4. VARIABILITY IN THE PHYSICAL AND TRANSPORT PROPERTIES REGARDING DRYING BEHAVIOUR FOR REGROWTH AND PLANTATION BLACKBUTT TIMBER IN NEW SOUTH WALES

4.1 Overview

Variability is a key issue in the processing of many biological materials, in this case the drying of hardwood timber. This section reports the measurements of variability in the diffusion coefficient (a drying property), the initial moisture content and the basic density (physical properties), which are relevant to the drying of blackbutt, *Eucalyptus pilularis* Sm, from Northern New South Wales in Australia. All blackbutt logs consisted of more than 80% heartwood. Fickian diffusion was considered to be the main moisture transport process (**Chapter 2.2.4**). The diffusion coefficient was quantified using a mathematical model solving Fick's Second Law of diffusion for mass transfer, and Fourier's Law for heat transfer. The initial moisture content and the basic density were measured using experimental procedures described in **Chapter 3**. Specifically, within—tree and between—tree variations are reported.

4.2 Parameter Estimation and Fitting to Results

The diffusion coefficient, D, was calculated using the Arrhenius—type Equation (2.5) and the procedure described in **Chapter 3.3**. Since the diffusion coefficient was dependent on temperature, T, the temperature value used to report the average coefficient was 333 K, because it reflects the mean temperature for each board during the whole drying process. No assumption was made about the temperature when fitting the diffusion coefficients because the temperature was obtained from a heat balance. The fitting procedure matched the observed drying behaviour, in over 95% of cases, within experimental uncertainties. The resulting standard error values from the fitting procedure were small compared with the moisture contents (the majority of the errors ranged between 0.004 kg kg^{-1} and 0.03 kg kg$^{—1}$). Figures 4.1 and 4.2, which are typical plots, show how well the predicted moisture contents fitted the actual moisture contents for experiment one (regrowth blackbutt: within—tree test) and experiment seven (plantation blackbutt: 'A' and 'E' boards of boards four to six for the within—tree test). The moisture content curves as functions of time for the other experiments are shown in Appendix 1.

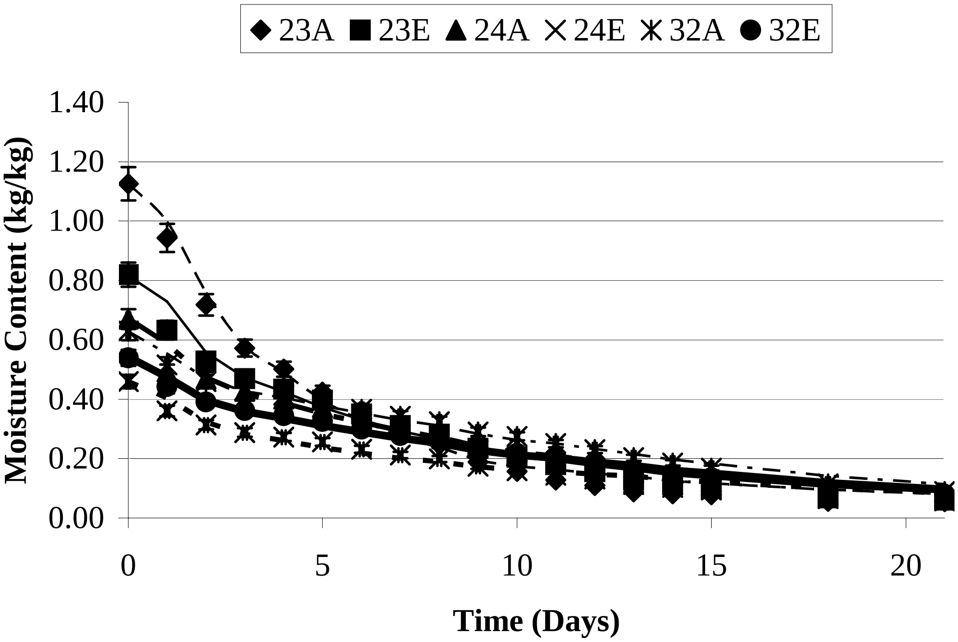


Figure 4.1. Moisture contents as a function of time for experiment one (within—tree test for regrowth blackbutt). The lines represent the results of the fitting procedure.

