguson et al., 2002). In New South Wales alone, the consumption of eucaly sawn wood was 263,000 m^3 in 2000-01 (ABARE, 2001). Therefore, the less timber that is harves locally, the more the country will have to rely on imports to meet increasing consumer demand reduce the importation of sawn timber from overseas, Australian timber drying companies may hav rely on getting most of their timber supplies from these hardwood plantations. However, tim companies report a growing difficulty in handling plantation timber for a number of reasons, on which is the increased amount of variation in timber properties that can affect the dried quality of timber. As a result, it is possible that large variations in intrinsic properties may require better cont hence optimized drying schedules that account for these variabilities may need to be developed.

Trial and error has been used for the development of kiln drying schedules in the past (Campb 1980; Mills, 1991). Subsequently, more rational approaches have been undertaken for the optimiza of kiln drying schedules. Optimized kiln drying schedules have been developed from simulations (Cro et al., 2003) that have considered the variability of final moisture contents. Continuous kiln dry schedules (Booker, 1994; Alexiou, 1993; Langrish et al., 1997) have also accounted for stress, str and checking/cracking. Pordage and Langrish (2000) developed a method for generating kiln dry schedules that considered the variability of timber properties, using very limited data on variabi from Doe and Innes (1999). In addition, the variability of the biological parameters was assumed Pordage and Langrish (2000) to be normally distributed, and the parameters were assumed to uncorrelated with one another. Kayihan (1993) also assumed that there was no correlation between green moisture content and the drying-rate parameters. Siau (1984) suggested that the variability in green moisture content may be correlated with the variability in the timber density but this hypoth has yet to be confirmed. Overall, there is little information about the variability in timber proper with respect to drying, including how strongly they are correlated. The remaining challenge optimizing kiln drying schedules thus include getting sufficient data on the variability of tim properties, and carrying out the optimization both to minimize cracking and to minimize the dispers of final moisture contents.

The tree species chosen for this study was blackbutt (*E.pilularis*), because blackbutt is predominant planted hardwood species in NSW, Australia (Boland et al., 1989) and is considered to one of the most important eucalypts for planting in NSW (Johnson and Nikles, 1996).

Since the amount of variability is a key issue in the processing of timber, the variation of diffus coefficients, basic densities, and green and final moisture contents for regrowth blackbutt, has b investigated in this paper. These investigations have been followed by a simulation study of the effe of different drying schedules on 12 blackbutt boards used in the experiments.

MATERIALS AND METHODS

Preparation of Samples

Blackbutt boards, 28 mm thick x 108 mm wide x 900 mm long, were cut from two regrowth l (Log 1 and Log 2). Each log was approximately 4.8 m in length. The boards were taken from differ locations within each log, as shown in Figures 1 and 2. Each 'A' board has its corresponding 'E' bo that was taken from the top end of each log. The boards were wrapped in thick polythene film u further processing. Thereafter, a 20 mm thick sample was taken from each end of each green 'A' 'E' board to calculate its corresponding initial moisture content using the oven-dry method. The f length of each green timber board was 800 mm after the moisture content, the green modulus of elasti (MOE) and the shrinkage samples were taken. However, the results for the green MOE and shrink tests are not shown in this paper. The remaining board length was end-sealed using silicone and alumin foil. Thereafter, the timber boards were kiln dried in a drying tunnel, using the conventional dry schedule published in the Australian Timber Seasoning manual (Mills, 1991) suited for mixed sa blackbutt boards, 25 mm in thickness, shown in Table 1.

Each kiln charge consisted of six boards. One board was taken from close to the pith, ano board was taken from close to the bark, and another board was taken at a certain circumferen distance from the two boards. The remaining three boards were at the same radial and circumferen distances but at the other end of the log. This procedure was followed for the first four drying experime The fifth kiln charge consisted of 12 boards (equivalent to two previous experiments) to increase amount of data gathered per experiment. The boards were stacked on top of each other, separated kiln stack, on a daily basis, to minimise stacking effects on drying. Timber density was based on oven-dry weight/green volume, where the original sample dimensions were measured for the calcula of the green volume.

