5. VARIABILITY IN THE MECHANICAL PROPERTIES FOR REGROWTH AND PLANTATION BLACKBUTT TIMBER IN NEW SOUTH WALES AND EVALUATING THE DISTRIBUTION OF THE TIMBER PROPERTIES

5.1 Overview

The variabilities in the mechanical properties for regrowth and plantation blackbutt timber, both in the timber's green and dried states, have been investigated in this chapter. The shrinkage behaviour was measured, since this affects the development of stresses and strains, and the knowledge of the timber's shrinkage properties is required to assess the fractional oversize cutting of the green timber boards at the saw—bench prior to drying (Haque, 2002). Moreover, correlations possibly exist between the mechanical properties, the physical properties and the transport properties (Siau, 1984; Alexiou, 1993; Andrews and Muneri, 2002; Cave and Walker, 1994; Kretschmann and Green, 1996). For example, density is likely to be correlated with both the moisture content and the stiffness of the timber (modulus of elasticity – as a measure of its stiffness). Potential correlations between such parameters may be used to evaluate better drying schedules because they affect the covariance between parameters.

5.2 Measured Trends and Comparisons with Literature

Table 5.1 shows the values for failure stress, failure strain and modulus of elasticity for each regrowth blackbutt board in the within—tree variability test, both in its green and dried state. Appendix 3 shows the mechanical properties for the other regrowth blackbutt boards (between—trees variability) and all the plantation blackbutt boards. It should be noted that the samples with no recorded data are due to being unable to get a 'dog bone' sample from the original boards because either the board had a crack throughout its length in its green state, or severe internal checking developed within the board during drying. Surface checking, end checking and internal checking in each timber board was assessed based on the Australian/New Zealand Standards (AS/NZS 4787, 2001). 90% of the regrowth timber and 90% of the plantation timber fell in the Class C quality for surface checking, where a maximum of 5% of the full length of each timber board was affected by surface checking. Regrowth timber fell in Class B for end checking, since 90% of the regrowth samples had end checks with lengths not exceeding 50 mm, while the end checks in the plantation timber had a maximum of 100 mm in length, thus, fell in Class C quality. Regrowth timber therefore appeared here to have slightly better quality than plantation material when dried with the same drying schedule, as here, in agreement with anecdotal suggestions that plantation material is more difficult to dry well. Lastly, 95% of both the regrowth and the plantation timber fell in Class E quality for internal checking because a maximum of 15% of the cross—section of the samples was affected by internal checking. Overall, along with the assessment that both regrowth and plantation timber was Class C quality for the variation of final moisture contents (**Chapter 4**), these regrowth timber boards and the plantation timber boards fell in the lower quality classes for the criteria of checking and target moisture content for appearance products.

Table 5.1. Failure stress, failure strain, and modulus of elasticity for each board in two regrowth blackbutt trees (within—tree variability).

Board ID	**Green Samples**			**Kiln—Dried Samples**		
	Failure Stress (MPa)	***Failure Strain (mm mm^{-1})***	***MOE (MPa)***	***Failure Stress (MPa)***	***Failure Strain (mm mm^{-1})***	***MOE (MPa)***
2A	7.43	0.0069	1077	10.00	0.0055	1818
2E	8.45	0.0086	983	6.88	0.0028	2457
3A	5.20	0.0095	547	7.41	0.0048	1544
3E	4.75	0.0058	819			
4A	3.72	0.0163	228			
4E	4.28	0.0214	200			
5A	3.85	0.0087	443			
5E	4.40	0.0097	454	5.83	0.0036	1619
7A						
7E	2.68	0.0065	412	1.32	0.0032	413
9A	6.41	0.0086	745			
9E	3.89	0.0077	505	3.85	0.0049	786
10A	6.92	0.0107	647	6.96	0.0026	2677
10E	8.60	0.0097	887	8.96	0.0040	2240
12A	7.08	0.0091	778	10.23	0.0056	1827
12E	6.58	0.0082	802	10.40	0.0083	1253
18A	6.30	0.0104	606	6.48	0.0044	1473
18E	6.25	0.0084	744	7.20	0.0055	1309
23 A						
23 E	5.05	0.0091	555			
24 A	8.40	0.0101	832	5.73	0.0047	1219
24 E	8.57	0.0068	1260	7.96	0.0073	1090*
28A	6.85	0.0090	761	9.37	0.0053	1768
28E	7.00	0.0114	614	7.64	0.0054	1415
30A	11.00	0.0062	1774	5.74	0.0067	857
30E	6.60	0.0056	1179	6.66	0.0039	1708
31A	6.19	0.0062	998	7.50	0.0050	1500
31E	6.76	0.0134	504			
32 A	14.87	0.010	1487			
32 E	12.25	0.014	875	8.27	0.0041	2017
33A	8.99	0.0052	1729	5.42	0.0028	1936
33E	7.35	0.0045	1633	8.25	0.0040	2063
35A	7.28	0.0111	656	2.23	0.0017	1312
35E						
36A	11.45	0.0074	1547	4.13	0.0024	1721
36E	10.11	0.0064	1580	11.90	0.0056	2125

A least squares technique was used to fit the modulus of elasticity (MOE). A single straight line is a reasonable representation of the behaviour of the overall stresses and strains in the best possible way (Haque, 2002). Figure 5.1 is a typical non—linear curve fitted with a straight line for all timber boards.

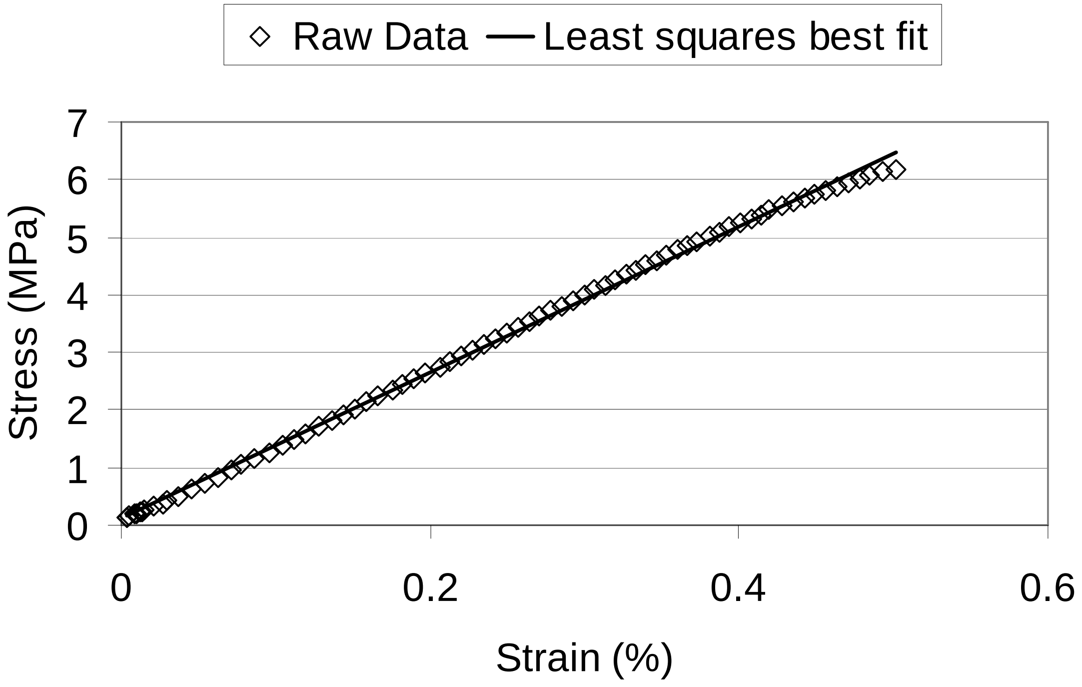

Figure 5.1. Stress as a function of strain for plantation board 4C in its kiln-dried state. This is a typical non—linear curve, fitted with a straight line, for all regrowth timber and plantation timber (green and kiln—dried states).