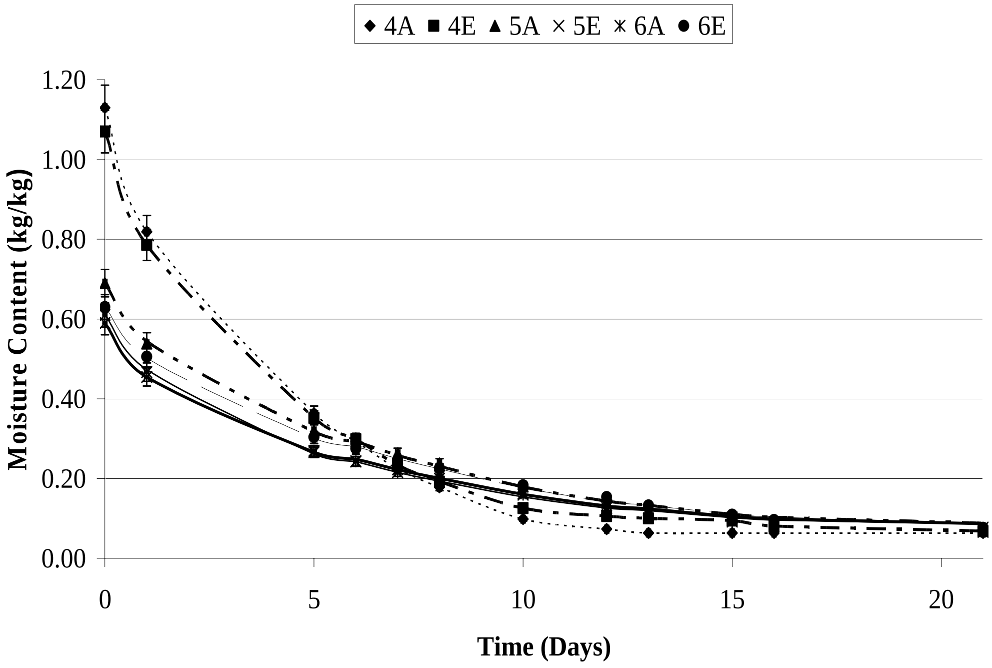


Figure 4.2. Moisture contents as a function of time for experiment seven (plantation blackbutt: ‘A’ and ‘E’ boards of boards four to six for the within—tree test). The lines represent the results of the fitting procedure. Together with Figure 4.1, this figure is typical for all experiments.

The dispersion of moisture contents for each experiment did not increase during drying, despite the samples being taken from different locations in the tree. The final moisture contents all converged towards the equilibrium moisture content of 6.5%. This value is the equilibrium moisture content at the final conditions of the drying process, i.e. a dry—bulb temperature of 70^{o}C and a wet—bulb temperature of 55^{o}C, taken from the CSIRO (Commonwealth Scientific and Industrial Research Organisation) psychometric chart (Mills, 1991). The small dispersion of the final moisture contents in the study of both regrowth blackbutt and plantation blackbutt satisfied the allowed amount of variation for final moisture contents associated with Class C quality timber according to the Australian/New Zealand Standards (AS/NZS 4787, 2001), i.e. 8%—17% is the moisture content range that a minimum of 90% of the boards must be inside (for a target moisture content of 12%) for Class C timber. Some industrial implications of these results can be assessed directly from Figures 4.1, 4.2 and Appendix 1, since all the boards were dried using the same time—based drying schedule. The convergence of the initially widely—spread range of initial moisture contents to a narrow range of final moisture contents at approximately the same time suggests that, for these 26 logs of blackbutt timber at least, the variation in initial moisture content is compensated for by a similar variation in diffusion coefficients. The fact that the moisture contents all converge at approximately the same time is important, because the convergence, in itself, only indicates that the equilibrium behaviour is the same, not necessarily that the variation in the initial moisture contents is compensated by a corresponding variation in the diffusion coefficients.

The coefficients of variation of the initial moisture contents and final moisture contents are shown in Table 4.1, when the average moisture content of the timber stack was around 12%. Industrial users usually dry down to a moisture content between 10% and 15% (Mills, 1991).

Table 4.1. Coefficients of variation for the initial and final moisture contents for regrowth and plantation blackbutt timber.