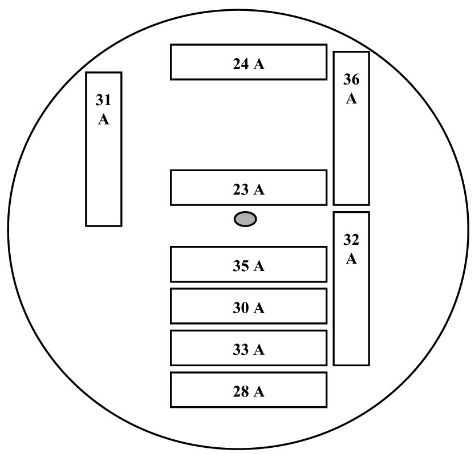

FIGURE 1. Cross-section of the bottom end of log 685, showing where each 'A' board was taken.

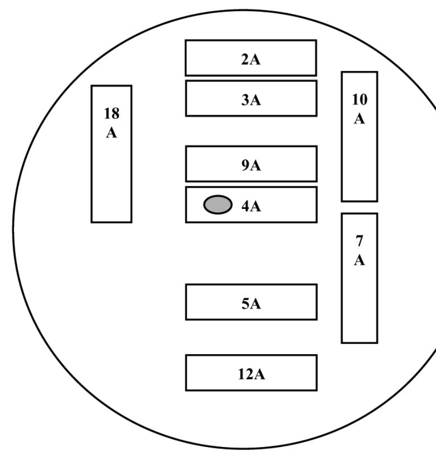

FIGURE 2. Cross-section of the bottom enc log 686, showing where each 'A' board was tal

Table 1. Drying schedule used for all experiments (Mills, 1991).

Day to Carry Out Change Point	**0**	**5**	**8**	**10**	**12**	**15**
Estimated Moisture Content at Change Points (%)	**Green**	**40**	**30**	**25**	**20**	**15 to fina (usually 12)**
Dry Bulb Temperature (^{o}C)	55	60	65	65	70	70
Wet Bulb Depression (^{o}C)	3	4	5	8	10	15

Drying Tunnel

Figure 3 shows the overall design of the pilot-scale batch dryer used for drying 800 mm tim boards. This conventional kiln was used to produce controlled drying conditions, with initial dry-b and wet-bulb temperatures of 55ºC and 52ºC (Table 1), respectively, and an air velocity of 1.3 across the flat surfaces of the boards. Manipulating the steam flowrate to a steam-injection system used to control the wet-bulb temperature to its desired setpoint. The steam-injection system consis of a dryer and six-point steam injection pipe over a 300 mm duct. The control mechanism for the bulb temperature involved the flowrate adjustment of 100 kPa (gauge) steam to a finned heat exchar using a control valve. The overall size of the kiln working section has a volumetric capacity of 0. m^3, a height of 0.45 m, a stream-wise length of 0.4 m, and a cross-stream width of 0.9 m. The mas

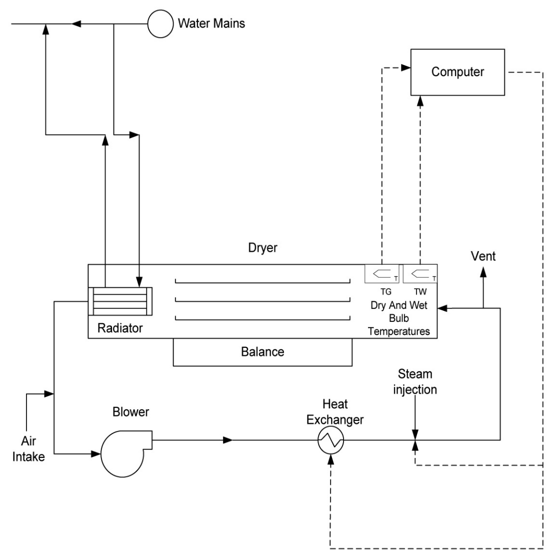

FIGURE 3. Schematic diagram of timber drying tunnel.