These curves were obtained from the tests carried out on an INSTRON 5567 machine as described in **Chapter 3** in this thesis, and then Young’s equation was applied:

$$E = \frac{\sigma}{\varepsilon} \tag{5.1}$$

The modulus of elasticity was calculated using the ratio of stress to strain at the last point of the straight line on the graph. The values for regrowth blackbutt timber, both within—trees and between—trees, are close to the values reported by Alexiou (1993) and Haque (2002) shown in Table 2.2 for blackbutt timber. In addition, Table 5.1 and Appendix 3 show that the kiln—dried values of the three parameters obtained for this work were similar to the values of the same parameters for regrowth blackbutt timber, at 14% moisture content, reported by Alexiou (1993) in Table 2.2.

In general, MOE increased significantly from the timber's green state to its kiln—dried state (Alexiou, 1993; Keey *et al*., 2000). This agrees with the experience that, as moisture is lost from a board up to its kiln—dried state, the MOE of the timber is expected to increase due to the influence of bound water on the stiffness for the timber structure (Mills, 1991; Oliver, 1991; Keey *et al*., 2000; Ilic, 2001). Moisture becomes more strongly bound to the cell walls when moisture contents fall below the fibre saturation point (around 0.3 kg water/kg dry material), meaning that the drying rate decreases (Keey *et al*., 2000). At the same time, though the timber becomes stronger when dried, it fails at a smaller ultimate strain because the plasticising effect of moisture in the cell walls diminishes as moisture is lost. The obtained failure strains and modulus of elasticity values for the timber boards (Tables 5.1 and A3.1 to A3.3), both in their green and dried states, support this expectation. On closer inspection, the MOEs (both green and kiln—dried states) of the plantation blackbutt were lower compared with the MOEs of the regrowth blackbutt. This result supports the work of Bao *et al*. (2001) when they compared the mechanical properties of plantation—grown material with the mechanical properties of naturally—grown material. A number of factors may have contributed to this observation. Walker (1993) reported that narrow, uniform growth rings, and high density outerwood (which possibly makes the timber stronger) makes old growth or regrowth timber ideal for timber drying companies. On the other hand, plantation timber has a high proportion of corewood/juvenile wood and a lower mean basic density (Walker, 1993). In this study, the basic density of regrowth blackbutt was higher than the basic density of plantation blackbutt. Since juvenile wood or corewood is lower in quality compared with mature wood or outerwood, Bao *et al*. (2001) suggested that the mechanical properties of plantation timber could be improved through a longer rotation age or a reduced juvenile wood content.

Tables A3.4 to A3.7 in Appendix 3 show the raw data for the respective tangential, radial, and differential shrinkage (tangential shrinkage/radial shrinkage) values for each board from the regrowth and plantation logs (from green to 12% moisture content). Table A3.4 also shows the measured predicted longitudinal modulus of elasticity (using acoustic methods) of the original 4.8m boards for the within—tree test of regrowth blackbutt timber. The samples with no recorded data are due to the original board/s being mixed sawn, where it is not possible to accurately measure radial and tangential shrinkage on these types of samples.

The shrinkage in the tangential direction was approximately twice the amount of radial shrinkage. Hence, these results support the reports by Siau (1984) and Oliver (1991), which found that tangential shrinkage is from 1.5 to two times the radial shrinkage

(Tables A3.4 to A3.7) in most woods. Similarly, other reports have shown that the tangential shrinkage in wood is greater than the radial shrinkage by a factor between 1.5 and 3.0 (Bodig and Jayne, 1993) and between 1.5 and 2.5 (Keey *et al*., 2000). The range of the measured radial shrinkage values, 0.024 – 0.094 mm mm^{-1} for regrowth blackbutt and 0.037 – 0.125 mm mm^{-1} for plantation blackbutt, is consistent with Oliver's (1991) report that the typical radial shrinkage is about 0.04 mm mm^{-1} for eucalypt materials. The higher shrinkage values (possibly due to the high juvenile wood content and low basic density) for plantation blackbutt timber potentially contributed to the instability of plantation material. In addition, these differential (tangential:radial) shrinkage values ranged from 1.12 – 2.93 for regrowth blackbutt and 1.09 – 2.92 for plantation blackbutt, which are close to the range (1.23—2.51) reported by Bao *et al*. (2001) for his study of plantation lemon eucalyptus, lankao paulownia, and sanbei poplar. Bao *et al*.'s (2001) values were also calculated without any reconditioning. Poku *et al*. (2001) also found, with their work on *Petersianthus macrocarpus* (a tropical hardwood species from Ghana), that the differential shrinkage of *Petersianthus macrocarpus* was approximately 1.7, which is within the range of values reported in this study. Moreover, a visual inspection during the shrinkage experiments showed that only five plantation samples, which were taken close to the pith, had some collapse (i.e. shrinkage above fibre saturation point due to the cell walls being pulled inwards during drying). This result possibly supports the finding that the dimensions of plantation blackbutt are less stable. The minute evidence of collapse in blackbutt timber supports the report from the Queensland Department of Primary Industries and Fisheries (2006) that there is a slight tendency for blackbutt samples near the pith to collapse. However, collapse can also result in the formation of internal checks in eucalypt timber, which usually first appear in the collapsing of the earlywood band (Innes, 1996). Furthermore, collapse can be another complication with timbers having thin cell walls and hence, sometimes, lower basic densities (Keey *et al*., 2000). Since the collapse of the cell walls causes a more complex path for the diffusion of moisture, such timber samples possibly have lower diffusivities due to higher resistance to diffusion. This feature will be discussed in **Chapter 6**. Overall, collapse shrinkage needs to be further investigated specifically for blackbutt samples in future work.

5.3 Within—Tree and Between—Trees Variability (Regrowth Timber compared with Plantation Timber): Analysis of Variance (ANOVA) of the Mechanical Properties

Figure 5.2 shows that the regrowth and the plantation boards close to the pith or at the pith had lower MOEs than the boards closer to the bark. Like the basic density from **Chapter 4**, MOE increases from pith to bark.

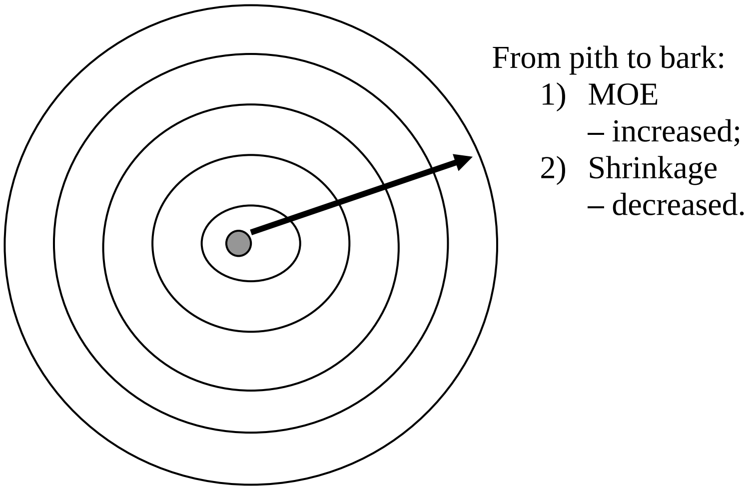

Figure 5.2. Cross—section of the log showing the trends of the modulus of elasticity and the shrinkage from pith to bark.