	Coefficient of Variation	
	Initial Moisture Content	**Final Moisture Content**
Regrowth Blackbutt		
Within—Tree	0.23	0.19
Between—Trees	0.21	0.15
Plantation Blackbutt		
Within—Tree	0.26	0.24
Between—Trees	0.18	0.36

There was more variation among the initial moisture contents compared with the final moisture contents, except for the between—tree test for plantation blackbutt timber. The coefficient of variation for both the within—tree and the between—trees tests of plantation timber were higher compared with the coefficient of variation for the same tests of regrowth material. It is possible that the variations in the diffusion coefficients for the plantation material are higher compared with the variations in the diffusion coefficients of the regrowth material, and as a result probably affected the amount of dispersion of the final moisture contents of the individual boards. Tables 4.2 to 4.5 show the diffusion coefficients for all the regrowth and plantation boards. An F distribution test (Spiegel and Stephens, 1999) was conducted to evaluate the variance of the diffusion coefficients between regrowth and plantation blackbutt timber. The null hypothesis states that the variances of the regrowth and plantation blackbutt timber's diffusion coefficients are equal, hence there is essentially no difference between the groups. However, the results of the F test suggested that the null hypothesis should be rejected and showed that there was a significant difference between the variances of the diffusion coefficients of regrowth and plantation blackbutt within trees at a 0.05 significance level (F_{actual}, 3.94 >

$F_{expected}$, 1.96). This result shows that the dispersion of the diffusion coefficients within plantation blackbutt trees was greater than the dispersion of the diffusion coefficient within regrowth blackbutt trees. The results of the F test showed that there was also a significant difference in the dispersion of diffusion coefficients between trees of regrowth and plantation blackbutt at a 0.05 significance level (F_{actual}, 2.54 > $F_{expected}$, 2.13). Moreover, the statistical analysis shown in Table 4.6 further supports the suggestion that there was a greater dispersion of diffusion coefficients in plantation blackbutt than the dispersion of diffusion coefficients in regrowth blackbutt. Therefore, the variation of diffusion coefficients possibly affected the variation of final moisture contents in both regrowth and plantation blackbutt timber. These results clearly support the anecdotal evidence that plantation timber has more variability in its timber properties, and specifically in its drying behaviour, than regrowth timber.

Table 4.2. The fitted diffusion parameters for each board in two regrowth blackbutt trees (within—tree variability).

Board ID	**D [$\times 10^{-10}$m^{2}s^{-1}]**
2 A	1.45
2 E	1.42
3 A	1.73
3 E	1.73
4 A	2.86
4 E	2.83
5 A	2.69
5 E	2.03
7 A	1.52
7 E	1.61
9 A	1.72
9 E	2.04
10 A	1.16
10 E	1.14
12 A	1.60
12 E	1.58
18 A	1.77
18 E	1.26
23 A	4.53
23 E	2.68
24 A	1.97
24 E	2.91
28 A	1.66
28 E	1.64
30 A	1.67
30 E	1.64
31 A	1.66
31 E	1.28
32 A	1.37
32 E	1.75
33 A	1.42
33 E	1.57
35 A	1.87
35 E	2.38
36 A	1.37
36 E	1.46

Table 4.3. The diffusion coefficients for 12 regrowth blackbutt trees (between—trees variability).

Board ID	D **[×10^{-10}m^{2}s^{-1}]**
1(S)	1.56
2(P)	1.77
3(S)	1.75
4(P)	1.81
5(P)	1.92
6(S)	1.41
7(P)	2.57
8(S)	1.96
9(S)	1.81
10(P)	1.98
11(S)	2.48
12(P)	2.53
13(S)	1.70
14(P)	2.33
15(S)	1.82
16(P)	2.09
17(P)	2.26
18(S)	1.71
19(S)	1.56
20(P)	1.74
21(P)	2.35
22(S)	1.70
23(S)	2.61
24(P)	2.36

Note: (S) – timber board close to the outer heartwood; (P) – timber board close to the pith.

Table 4.4. The diffusion coefficients for two plantation blackbutt trees (within—tree variability).

Board ID	**D [$\times 10^{-10} m^2 s^{-1}$]**
1A	2.62
1E	2.62
2A	2.52
2E	2.63
3A	2.89
3E	3.17
4A	6.77
4E	6.57
5A	2.41
5E	2.66
6A	2.99
6E	2.33
7A	2.40
7E	1.75
8A	2.20
8E	2.12
9A	1.35
9E	1.76
10A	1.76
10E	1.68
11A	3.33
11E	3.74
12A	2.03
12E	2.92

Table 4.5. The diffusion coefficients for ten plantation blackbutt trees (between—trees variability).