Fitting Procedure for Diffusion Coefficients

The predicted overall drying curve is dependent on the diffusion coefficients and operating temperatu for each experiment (Langrish et al., 1997). The model is based on solving Fick's Second Law of diffus for mass transfer and Fourier's Law for heat transfer. The equations used for the mass transfer and h transfer of the timber boards were based on the equations used by Langrish et al. (1997). Moistur assumed to diffuse through the timber and evaporate near the surface. It is often difficult to measure diffusion coefficient directly, but it can be fitted to experimental data, as here. Schaffner (1981) and (1989) both successfully fitted diffusion coefficients to observed data for eucalypt timbers. Therefore, le squares parameter fitting was used to adjust the value of the reference diffusion coefficient, D_r in an Arrhen type equation:

$$D = D_r \exp\left(-D_E / T\right)$$

The parameter fitting minimizes the sum of squares of the difference between the predicted and ac average moisture contents for each board. A typical initial value of D_r was 0.6x10^{-5} m^2s^{-1}. D_E, in unit Kelvin, represents the *E/R* in the exponent term (where *E* is the activation energy in J/mol, and *R* is the constant, 8.314 J/mol.K) since it represents the temperature dependence of moisture diffusion (Keey et 2000). The value of D_E used in this simulation was 3800 K because this value was also used by Wu (19 and Schaffner (1981) in their simulations of Tasmanian eucalypts. In addition, Haque (2002) used the va of 3800 K for D_E for his drying simulation of blackbutt, which is the same species studied in this pa When calculating each of the timber board's respective diffusion coefficients, *D*, using Equation (1), 6 (333 K) was used for the temperature value, *T*, to represent the temperature of each board, as an avera during the whole drying process.

The recorded moisture contents that were measured throughout the drying process, and the dry and w

characterized the drying behaviour of the corresponding timber board, and along with the D_E value of 3
K and 60ºC as the value for T, the individual board's diffusion coefficient, D, was calculated.

RESULTS AND DISCUSSION

Drying Properties and Analysis of Variance (ANOVA)

The fitting procedure fitted the drying behaviour over 95% of the cases within experimental uncertain when comparing the measured and the predicted average moisture content. The range of the diffus coefficients, the initial and final moisture contents, and the basic densities, are shown in Table 2. The in moisture contents decreased from pith to bark, and the basic densities increased from pith to bark. Prelimin ANOVAs were performed on each log separately with a 75% confidence level (with 12 boards represen each log). The preliminary ANOVA showed that circumferential and radial effects were significant sou of the within-tree variation for the diffusion coefficients, the initial moisture contents and the basic densi No effects were significant for the variation of the final moisture contents within trees. Moreover, the res for the initial moisture contents and basic densities agreed with the work reviewed by Walker (1993) regard hardwoods such as Yellow Birch, American Beech, and Shining Gum. He observed the same behav within a single tree, i.e. initial moisture contents and basic densities varied from pith to bark. In addit Wimmer (2000) observed an increase in basic density and a decrease in moisture content from pith to b for softwoods, similar to our results with hardwoods. Walker (1993) also suggested that wood material w low basic density had a high initial moisture content and vice versa. Wood with a low basic density h considerable volume of void space that water can fill when the timber is green, because the low b density means a small volume of wood material in the cell walls. Furthermore, the ANOVA showed that height effect (except for initial moisture content) is not a significant source of variation for the basic dens and the diffusion coefficients. For this work, an ANOVA using 18 boards from each log was also conduc and the results emphasise that only radial effects were likely to be significant sources of variation for diffusion coefficient. Overall, these results support the previous suggestion that the behaviour of these th parameters changes across the radius of the log.

Table 2. Timber properties for blackbutt timber (thirty-six boards).