The data show a possible correlation between these two parameters, since density is a measure of the mass of wood material present in a given volume of timber (Cave and Walker, 1994). This finding agrees with what Alexiou (1993) found in his study of blackbutt. However, the use of density to predict timber’s stiffness and strength can be misleading at times, since various timbers of the same density can have a wide range of mechanical properties due to different grain lengths and microfibril angles (Cave and Walker, 1994). A better single indicator of stiffness and strength in wood than the density has been suggested to be the microfibril angle (Evans and Ilic, 2001).

These results are also consistent with the literature (Lichtenegger *et al.*, 1999) regarding the likely effect of microfibril angle on mechanical properties. It has been shown (Cave and Walker, 1994; Cave, 1996; Reiterer *et al.*, 1999) that microfibril angle is an important factor for predicting the mechanical properties of wood. Wood with low strength and stiffness has a large angle, while a small angle corresponds to wood of high strength and stiffness. From pith to bark, the microfibril angle decreases (Lichtenegger *et al*., 1999). Tables 5.2 and 5.3 show that the radial direction appears to be one of the dominant sources of variation for most mechanical properties of regrowth and plantation blackbutt timber. Therefore, this result is a good indication that density and most likely the microfibril angle are the sources of these variations, since both parameters vary in the radial direction.

Radial variations were also evident with basic density (**Chapter 4**), diffusion coefficient (**Chapter 4**), and shrinkage. From pith to bark, the diffusion coefficient and shrinkage decreased (shown in Figure 5.2), while the basic density increased. Similarly, the diffusion coefficient and shrinkage values were higher, and the basic density was lower for plantation blackbutt, while regrowth blackbutt had lower diffusion coefficients, and shrinkage values and higher basic densities. It is possible that timber with high diffusion coefficients means that more moisture is lost because there is less wood (i.e. low basic density) to resist moisture transport, and hence the timber is likely to experience more shrinkage. Shupe *et al*. (1995a) also observed a general increase in shrinkage and decrease in basic density from bark to pith for two yellow—poplar trees. However, these findings are in contrast with the suggestions of Poku *et al*. (2001) and Shupe *et al*. (1995b) for *Petersianthus macrocarpus* and a single cottonwood tree, respectively, that shrinkage increases with increasing density. However, diffusion coefficients were not given by Poku *et al*. (2001) and Shupe *et al*. (1995a; 1995b) because they did not study transport processes in the timber. Bao *et al*. (2001), on the other hand, calculated the diffusion coefficients and observed that, as the diffusion coefficient decreased from pith to bark, the radial and tangential shrinkages increased for lemon eucalyptus, which is the reverse of these findings. This variation in trends from pith to bark between shrinkage, basic density, and diffusion coefficient may be the result of different hardwood species being studied, since different timber properties appear to behave differently with different species from the above review.

Tables 5.2 and 5.3 show the sources of variation common to the ANOVAs of each log for the within—tree variability of the mechanical properties, using eight boards from each regrowth log and six boards from each plantation log. To further support the previously mentioned trends, the ANOVA showed that the main variabilities for most of the mechanical properties are in the circumferential and radial directions. Tables 5.2 and 5.3 also present the results when 12 boards from each regrowth log and 8 boards from each plantation log were used in the ANOVA. The results from these ANOVAs further emphasise that the radial and circumferential directions are likely to be the sources of variation for most of the parameters, and that the longitudinal direction (height variation) also contributes to the variability of the mechanical properties within—trees. It should be pointed out that there is a possible correlation between the diffusion coefficient and mechanical properties, such as the modulus of elasticity. No reports have stated a link between the two properties. If such a correlation exists, then it is beneficial for timber drying companies to evaluate important drying properties, prior to drying, by simply measuring the basic density, or by using acoustic methods that are presently being utilized by such companies to measure the longitudinal MOE and then relate it to the cross grain MOE, the diffusion coefficient, and other parameters. Such a simple correlation is most likely to be applicable to species that are not highly susceptible to collapse, since the variability associated with collapse may be difficult to assess in such a simple way. Tables 5.2 and 5.3 also suggest that all sub—samples of eight boards for each regrowth log and all sub—samples of six boards for each plantation log are adequately—sized statistical samples to represent the population behaviour in terms of the analysis of variance for the mechanical properties, because all sub—samples of the eight—board and six—board cases gave less than 1% change in the ANOVA statistics compared with the ANOVA results of the full set. Subsets with a number of samples smaller than eight boards and six boards for regrowth and plantation blackbutt analysis, respectively, resulted in a more than 4% deviation from the full—board case.

Table 5.2. Common assessments for the ANOVA of each regrowth blackbutt log (within—tree variation of logs 685 and 686).

Variation	**Subsets of Eight Boards**						**Full Set**					
	Tangential Shrinkage [%]	**Radial Shrinkage [%]**	**Differential Shrinkage [%]**	**Green Samples**			**Tangential Shrinkage [%]**	**Radial Shrinkage [%]**	**Differential Shrinkage [%]**	**Green Samples**		
				Failure Stress (MPa)	***Failure Strain (mm/mm)***	***MOE (MPa)***				***Failure Stress (MPa)***	***Failure Strain (mm/mm)***	***MOE (MPa)***
	495 combinations of 8 boards from each log. Total: 16 boards						*12 boards from each log. Total: 24 boards*					
Radial	491	491	0	491	491	491	1	1	0	1	1	1
Circumferential	0	0	492	492	492	491	0	0	1	1	1	1
Height	0	491	491	0	0	0	0	1	1	0	0	0
Radial × Circumferential	0	1	491	1	492	492	0	0	1	0	1	1
Radial × Height	491	491	491	0	0	491	1	1	1	0	0	1
Height × Circumferential	491	491	492	1	0	492	1	1	1	0	0	1

Table 5.3. Common assessments for the ANOVA of each plantation blackbutt log (within—tree variation of logs 7 and 8).

Variation	**Subsets of Six Boards**						**Full Set**					
	Tangential Shrinkage [%]	**Radial Shrinkage [%]**	**Differential Shrinkage [%]**	**Green Samples**			**Tangential Shrinkage [%]**	**Radial Shrinkage [%]**	**Differential Shrinkage [%]**	**Green Samples**		
				Failure Stress (MPa)	***Failure Strain (mm/mm)***	***MOE (MPa)***				***Failure Stress (MPa)***	***Failure Strain (mm/mm)***	***MOE (MPa)***
	28 combinations of 6 boards from each log. Total: 12 boards						*8 boards from each log. Total: 16 boards*					
Radial	26	26	26	26	26	26	1	1	1	1	1	1
Circumferential	26	26	26	26	26	26	1	1	1	1	1	1
Height	26	0	26	26	26	26	1	0	1	1	1	1
Radial × Circumferential	26	26	26	26	26	26	1	1	1	1	1	1
Radial × Height	0	0	26	26	26	26	0	0	1	1	1	1
Height × Circumferential	0	26	26	0	0	0	0	1	1	0	0	0

Following the same procedure as the ANOVA in **Chapter 4.3**, the results of the ANOVA for the between—trees tests for regrowth and plantation blackbutt timber are shown in Tables 5.4 and 5.5. Different combinations of two to twenty—two boards and two to eighteen boards were studied for regrowth and plantation blackbutt, respectively. This was followed by the ANOVA of all 24 and 20 boards. Similar to the results of the within—tree test, radial and circumferential effects and the interaction between the two effects proved to be significant sources of variation between—trees, despite the logs being plantation or regrowth material. The ANOVA results support the previously-mentioned trend that the radial variation affects the outcome of the ANOVA for the mechanical properties even between trees. In addition, the use of four and six boards for regrowth and plantation timber in the ANOVA, respectively, was enough to describe the behaviour of the mechanical properties of the overall population, provided that all sub—sets are considered. These smaller sized samples are unusually small statistical representations of the "true" picture, similar to the ANOVA study in **Chapter 4**. However, all combinations of four and six boards were assessed, so this result may be less surprising. Moreover, previous work on the study of the behaviour of mechanical properties also used sample sizes similar to this work. Evans *et al*. (2000) studied six red alder trees for their study of MOE and specific gravity, Innes and Redman (2003) used ten boards for their work on the behaviour of unconfined shrinkage for blackbutt, and lastly, Langrish *et al*. (1997) used four boards from one grey ironbark tree to evaluate the mechanical properties.