Board ID	***D*** **[$\times 10^{-10}$m^{2}s^{-1}]**
1(S)	1.99
2(P)	2.34
3(S)	1.16
4(P)	1.98
5(P)	1.97
6(S)	2.41
7(S)	1.70
8(P)	2.18
9(S)	1.71
10(P)	2.44
11(P)	1.80
12(S)	2.01
13(S)	1.28
14(P)	3.01
15(S)	1.73
16(P)	3.06
17(S)	1.21
18(P)	1.26
19(S)	1.20
20(P)	2.49

Note: (S) – timber board close to the outer heartwood; (P) – timber board close to the pith.

Table 4.6. Statistical summary of the diffusion coefficients of regrowth and plantation blackbutt timber.

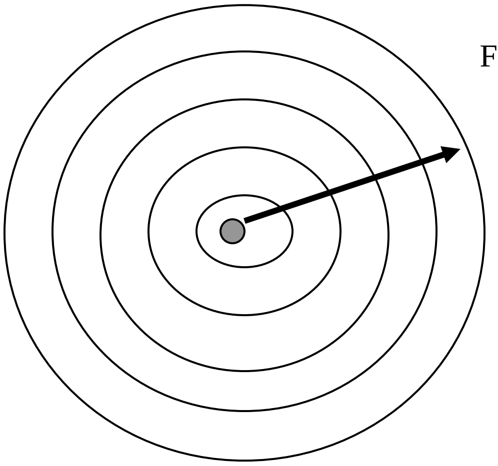
Timber	**Number of Samples**	**Average [$\times 10^{-10}$m^{2}s^{-1}]**	**Standard Deviation [$\times 10^{-10}$m^{2}s^{-1}]**
Regrowth	60	1.91	0.56
Plantation	44	2.41	1.12

The diffusion coefficients for this study ranged between 1.14×10^{-10} and 6.77×10^{-10} m^2s^{-1}, shown in Tables 4.2 to 4.5, and fell within the range reported by Keey *et al*. (2000), i.e. between 10^{-8} and 10^{-10} m^2s^{-1}. Liu and Simpson (1999) also used a numerical approach to calculate diffusion coefficients for their work on northern red oak (*Quercus rubra*). Their diffusion coefficients ranged between 1.26×10^{-10} and 1.70×10^{-10} m^2s^{-1}, falling into the range of values reported by Keey *et al*. (2000). This gives confidence that this numerical approach to fitting diffusion coefficients gave values that are within the range of most previous values.

Fotsing and Tchagang (2004) calculated the diffusion coefficients of frake (*Terminalia superba*) using an analytical solution of a Fickian diffusion model for experiments at three different temperatures and zero relative humidity. Their diffusion coefficients in the radial direction were approximately one order of magnitude less than these values (i.e. between 1.35×10^{-11} m^2s^{-1} at 30^{o}C, 3.70×10^{-11} m^2s^{-1} at 35^{o}C, and 5.37×10^{-11} m^2s^{-1} at 40^{o}C). Similarly, a smaller averaged value (from five boards) of the diffusion coefficient of blackbutt timber (also obtained by numerical fitting) was calculated by Innes and Redman (2003), i.e. 2.64×10^{-11} m^2s^{-1}. The temperatures varied between 23 and 25^{o}C (dry—bulb), and between 21.5 and 20^{o}C (wet—bulb), respectively (Innes and Redman, 2003). Thus, the values in this thesis are higher, i.e. a faster drying rate, since D is dependent on temperature, as previously mentioned, possibly due to the higher temperatures and the varying wet—bulb depressions used throughout these drying experiments in this thesis. Innes and Redman (2003) used low temperatures for drying because the ash—type of eucalypt that they dried is very susceptible to collapse, making the use of low drying temperatures necessary. Despite obtaining values within the same range as those reported by Keey *et al*. (2000), Bao *et al*. (2001) also found that the radial diffusion coefficients for their study of lemon eucalyptus suggested a trend from pith to bark (juvenile to mature wood) that was similar to these values, which showed the same pattern (i.e. diffusion coefficients decreased from pith to bark). The corresponding diffusion coefficients that Bao *et al*. (2001) calculated between juvenile and mature wood for lemon eucalyptus (plantation) were 3.23×10^{-9} m^2s^{-1} and 2.95×10^{-11} m^2s^{-1}, respectively. As a result, the same trend exists for both regrowth and plantation blackbutt material (the timber studied for this work) and the plantation timber studied by Bao *et al*. (2001), despite the different timber species used in this work and that of Bao *et al*. (2001). In addition, plantation blackbutt samples had higher diffusion coefficient values than the regrowth blackbutt samples. This result was also observed by Bao *et al*. (2001) for their work when comparing plantation— and naturally—grown trees. The difference in the diffusion coefficients was possibly due to the variation in the basic densities of regrowth and plantation blackbutt timber, i.e. the basic density of plantation blackbutt was lower than the basic density of regrowth blackbutt, thus affecting the behaviour of the diffusion coefficient for each age class. This aspect will also be further discussed in **Chapters 5** and **6**.