Timber Property	Minimum	Maximum
Diffusion Coefficient, D ($\times 10^{-10}$ m^{2}s^{-1})	1.14	4.53
Basic Density (kg m^{-3})	356	934
Initial Moisture Content (kg/kg)	0.46	1.13
Final Moisture Content (kg/kg)	0.08	0.18

Principal Components Analysis

A correlation between high initial moisture contents, higher diffusion coefficients, and low basic dens was observed with the measured and calculated drying properties. The timber boards with higher dens had more wood material per unit volume. This may either be due to large cell volumes and/or more cell-w material, leaving less space for water to occupy, which explains the low initial moisture contents for tim boards with high densities (Keey *et al.*, 2000; Walker, 1993). In addition, more wood material mea higher resistance to diffusive transport of moisture (Keey *et al.,* 2000). Therefore the diffusion coefficie expected to be low in high density wood. A principal component analysis (PCA) (Smith, 2002) was perfor correlation between the parameters. The strong correlation between the diffusion coefficient, D, and initial moisture content, X_i (and basic density) is represented by Equation (2):

$$D = (6\times10^{-10})X_i - (2\times10^{-10})$$

Figure 4 shows that boards with high initial moisture contents have low basic densities, and thus h diffusion coefficients. One board from log 1 had a high basic density, but had a high diffusion rate; poss due to the crack present throughout the length of the board.

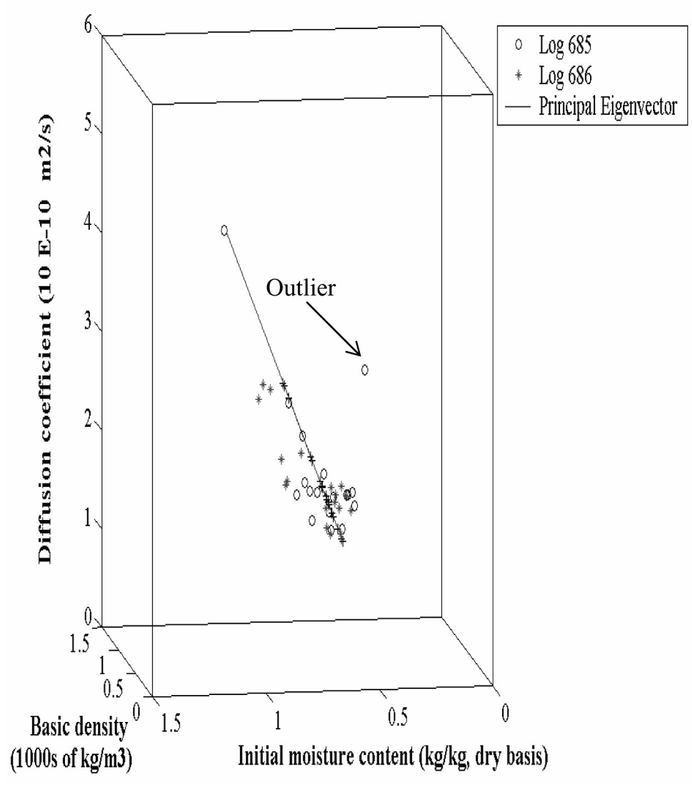

FIGURE 4. Three-dimensional plot of the parameters from Principal Components Analysis, togethe with the principal eigenvector.

Comparing the Effects of Different Drying Schedules

The effects of different drying schedules and the measured variabilities of initial moisture contents diffusion coefficients on the variability of final moisture contents, when the average moisture content wi a stack of timber reached 15%, were predicted by using the same drying model. Tables 3 to 5 show drying schedules used for this comparison. These drying schedules were used by Kärki (2002), wh experiment dried European aspen (hardwood), Innes and Redman (2003) to model the drying of six diffe regrowth hardwoods including blackbutt, and for this study, a revised drying schedule by adding 5ºC to

Table 3. Drying schedule used by Kärki (2002) to dry European aspen.

Time (hours)	Dry-Bulb Temperature (ºC)	Wet-Bulb Temperature (ºC
0	20	18
20	50	47
40	50	46
60	50	45
80	55	47
100	60	49
120	65	50
140	70	52
160	70	52
180	55	50

Table 4. Drying schedule used by Innes and Redman (2003) to dry blackbutt timber.