Table 5.4. Effects that were significant for each parameter between trees (12 regrowth blackbutt logs).

Variation	**Subsets of Four Boards**						**Full Set**					
	Tangential Shrinkage [%]	**Radial Shrinkage [%]**	**Differential Shrinkage [%]**	**Green Samples**			**Tangential Shrinkage [%]**	**Radial Shrinkage [%]**	**Differential Shrinkage [%]**	**Green Samples**		
				Failure Stress (MPa)	***Failure Strain (mm/mm)***	***MOE (MPa)***				***Failure Stress (MPa)***	***Failure Strain (mm/mm)***	***MOE (MPa)***
	10.626 combinations of 4 boards from the full 24 boards.						*1 combination of 24 boards.*					
Radial	10,617	10,617	10,617	10,617	10,617	10,617	1	1	1	1	1	1
Circumferential	10,620	10,620	10,620	10,620	10,620	10,620	1	1	1	1	1	1
Height	0	0	0	0	0	0	0	0	0	0	0	0
Radial × Circumferential	10,617	10,617	10,617	10,617	10,617	10,617	1	1	1	1	1	1
Radial × Height	0	0	0	0	0	0	0	0	0	0	0	0
Height × Circumferential	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.5. Effects that were significant for each parameter between trees (10 plantation blackbutt logs).

Variation	**Subsets of Six Boards**						**Full Set**					
	Tangential Shrinkage [%]	**Radial Shrinkage [%]**	**Differential Shrinkage [%]**	**Green Samples**			**Tangential Shrinkage [%]**	**Radial Shrinkage [%]**	**Differential Shrinkage [%]**	**Green Samples**		
				Failure Stress (MPa)	***Failure Strain (mm/mm)***	***MOE (MPa)***				***Failure Stress (MPa)***	***Failure Strain (mm/mm)***	***MOE (MPa)***
	38,760 combinations of 6 boards from the full 20 boards.						*1 combination of 20 boards.*					
Radial	38,755	38,755	38,755	38,755	38,755	38,755	1	1	1	1	1	1
Circumferential	38,757	38,757	38,757	38,757	38,757	38,757	1	1	1	1	1	1
Height	0	0	0	0	0	0	0	0	0	0	0	0
Radial × Circumferential	38,755	38,755	38,755	38,755	38,755	38,755	1	1	1	1	1	1
Radial × Height	0	0	0	0	0	0	0	0	0	0	0	0
Height × Circumferential	0	0	0	0	0	0	0	0	0	0	0	0

5.4 Evaluating the Distribution of the Physical, Transport and Mechanical Properties

Normality tests were conducted to determine the degree of statistical normality for the distribution of each property (physical, transport, and mechanical). The purpose of testing the degree of normality for the data is that, if the sample data have a normal distribution, the mean and the standard deviation of the data may be used to represent many properties of the distribution, particularly the sampling of the population behaviour that may be required in the optimizing of the drying schedules. This was followed by tests of significance to determine if there was a significant difference between the within—tree and between—tree variability of both the regrowth and plantation blackbutt timber.

The *W* tests for normality, and a graphical approach, plotting probability density functions, were applied for each timber property. For the parameters that did not exhibit a normal distribution, three—parameter lognormal and Weibull methods, as described in the work of Ristea and Maness (2005), were assessed as representations of their distributions.

5.4.1 W Test for Normality

A test for normality was conducted that was based on analysis of variance, the *W* test (Shapiro and Wilk, 1965), for the measured timber properties. This test for normality uses a test statistic, *W*, that is obtained by dividing the square of an appropriate linear combination of the sample order statistics by the usual symmetric estimate of variance.

The procedure for the *W* test employed in this work is that described by Shapiro and Wilk (1965).

5.4.2 Probability Density Functions

The construction of probability density functions involves grouping the data for each timber property into “bins” that represent a particular range for that specific timber property. Once each data point is allocated to the appropriate “bin”, the experimental probability density function for each property is plotted using Equation (5.2):

$$pdf(x) = \frac{Number\ in\ bin(x)}{Total\ \ Number} \tag{5.2}$$

Here x represents a data point for the timber property, *Number in bin(x)* is the number of occurrences of data points within that “bin” range, and the *Total Number* is the total number of data points for the timber property under consideration. The total area integrated under a probability density function is equal to unity (Spiegel and Stephens, 1999). Afterwards, the normal probability density and the log normal probability density functions were also plotted for each timber property using Equations (5.3) and (5.4), respectively. The rationale for this approach was to graphically compare if the experimental data fitted a normal distribution or a log normal distribution more closely.

$$normpdf(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \tag{5.3}$$

$$\log normpdf(x) = \frac{1}{xs\sqrt{2\pi}\exp}\left[-\frac{(\ln(x)-m)^2}{2s^2}\right] \quad (5.4)$$

Here μ is the mean of all x, σ is the standard deviation of all x, m is the mean of all ln(x), and s is the standard deviation of all ln(x).

5.4.3 Three—Parameter Lognormal Distribution

For each timber property that did not exhibit a normal distribution, the construction of a three—parameter lognormal plot was considered. Though the lognormal probability density function (that has a scale μ, shape σ, and a lower bound of zero) was already plotted alongside the experimental probability density function (as mentioned in the previous section) to give a tentative view of the distribution of the data being analysed, a third parameter, a threshold (θ), needs to be considered. This is due to the suggestion that the timber moisture content has a positive lower bound (Ristea and Maness, 2005). Ristea and Maness (2005) indicated that the threshold parameter should be subtracted from all the data in order to obtain a straight line, and ignoring such a step may lead to incorrect conclusions regarding the distribution of the moisture content. In this work, the construction of the three—parameter lognormal plots was based on the method described by Ristea and Maness (2005).

5.4.4 Weibull Distributions

The Weibull analysis was also assessed to determine if any of the measured timber properties was best fitted by this distribution. It is similar to the three—parameter lognormal distribution in the sense that a threshold value must be considered. Applying this method is a way of testing the likelihood of the hypothesis by Kayihan (1993) that initial moisture contents usually follow a Weibull distribution. The procedure for the Weibull probability analysis used in this work is described in detail by Ristea and Maness (2005).

5.4.5 Results of the W Test and the Distribution Plots

The distributions of most timber properties, within and between trees, of both regrowth and plantation blackbutt, were normally distributed, based on the W test (Tables 5.6 to 5.9). It should be noted that GS refers to the 'green sample' while 'DS' refers to the dried sample, and '*(ln)' was used when the logarithms of the data were analysed for the W tests. The probability density plots also supported this finding of normality for most properties. For example, on a visual inspection, the failure stresses of both the green and kiln—dried samples for within and between—tree variabilities of regrowth blackbutt appeared to fit a normal distribution better than a log normal distribution (Figures 5.3 to 5.6). The other timber properties with normal distributions from the W test had similar distribution plots (shown in Appendices 4 and 5).

Table 5.6. Results for the distribution of each timber property, tested for normality using the *W* test (regrowth blackbutt: within—tree variability).