4.3 Within—Tree and Between—Trees Variability (Regrowth Timber Relative to Plantation Timber): Analysis of Variance (ANOVA) of the Diffusion Coefficients, the Initial Moisture Contents, and the Basic Densities

The initial moisture content and the diffusion coefficient decreased from pith to bark, and the basic density increased from pith to bark, for both regrowth timber and plantation timber, as shown in Figure 4.3. The data for the physical and transport properties of both regrowth and plantation blackbutt timber are shown in Appendix 2.



From pith to bark:
1) Initial moisture content
   – decreased;
2) Basic density
   – increased;
3) Diffusion coefficient
   – decreased.

Figure 4.3. Cross—section of the log showing the trends of the initial moisture content, the basic density, and the diffusion coefficient from pith to bark.

Overall, the analysis of variance (ANOVA) for the within—tree test (75% confidence level) showed that radial and circumferential effects, and the interaction between radial and circumferential effects, were significant sources of the within—tree variation for the diffusion coefficients, initial moisture contents and basic density of both regrowth and plantation blackbutt (Tables 4.7 and 4.8). Statistically, these results cannot be stated with a higher confidence level, e.g. 90%, indicating that the effects on their own are not strongly significant at confidence levels greater than 75%. However, the combined effects will be assessed, together with the mechanical properties, in **Chapter 6**, using Principal Components Analysis. The ANOVA was conducted on all the combinations from two to twelve boards (regrowth), and from two to eight boards (plantation), from the full 12 boards and 8 boards (for each log), respectively, used for this ANOVA. The 12 board (times two = 24) and 8 board (times two = 16) cases gave the best estimates of the ANOVA because these cases include the maximum number of boards measured in this study. However, this study also considered what the lowest number of samples that can be used for the ANOVA to represent the final “true” picture, i.e. the ANOVAs of the smallest number of samples that do not change significantly compared with the ANOVA results of the 12 (×2 = 24) and 8 (×2 = 16) board cases. Firstly, ANOVAs were conducted on each and every sub-set of boards that were less than the total number of boards to determine the smallest number of samples that are reasonable for representing the ANOVA results of the full set. For the within—tree variability tests, all sub—samples of eight boards from each regrowth log, and all sub—samples of six boards from each plantation log, were the smallest number of samples, in the sense that both sub-sets gave less than 1% change in the ANOVA statistics compared with the full set. There were 495 combinations of eight boards from the full 12 boards, and 28 combinations of six boards from the full 8 boards. This ANOVA overview procedure was also applied for the ANOVAs of the between—tree tests for the regrowth and plantation blackbutt studies. The ANOVAs were performed on each log separately. Tables 4.7 and 4.8 show the effects that were common to both ANOVAs, assessing within—tree variability.

Table 4.7. Common assessments for the ANOVA of each regrowth blackbutt log

(within—tree variation of logs 685 and 686).

Variation	**Sub-sets of Eight Boards**			**Full Set**		
	Diffusion coefficient, D [m^2s^{-1}]	**Initial moisture content, X_i [$kg\ kg^{-1}$]**	**Basic Density [$kg\ m^{-3}$]**	**Diffusion coefficient, D [m^2s^{-1}]**	**Initial moisture content, X_i [$kg\ kg^{-1}$]**	**Basic Density [$kg\ m^{-3}$]**
	495 combinations of 8 boards from each log. *Total: 16 boards*			*12 boards from each log.* *Total: 24 boards*		
Radial	491	491	491	1	1	1
Circumferential	492	492	492	1	1	1
Height	0	491	491	0	1	1
Radial × Circumferential	491	492	492	1	1	1
Radial × Height	0	0	491	0	0	1
Height × Circumferential	0	492	492	0	1	1

Table 4.8. Common assessments for the ANOVA of each plantation blackbutt log (within—tree variation of logs 7 and 8).