Time (hours)	Dry-Bulb Temperature (ºC)	Wet-Bulb Temperature (ºC
0	23	21.5
168	23	21
336	24	21.5
504	24	21
840	25	20.5
1008	25	20

Table 5. Revised drying schedule, for this study, by using the drying schedule from Mills (1991) to d
25 mm thick blackbutt timber and adding 5ºC to the temperatures.

Time (hours)	Dry-Bulb Temperature (ºC)	Wet-Bulb Temperature (ºC
0	60	57
120	65	61
192	70	65
240	70	62
288	75	65
360	75	60

Table 6. Statistical analysis of the predicted final moisture contents using the different drying schedul

Drying Schedule Used	Time (hours)	Final Moisture Content (kg/kg)		
		Average	*Standard Deviation*	*Coefficient of Variation*
1.Original drying schedule	396	0.15	0.013	0.087
2.Kärki (2002)	255	0.15	0.029	0.193
3.Innes and Redman (2003)	1386	0.15	0.014	0.093
4.Original drying schedule + 5ºC	378	0.15	0.013	0.087

content, but its conditions produced the largest dispersion of final moisture contents. Drying schedu gave the longest drying time, but the dispersion of final moisture contents was two times smaller (0.0 compared with the dispersion of final moisture contents from drying schedule number 2 (0.193). On other hand, the conditions of drying schedules 1 and 4 seem to be similar in terms of the distribution of f moisture contents. However, increasing all the temperatures in drying schedule 1 by 5ºC (drying schedul reduced the drying time. Elevated temperatures increase the diffusion coefficient and hence the drying r decreasing the drying time.

There are limitations, however, associated when using high temperatures in kiln drying. Collapse i abnormal shrinkage in the timber at moisture contents above the fibre saturation point during drying, many Australian eucalypt timbers are prone to collapse (Chafe et al., 1992; Innes, 1996). Innes (1995) u a stress-strain model to assess the stress and strain distributions within the fibre cell walls of Tasmar eucalypt and found that the stresses and strains in the fibre cell wall were sensitive to small variation temperature. In another study comparing three drying strategies aimed to avoid collapse checking Tasmanian eucalypt, Innes (1996) suggested there was a "collapse threshold" temperature for any tim specimen, above which collapse was likely to be severe. In addition, due to reactions involving so constituents in the wood along with the combined effect of high temperature and relative humidity (M 2002), sometimes discolouration of the timber occurs when kiln drying. The discolouration of the tim may become unacceptable, especially for appearance grade products (AS/NZS 4787:2001). McCurdy e (2003) reported that high drying temperatures (as high as 120ºC) enhanced the darkening of *Pinus rad* sapwood boards and thus, both temperature and drying time were significant factors for timber discoloura during drying.

In general, from this study, it may be possible to develop a drying schedule that increases the producti of timber, i.e. amount of good quality timber divided by the drying time, (Pordage and Langrish, 2000 accounting for biological variability and considering the mentioned limitations (which were stress strain constraints, and the maximum temperatures that can be reached before collapse and discoloura occurs). This development can be done by using the data for this variability in the diffusion coefficients, initial moisture contents, and the basic densities measured in this work, and the shrinkage coeffici (which are not reported in this paper).

CONCLUSIONS

Within a tree, the initial moisture contents decreased from pith to bark, and the basic densities increa from pith to bark. A correlation between the initial moisture content, the basic density, and the diffus coefficient, using Principal Components Analysis (PCA), was observed from each board. Timber boa with high initial moisture contents had low basic densities and high diffusion coefficients. This observa may be connected with the link between less wood material, more space for water in the green timber, the increased ease with which moisture can diffuse through the timber board.

Different drying schedules affected the time taken to reach an average stack moisture content of 1 and the distribution of final moisture contents of the 12 timber boards. The drying schedule that was used for the experiments, and the revised version of the same schedule, were similar in terms of the dispers of final moisture contents, but the latter producing a shorter drying time. Overall, from this simulation stu the presence of variability in the timber properties implicitly affects the drying rate and the dispersion final moisture contents by the choice of the drying schedule used.

ACKNOWLEDGEMENTS

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