Parameter	Observations (n)	W_{actual}	$W_{expected}$	Normal/ Non-normal	Level (%)	Confidence (%)
Initial Moisture Content	36	0.914	0.912	Normal	1	99
Basic Density	36	0.934	0.922	Normal	2	98
Diffusion Coefficient	36	0.780	0.912	Non-normal	<1	99
Diffusion Coefficient *(ln)	36	0.906	0.912	Non-normal	<1	99
Failure Stress (GS)	33	0.944	0.942	Normal	10	90
Failure Strain (GS)	33	0.870	0.906	Non-normal	<1	99
Failure Strain (GS) *(ln)	33	0.977	0.968	Normal	50	50
MOE (GS)	33	0.921	0.917	Normal	2	98
Failure Stress (DS)	25	0.978	0.964	Normal	50	50
Failure Strain (DS)	25	0.975	0.964	Normal	50	50
MOE (DS)	25	0.993	0.989	Normal	99	1
Tangential Shrinkage	33	0.939	0.931	Normal	5	95
Radial Shrinkage	33	0.912	0.906	Normal	1	99
Differential Shrinkage	33	0.950	0.942	Normal	10	90

Table 5.7. Results for the distribution of each timber property, tested for normality using the *W* test (regrowth blackbutt: between—trees variability).

Parameter	**Observations (n)**	**W_{actual}**	**$W_{expected}$**	**Normal/ Non-normal**	**Level (%)**	**Confidence (%)**
Initial Moisture Content	24	0.882	0.884	Non-normal	<1	99
Initial Moisture Content	24	0.911	0.898	Normal	2	98
Basic Density	24	0.919	0.916	Normal	5	95
Diffusion Coefficient	24	0.923	0.916	Normal	5	95
Diffusion Coefficient *(ln)	24	0.940	0.930	Normal	10	90
Failure Stress (GS)	24	0.968	0.963	Normal	50	50
Failure Strain (GS)	24	0.942	0.30	Normal	10	90
MOE (GS)	24	0.968	0.963	Normal	50	50
Failure Stress (DS)	19	0.960	0.957	Normal	50	50
Failure Strain (DS)	19	0.829	0.863	Non-normal	<1	99
Failure Strain (DS) *(ln)	19	0.948	0.917	Normal	10	90
MOE (DS)	19	0.941	0.917	Normal	10	90
Tangential Shrinkage	24	0.911	0.898	Normal	2	98
Radial Shrinkage	24	0.936	0.930	Normal	10	90
Differential Shrinkage	24	0.979	0.963	Normal	50	50

Table 5.8. Results for the distribution of each timber property, tested for normality using the *W* test (plantation blackbutt: within—tree variability).

Parameter	Observations (n)	W_{actual}	$W_{expected}$	Normal/ Non—normal	Level (%)	Confidence (%)
Initial Moisture Content	24	0.861	0.884	Non—normal	<1	99
Initial Moisture Content *(ln)	24	0.930	0.916	Normal	5	95
Basic Density	24	0.889	0.884	Normal	1	99
Diffusion Coefficient	24	0.735	0.884	Non—Normal	<1	99
Diffusion Coefficient *(ln)	24	0.907	0.884	Normal	2	98
Failure Stress (GS)	24	0.922	0.916	Normal	5	95
Failure Strain (GS)	24	0.870	0.884	Non—Normal	<1	99
Failure Strain (GS)*(ln)	24	0.953	0.930	Normal	10	90
MOE (GS)	24	0.965	0.963	Normal	50	50
Failure Stress (DS)	20	0.978	0.959	Normal	50	50
Failure Strain (DS)	20	0.912	0.905	Normal	5	95
MOE (DS)	20	0.946	0.920	Normal	10	90
Tangential Shrinkage	23	0.886	0.881	Normal	1	99
Radial Shrinkage	23	0.785	0.881	Non—Normal	<1	99
Radial Shrinkage *(ln)	23	0.907	0.895	Normal	2	98
Differential Shrinkage	23	0.952	0.928	Normal	10	90

Table 5.9. Results for the distribution of each timber property, tested for normality using the *W* test (plantation blackbutt: between—trees variability).

Parameter	Observations (n)	W_{actual}	$W_{expected}$	Normal/ Non—normal	Level (%)	Confidence (%)
Initial Moisture Content	20	0.884	0.868	Normal	1	99
Basic Density	20	0.970	0.959	Normal	50	50
Diffusion Coefficient	20	0.940	0.920	Normal	10	90
Failure Stress (GS)	20	0.972	0.959	Normal	50	50
Failure Strain (GS)	20	0.905	0.884	Normal	2	98
MOE (GS)	20	0.978	0.959	Normal	50	50
Failure Stress (DS)	14	0.858	0.846	Normal	2	98
Failure Strain (DS)	14	0.942	0.895	Normal	10	90
MOE (DS)	14	0.918	0.895	Normal	10	90
Tangential Shrinkage	20	0.797	0.868	Non—Normal	<1	99
Tangential Shrinkage *(ln)	20	0.907	0.905	Normal	5	95
Radial Shrinkage	20	0.892	0.884	Normal	2	98
Differential Shrinkage	20	0.830	0.868	Non—Normal	<1	99
Differential Shrinkage *(ln)	20	0.927	0.920	Normal	10	90

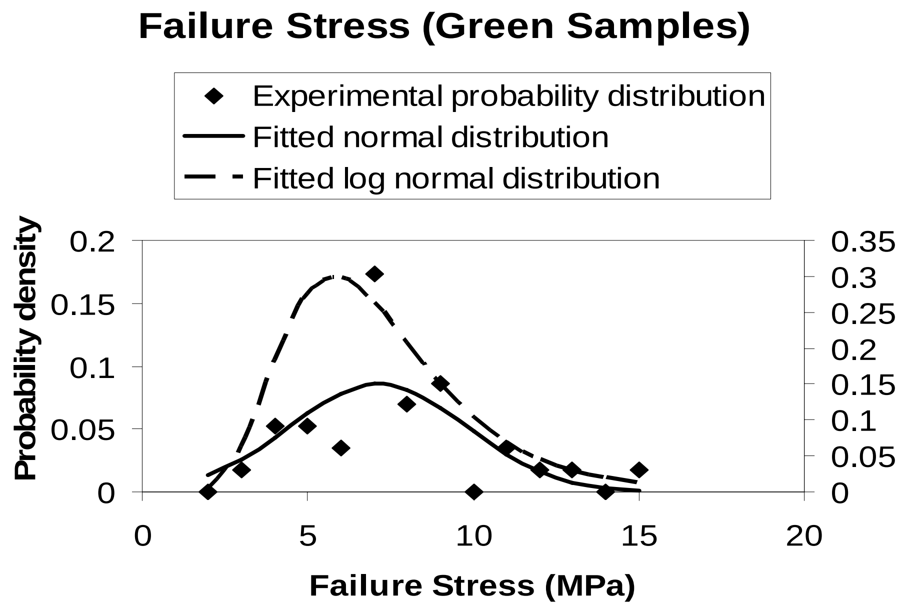

Figure 5.3. Probability density functions of the green failure stress for within—tree variability of regrowth blackbutt.