Variation	**Sub-sets of Six Boards**			**Full Set**		
	Diffusion coefficient, D [m^2s^{-1}]	**Initial moisture content, X_i [$kg\ kg^{-1}$]**	**Basic Density [$kg\ m^{-3}$]**	**Diffusion coefficient, D [m^2s^{-1}]**	**Initial moisture content, X_i [$kg\ kg^{-1}$]**	**Basic Density [$kg\ m^{-3}$]**
	28 combinations of 6 boards from each log. *Total: 12 boards*			*8 boards from each log.* *Total: 16 boards*		
Radial	26	26	26	1	1	1
Circumferential	26	26	26	1	1	1
Height	0	26	26	0	1	1
Radial × Circumferential	26	26	26	1	1	1
Radial × Height	0	26	26	0	1	1
Height × Circumferential	0	26	0	0	1	0

There was no difference between the common features of all sub-sets of eight boards and the twelve—board case from each regrowth blackbutt log, and all sub-sets of six boards and the eight—board case for each plantation blackbutt log. This suggests that the sub—samples of eight boards and six boards, from each regrowth blackbutt log and each plantation blackbutt log, respectively, were adequate to obtain a reasonable measure of within—tree variability providing that all sub—sets are considered. Table 4.9 shows how much the results of the other combinations changed compared with the full set (12 boards for the within—tree test of regrowth blackbutt and eight boards for the within—tree test of plantation blackbutt).

Table 4.9. 'Performance degrade' of other combinations compared with the full set for the ANOVA test (all sub—sets considered).

Within—Tree Variability							
Regrowth Blackbutt (Number of Boards per Combination) *(% change compared with the full set)*					**Plantation Blackbutt (Number of Boards per Combination)** *(% change compared with the full set)*		
2	**4**	**6**	**8**	**10**	**2**	**4**	**6**
15%	*2%*	*1%*	*0.8%*	*3%*	*21 %*	*5%*	*0.9%*

The results for the initial moisture contents and basic densities agree with the work of Walker regarding hardwoods (Walker, 1993) (on Yellow Birch, *Betula lutea*; American Beech, *Fagus grandifolia*; and Shining Gum, *Eucalyptus nitens*) and Wimmer's (2000) study on softwoods (Western Hemlock, *Tsuga heterophylla*; Douglas Fir, *Pseudotsuga menziesii*; and Yellow Cypress, *Taxodium distichum*). They observed the same behaviour within a single tree, i.e. initial moisture contents and basic densities varying from pith to bark. In addition, Wimmer (2000) observed an increase in basic density and a decrease in moisture content from pith to bark for softwoods, similar to these results. Walker (1993) also suggested that wood material with low basic density had a high initial moisture content and vice versa, because material with a low basic density has large intercellular spaces for the storage of water. Overall, these results support the previous suggestion that the behaviour of these three parameters changes across the radius of the log.

Furthermore, Tables 4.7 and 4.8 show that height (except for the diffusion coefficient) is a significant source of variation for the basic density and the initial moisture content. However, there was an inconsistent trend between the values of the corresponding boards in the longitudinal direction, in the sense that the density and the initial moisture content of some boards increased up the tree, while the values of the other boards decreased for the within—tree variability tests of both regrowth and plantation blackbutt timber. As a consequence, the vertical variations are insignificant, overall, compared with the radial variations. This result contrasts with what Evans *et al.* (2001), Raymond and Muneri (2001) and Burdon *et al*. (2004) found with their study of *Eucalyptus nitens* (Evans *et al.*, 2001; Raymond and Muneri , 2001), *Eucalyptus globulus* (Raymond and Muneri, 2001) and the species *Eucalyptus* in general (Burdon *et al*., 2004). They found that basic density increased up the stem, the amount of vertical variation was greater than the amount of radial variation (Burdon *et al*., 2004), and basic density initially decreased from the base (between 0—10% of the total height of the tree) and then gradually increased up the tree in a linear manner for both *E. nitens* and *E. globulus* (Raymond and Muneri, 2001). However, these results in this thesis are consistent with the results of Kibblewhite and Riddell (2001) in their study of *E. fastigata*. They observed that there was no evidence of comparable vertical variation in density for *E. fastigata*. Therefore, it is possible that the presence of vertical trends depend on the type of *Eucalyptus* being studied (Kibblewhite and Riddell, 2001).