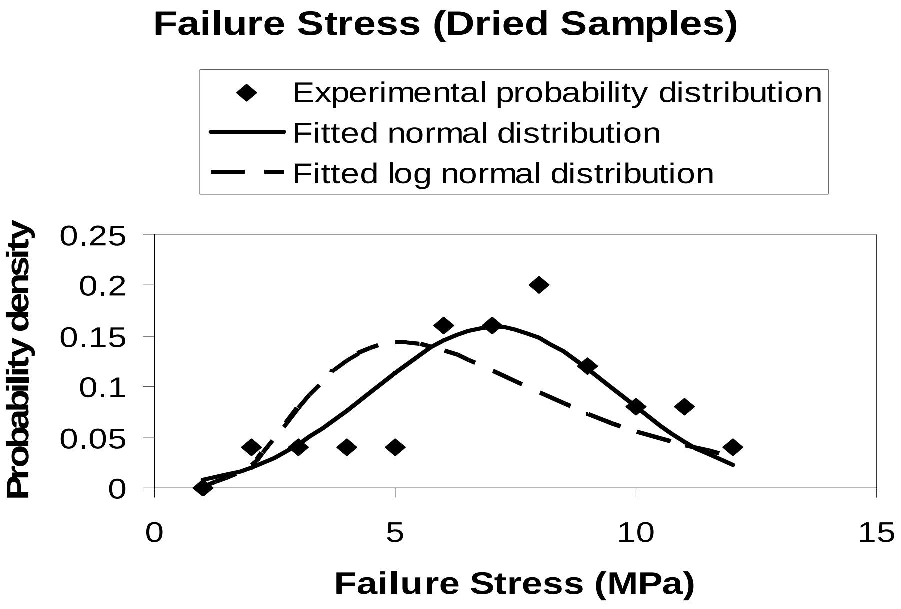

Figure 5.4. Probability density functions of the dried failure stress for within—tree variability of regrowth blackbutt.

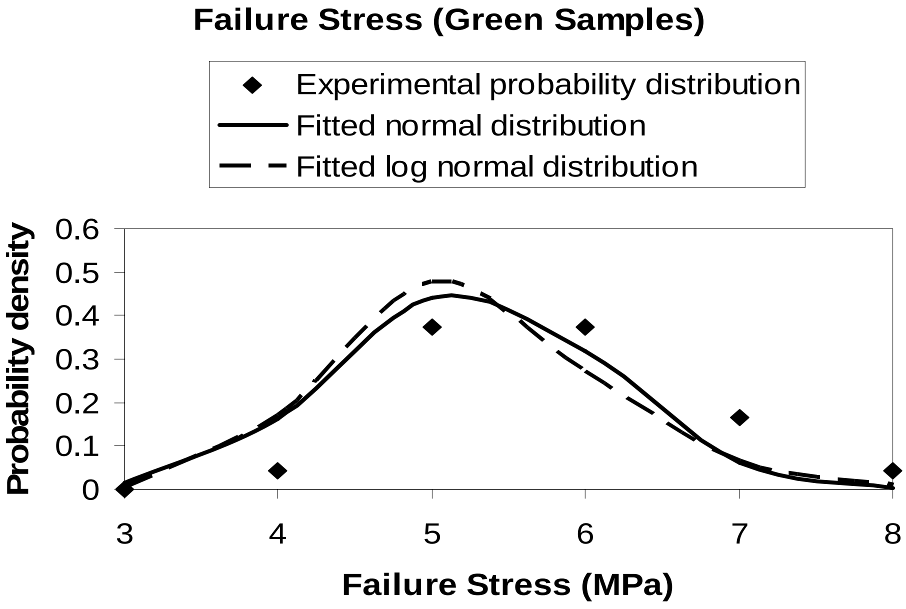

Figure 5.5. Probability density functions of the green failure stress for between—trees variability of regrowth blackbutt.

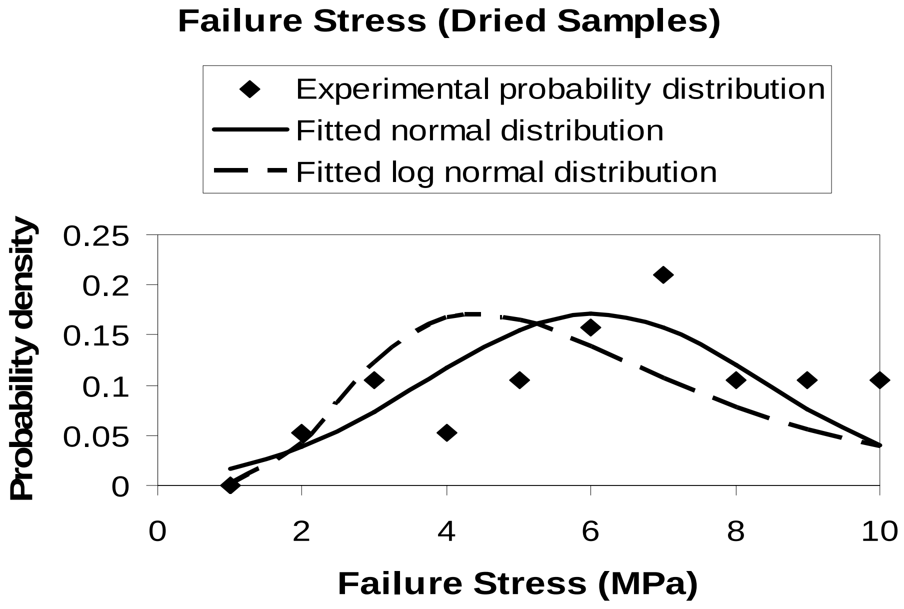

Figure 5.6. Probability density functions of the dried failure stress for between—trees variability of regrowth blackbutt.

Table 5.10. Timber properties with non—normal distributions based on the *W* test for normality.

Variability Test	**Timber Property with a Non-normal Distribution based on the *W* Test**
Within—Tree: Regrowth Blackbutt Timber	Diffusion Coefficient, Green Failure Strain
Between—Trees: Regrowth Blackbutt Timber	Initial Moisture Content, Dried Failure Strain
Within—Tree: Plantation Blackbutt Timber	Initial Moisture Content, Diffusion Coefficient, Green Failure Strain, Radial Shrinkage
Between—Trees: Plantation Blackbutt Timber	Tangential and Differential Shrinkage

Table 5.10 shows the timber properties that resulted in non—normal distributions with the *W* test. The timber properties listed in Table 5.10 showed a better fit to the three—parameter log normal distribution compared with the Weibull distribution. Figures 5.7 and 5.8 are typical plots that show this observation for the distribution of the diffusion coefficients of regrowth timber within trees. Figure 5.7 shows that the distribution of the diffusion coefficient follows a straight line using the three—parameter log normal model, suggesting that it is a good model to represent the distribution of the diffusion coefficients. The Weibull distribution (shown in Figure 5.8), on the other hand, shows a greater departure from a straight line. Moreover, the R^2 value for each model was calculated using Equations (5.5) to (5.7) to further emphasise the degree to which each model explained the actual variation in the data (Pangloss, 2003).

$$SSR = \sum_{i=1}^{n} (z_{curve_i} - \bar{z})^2 \tag{5.5}$$

$$SST = \sum_{i=1}^{n} (z_i - \bar{z})^2 \tag{5.6}$$

$$R^2 = \frac{SSR}{SST} \tag{5.7}$$

Here SSR means the sums of squares (regression), SST is the total sum of squares, $\bar{z}$ is the mean of all the experimental data points, z_i are the experimental data points, and z_{curve} are the data points on the fitted line/curve. The R^2 value of the three—parameter lognormal model was 0.99 compared with the R^2 value of 0.61 for the Weibull distribution. Based on these R^2 values, the three—parameter log normal distribution appears to give a better fit for the diffusion coefficient data than a Weibull distribution. The other three—parameter log normal distribution and Weibull plots are shown in Appendices 4 and 5.

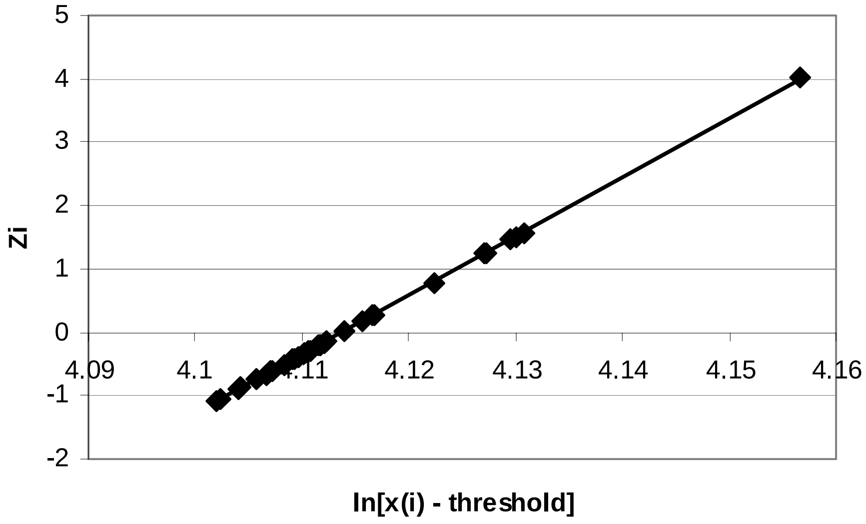

Figure 5.7. Three—parameter lognormal probability (considering the threshold) plot for the diffusion coefficient data, for within—tree variability of regrowth blackbutt.

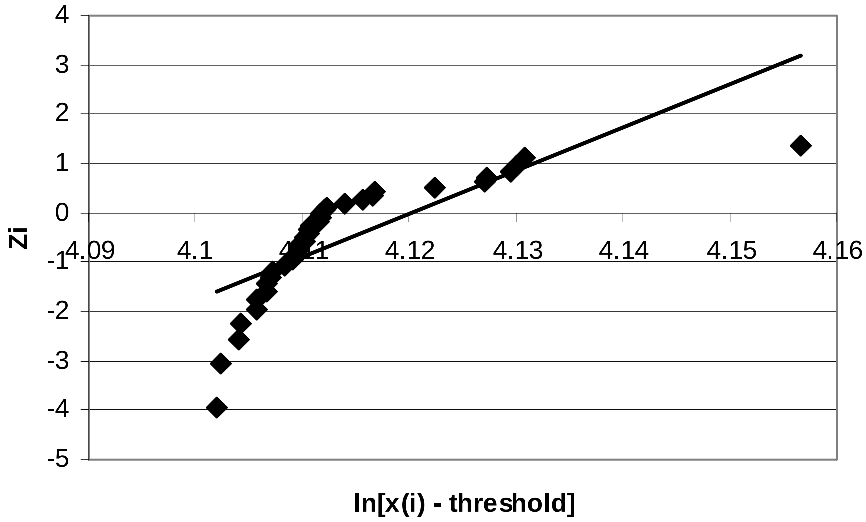

Figure 5.8. Weibull probability plot for the diffusion coefficient data, for within—tree variability of regrowth blackbutt.

In addition, the sample data for the initial moisture contents within and between trees for both regrowth and plantation timber contrast with Kayihan's (1993) suggestion that the initial moisture contents of a stack of boards usually obey a Weibull distribution. Overall, the distributions that exhibited non—normal distributions appeared to become significantly more normal by taking the logarithm of the data. Tables 5.6 to 5.9 show that taking the logarithm of the non—normal timber property moved the distribution closer to a normal one. For example, taking the logarithm of the diffusion coefficient data for the within—trees of regrowth blackbutt moved the distribution closer to a normal one, since $W_{actual} > W_{expected}$ for normality and the value of W_{actual} increased from 0.780 to 0.906. This resulted in the distribution being skewed to lower diffusion coefficients by the logarithmic transformation.

5.4.6 Statistical Analysis of the Timber Properties

Means and standard deviations for the timber properties within and between trees are presented in Tables 5.11 (regrowth) and 5.12 (plantation).

Table 5.11. Statistical summary of the within—tree and between—trees data for regrowth blackbutt timber, and the failure strain regrowth blackbutt data of Alexiou (1993).

Parameter	***Group 1:* Within—Tree Variability (Two Trees)**		***Group 2:* Between—Tree Variability (12 Trees)**		**Alexiou (1993) (Three Trees)**	
	Mean	*Standard Deviation*	*Mean*	*Standard Deviation*	*Mean*	*Standard Deviation*
Initial Moisture Content (kg kg^{-1})	0.67	0.15	0.66	0.14		
Basic Density (kg m^{-3})	705	140	642	63		
Diffusion Coefficient ($\times 10^{-10}$ m^{2}s^{-1})	1.86	0.66	1.99	0.36		
Failure Stress (GS) (MPa)	7.14	2.65	5.25	0.87		
Failure Strain (GS) (mm mm^{-1})	0.0092	0.0034	0.0146	0.0052	0.0138	0.0043
MOE (GS) (MPa)	875	433	407	149		
Failure Stress (DS) (MPa)	7.05	2.26	6.03	2.33		
Failure Strain (DS) (mm/mm)	0.0046	0.0013	0.0061	0.0031		
MOE (DS) (MPa)	1606	525	1234	419		
Tangential Shrinkage (%)	9.26	3.14	10.89	3.65		
Radial Shrinkage (%)	5.03	2.06	6.15	1.73		
Differential Shrinkage	1.93	0.40	1.78	0.30		

Table 5.12. Statistical summary of the within—tree and between—trees data for plantation blackbutt timber.

Parameter	***Group 3:* Within—Tree Variability (Two Trees)**		***Group 4:* Between—Tree Variability (10 Trees)**	
	Mean	*Standard Deviation*	*Mean*	*Standard Deviation*
Initial Moisture Content (kg kg^{-1})	0.67	0.17	0.65	0.11
Basic Density (kg m^{-3})	625	83	663	65
Diffusion Coefficient ($\times 10^{-10}$ m^2s^{-1})	2.80	1.32	1.95	0.57
Failure Stress (GS) (MPa)	4.85	1.87	5.75	1.04
Failure Strain (GS) (mm mm^{-1})	0.0156	0.0060	0.0139	0.0042
MOE (GS) (MPa)	374	198	446	120
Failure Stress (DS) (MPa)	6.36	1.86	7.98	1.82
Failure Strain (DS) (mm/mm)	0.0057	0.0013	0.0067	0.0013
MOE (DS) (MPa)	1155	292	1202	175
Tangential Shrinkage (%)	9.41	2.31	10.49	4.53
Radial Shrinkage (%)	5.78	1.95	6.55	2.22
Differential Shrinkage	1.69	0.35	1.61	0.39

A two—tailed *t* test of significance (Spiegel and Stephens, 1999) at 0.01 and 0.05 levels, was conducted based on the means and standard deviations to determine whether or not both samples of data (groups 1 and 2, and groups 3 and 4) come from the same regrowth and plantation populations. The null hypothesis of the significance test is that the means of both groups is equal, and thus the two groups of trees come from the same population. Otherwise, if the *t* test suggests that the means are not equal to one another, there is a significant chance that the two groups come from different populations. At a 0.05 significance level, if the calculated *t* lies outside the range of the critical values, t_c, for the specified significance test, there is likely to be a significant difference between the two groups. Tables 5.13 to 5.15 show the corresponding *t* statistic for each significance test.

Table 5.13. Results of the significance test for regrowth blackbutt timber: within—tree variability (group 1) compared with between—trees variability (group 2).

Timber Property	*t* Statistic
Initial Moisture Content	0.26
Basic Density	1.99
Diffusion Coefficient	0.87
Failure Stress (Green Sample)	3.32
Failure Strain (Green Sample)	4.78
Modulus of Elasticity (Green Sample)	5.01
Failure Stress (Dried Sample)	2.01
Failure Strain (Dried Sample)	2.54
Modulus of Elasticity (Dried Sample)	2.86
Tangential Shrinkage	1.81
Radial Shrinkage	1.97
Differential Shrinkage	1.54
t_c	**±2.00**

Table 5.14. Results of the significance test for plantation blackbutt timber: within—tree variability (group 3) compared with between—trees variability (group 4).