The results of the ANOVAs for the between—trees tests with regrowth and plantation blackbutt timber are shown in Tables 4.10 and 4.11. 24 boards (for regrowth timber) and 20 boards (for plantation timber) were used for this analysis. Initially, different combinations of two to twenty—two boards (regrowth), and two to eighteen boards (plantation) were studied, and this was followed by the ANOVA of all 24 and 20 boards. The ANOVAs of the smallest number of samples that did not change significantly compared with the ANOVAs of the 24 board (regrowth) and 20 board (plantation) cases where all the sub—samples of four boards and all the sub—samples of six boards were considered, respectively. The ANOVA results of all the sub—samples of the four—board and six—board cases gave less than 1% change in the ANOVA statistics compared with the ANOVA results of the full set. Similar to the ANOVAs conducted on the within—tree tests, sub—samples with a number of boards less than four and six gave ANOVA results that changed by more than 4% compared with the results of the full board cases. Therefore, the number of boards that only gave a small (1%) change in the ANOVA results, compared with the full set, was chosen. Overall, the benefits of using smaller samples are that it potentially requires fewer samples and less time to measure the timber properties and the variability between trees (but not if all combinations or sub-sets have to be considered).

Table 4.10. Effects that were significant for each parameter between trees (12 regrowth blackbutt logs).

Variation	**Sub-sets of Four Boards**			**Full Set**		
	Diffusion coefficient, D $[m^2s^{-1}]$	**Initial moisture content, X_i $[kg\ kg^{-1}]$**	**Basic Density $[kg\ m^{-3}]$**	**Diffusion coefficient, D $[m^2s^{-1}]$**	**Initial moisture content, X_i $[kg\ kg^{-1}]$**	**Basic Density $[kg\ m^{-3}]$**
	10.626 combinations of 4 boards from the full 24 boards.			*1 combination of 24 boards.*		
Radial	10,617	10,617	10,617	1	1	1
Circumferential	10,620	10,620	10,620	1	1	1
Height	0	0	0	0	0	0
Radial × Circumferential	10,617	10,617	10,617	1	1	1
Radial × Height	0	0	0	0	0	0
Height × Circumferential	0	0	0	0	0	0

Table 4.11. Effects that were significant for each parameter between trees (10 plantation blackbutt logs).

Variation	**Sub-sets of Six Boards**			**Full Set**		
	Diffusion coefficient, *D* [m^2s^{-1}]	**Initial moisture content, X_i [$kg\ kg^{-1}$]**	**Basic Density [$kg\ m^{-3}$]**	**Diffusion coefficient, *D* [m^2s^{-1}]**	**Initial moisture content, X_i [$kg\ kg^{-1}$]**	**Basic Density [$kg\ m^{-3}$]**
	38,760 combinations of 6 boards from the full 20 boards.			*1 combination of 20 boards.*		
Radial	38,755	38,755	38,755	1	1	1
Circumferential	38,757	38,757	38,757	1	1	1
Height	0	0	0	0	0	0
Radial × Circumferential	38,755	38,755	38,755	1	1	1
Radial × Height	0	0	0	0	0	0
Height × Circumferential	0	0	0	0	0	0

Tables 4.10 and 4.11 suggest that all sub—samples of four boards from 12 different regrowth blackbutt logs (i.e. two boards from each log), and all sub—samples of six boards from 10 different plantation blackbutt logs (i.e. two boards from each log), were the smallest number of samples that enabled the key effects to be quantified within 1% for the between—trees variability of the physical and transport properties. Similar to the results for within—tree variability, radial and circumferential effects, and the interaction between the radial and circumferential effects, were significant sources of variation between—trees for the initial moisture content, the basic density, and the diffusion coefficient of regrowth and plantation blackbutt. Moreover, Tables 4.7 and 4.8 show that the influence of covering more horizontal and vertical variations in the within—tree test

increased the number of sources of variation compared with the results shown in Tables 4.10 and 4.11 (between—trees test).

Overall, the ANOVA results for both the regrowth and plantation blackbutt material showed that there were similar trends for the initial moisture content, the diffusion coefficient, and the basic density within—trees and between—trees, despite the blackbutt logs being taken from regrowth and plantation sources. In addition, the ANOVA assessments for all the sub-sets of eight and four boards for the within—tree and between—tree tests of regrowth blackbutt, respectively, and all the sub-sets of six boards for both the within—tree and between—tree tests of plantation blackbutt, indicate that the pattern of ANOVA outcomes begins to change significantly when sub-sets of less than the stated number of boards are assessed. Such small sub-sets of six and eight boards might be considered to be unusual as representations of population statistics. However, all combinations of sub-sets were assessed here, so an averaged picture of what is happening with smaller sample sizes is being given. Furthermore, the smaller sample sizes used here to assess the behaviour of the initial moisture content, the basic density, and the diffusion coefficient were also similar to the sample sizes used in previous work. Langrish *et al*. (1997) used four grey ironbark boards from one tree, Alexiou (1993) used four boards from each of three blackbutt trees, and Innes and Redman (2003) used ten blackbutt boards to investigate the behaviour of the diffusion parameters, the initial moisture contents, and the basic densities. Overall, the full set of samples used here was larger than in previous work that did not aim to explore the question of variability so deeply.

4.4 Conclusions

Compensating differences in the diffusion coefficients of the timber boards were a significant reason for the small dispersion of final moisture contents, despite the large variation in initial moisture contents. Moreover, the dispersion of the final moisture contents was greater with the plantation blackbutt timber than with the regrowth blackbutt timber for both within—tree and between—trees variability. There was a significant difference between the diffusion coefficients of the plantation and regrowth blackbutt timber for the within—tree test at a 0.05 significance level. The variation in the diffusion coefficients within a single plantation blackbutt log was higher than the variation in the diffusion coefficients within a regrowth blackbutt log. In addition, there was also a significant difference between the diffusion coefficients of regrowth and plantation blackbutt timber at a 0.05 significance level for between—trees variability. Overall, the quality of the dried regrowth and plantation blackbutt boards in terms of the criterion for the target moisture content fell under Class C according to the Australian/New Zealand Standards.

The initial moisture contents and the diffusion coefficient decreased from pith to bark and basic densities increased in the same direction, within a tree, for both regrowth and plantation blackbutt. However, there was an inconsistent trend within the longitudinal direction for the initial moisture content, the diffusion coefficient, and the basic density along the length of the regrowth and plantation logs, in the sense that there was no consistent increase or decrease along the whole length of the log. Plantation blackbutt samples had higher diffusion coefficients than regrowth blackbutt samples. The difference in the diffusion coefficients was possibly due to the variation in basic densities of regrowth and plantation blackbutt timber, i.e. the basic density of plantation blackbutt was lower than the basic density of regrowth blackbutt, thus affecting the behaviour of the diffusion coefficient for each age class. An analysis of variance (ANOVA) for the within—tree test of regrowth and plantation blackbutt supported many of these observed trends. The ANOVA results showed that radial and circumferential effects, and the interaction between radial and circumferential effects, were significant sources of the within—tree variations for the diffusion coefficient, the initial moisture content and the basic density. Height (except for the diffusion coefficient) was also a significant source of variation for the basic densities and the initial moisture contents but, as has been noted, the vertical variations were small compared with the radial variations. Lastly, radial and circumferential effects and their interaction were also significant sources for the variation of the same properties for the between—trees test of regrowth and plantation blackbutt.

Furthermore, the ANOVA results also indicated that the smaller sized samples used for the analysis (i.e. sub—samples of eight boards for the within—tree test of regrowth blackbutt, sub—samples of four boards for the between—trees test of regrowth blackbutt, sub—samples of six boards for the within—tree test of plantation blackbutt, and sub—samples of six boards for the between—trees test of plantation timber) were sufficient to measure the key effects adequately for the variabilities of the physical and transport properties. There was no significant difference (<1%) between the ANOVA results for these smaller sized samples, considering all combinations, and the ANOVA results for the ‘full’ board cases. Though the sample sizes were unusually small to represent population statistics by most standards, all combinations of the sub-sets were assessed and an averaged picture of the situation with smaller sample sizes was given. Overall, the full sample sizes used here were larger than the sample sizes used by previous work that has also studied the behaviour of the transport and physical properties of hardwood timber.