Timber Property	*t* Statistic
Initial Moisture Content	0.44
Basic Density	1.63
Diffusion Coefficient	2.00
Failure Stress (Green Sample)	1.88
Failure Strain (Green Sample)	1.04
Modulus of Elasticity (Green Sample)	1.39
Failure Stress (Dried Sample)	2.84
Failure Strain (Dried Sample)	2.48
Modulus of Elasticity (Dried Sample)	0.62
Tangential Shrinkage	1.00
Radial Shrinkage	1.20
Differential Shrinkage	0.70
t_c	**±2.02**

Table 5.15. Results of the significance test for the difference between regrowth blackbutt timber and plantation blackbutt timber.

Timber Property	***t* Statistic**
Initial Moisture Content	0.25
Basic Density	2.48
Diffusion Coefficient	3.58
Failure Stress (Green Sample)	3.61
Failure Strain (Green Sample)	5.17
Modulus of Elasticity (Green Sample)	5.22
Failure Stress (Dried Sample)	2.98
Failure Strain (Dried Sample)	3.16
Modulus of Elasticity (Dried Sample)	3.77
Tangential Shrinkage	0.20
Radial Shrinkage	1.39
Differential Shrinkage	2.35
t_c	**±1.99**

For regrowth blackbutt, Table 5.13 shows that the behaviour of the timber properties associated with the basic structure (the initial moisture content and the basic density), the diffusion coefficient, and shrinkage were similar for both groups 1 and 2 at a 0.05 significance level because the *t* statistics for each of these timber properties lie within the range of -2 to 2. On the other hand, the mechanical behaviour (i.e. failure stress, failure strain, and modulus of elasticity) was significantly different between each group at a 0.05 significance level, regardless of whether or not the timber had been dried. Since the two trees for group 1 were taken from separate sites, while all twelve trees for group 2 were taken from one location, this result suggests that different sites had a significant impact on the variability of the mechanical properties of regrowth blackbutt, but not on a key transport property (diffusion coefficient), the basic structure or the shrinkage. The two trees in group 1 were stiffer than the trees in group 2. The ages of logs 685 and 686 are unknown, but it is possible that the boards from group 1 had been taken from more mature logs compared with the logs from group 2, based on the higher stiffness values. Lastly, the dispersion of the failure strain was approximately 1.5 times higher for the between—trees test compared with the values of the failure strain for the within—tree test (Table 5.11). Since the location where the logs from the within—tree test was felled was different from the location where the logs were taken for the between—trees test, the timber properties of regrowth blackbutt were significantly different for the within—tree and between—trees tests.

Bao *et al*. (2001) found that older, more mature (naturally—grown), logs were stiffer compared with younger (naturally—grown) ones. In addition, the slightly higher percentage of heartwood in group 1 (an average of 85% heartwood between the two logs, while group 2 had an average of 82% heartwood between the 12 logs) supports the suggestion that logs 685 and 686 are from older trees. The higher heartwood content may also have contributed to the higher modulus of elasticity, since heartwood is known to provide strength to the tree. Moreover, the mean and standard deviation for the green failure strain in groups 2 and 4 were similar to the values that Alexiou (1993) reported for his 'between—trees' study of the same species. Alexiou's (1993) results came from three regrowth blackbutt trees felled in one location, Whian Whian State Forest, near Lismore, New South Wales, whereas the regrowth blackbutt logs used in group 2 were all felled in the Lower Bucca area, and the plantation blackbutt logs studied in group 4 (between—trees variability) were felled in the Wedding Bells/Conglomerate region. Therefore, the mechanical properties for a group of boards also appear to be dependent on the geographic location where the tree was felled. The knowledge of the geographic location involves the conditions to which the trees were exposed during growth. These conditions include climate, soil type, and whether the ground on which the trees were felled was inclined or flat. These factors, and the complex interactions among them, possibly contributed to the quality of the tree, hence, the properties of that tree. It is important to take this into account during tree selection regarding whether the kiln—dried timber will be used for construction purposes or other applications that require higher strength and stability (Poku *et al*., 2001).

On the other hand, a different result was obtained for plantation blackbutt (Table 5.14). The basic structural parameters, the diffusion coefficient, the shrinkage and the stiffness were similar for both groups 3 and 4, according to the significance test at a 0.05 significance level. Once more, this result supports the previously mentioned suggestion that the timber properties were affected by geographic location. All the plantation logs used for the within and between—trees tests were taken from one location only (i.e. Wedding Bells/Conglomerate area – unlike with the tests for regrowth blackbutt timber), and there was no significant difference between the properties of the 24 boards taken from different positions within two plantation logs and the 20 boards taken from 10 different plantation logs. Apart from the silviculture of the plantation trees used here being the same, the age of all the plantation trees was also the same, i.e. approximately 41 years old, perhaps contributing to the small variation of the timber properties between groups 3 and 4.

A significance test (*t* test) was further conducted to compare the properties of regrowth and plantation blackbutt timber. At a 0.05 significance level, most of the timber properties (except for the initial moisture content, tangential and radial shrinkages) were significantly different between regrowth and plantation blackbutt, as shown in Table 5.15. Firstly, the basic density was lower for plantation timber, which may be one reason why the diffusion coefficient and the shrinkage were higher, and the modulus of elasticity (both in its green and dried states) was lower for plantation material. Another factor that probably contributed to the lower MOE of plantation timber was that the plantation logs had an average of 79% heartwood, which was lower than the 82—85% heartwood content in the regrowth logs. The heartwood content was measured based on the diameter of the dark heartwood section within each log. In addition, the lower heartwood amount in plantation blackbutt compared with regrowth blackbutt suggests that plantation timber has more juvenile wood than regrowth trees. These results are similar to the results reported by Bao *et al*. (2001). They concluded, based on their findings, that plantation—grown hardwoods and softwoods had lower wood densities, larger diffusion coefficients, higher shrinkage values and lower moduli of elasticity. The timber properties of plantation—grown trees possibly depend on their juvenile wood/heartwood contents, thus, on their rotation age. For structural timber, for example, the longer the rotation age, the lower the juvenile wood content and the stronger the timber (Bao *et al*., 2001).

5.5 Conclusions

In general, the modulus of elasticity increased significantly from the green state of the timber to its kiln—dried state. However, dried timber failed at a smaller ultimate strain because the plasticising effect of moisture in the cell walls diminishes as moisture is lost. Like density, MOE increases from pith to bark. Conversely, shrinkage decreased from pith to bark, like the diffusion coefficient. The mechanical properties show a possible correlation with the physical and transport properties (diffusion). The higher shrinkage values and low MOE values for plantation blackbutt timber show that plantation material is less stable dimensionally and is weaker, possibly due to the high juvenile wood content, large microfibril angle, and low basic density.

The ANOVA (analysis of variance) showed that the main sources of variability for most of the mechanical properties of regrowth and plantation blackbutt are in the circumferential and radial directions for within—tree and between—trees variability. This result from the ANOVA suggests that the density and most likely the microfibril angle may be the actual sources of these variations, and both parameters vary in the radial direction. Similar to the ANOVA procedure used in **Chapter 4**, the smaller sized samples of eight boards for the within—tree test of regrowth blackbutt, four boards for the between—trees test of regrowth blackbutt, six boards for the within—tree test of plantation blackbutt, and six boards for the between—trees test of plantation timber, were sufficient to describe the overall ANOVA behaviour of the mechanical properties provided that all combinations of these smaller sample sizes are considered. This is also supported by the sample sizes used by previous work that studied the mechanical properties of hardwood timber. However, more samples were taken here than in previous studies, reflecting the emphasis on measuring and quantifying variability.

Overall, most timber properties for regrowth and plantation blackbutt timber were distributed normally on a linear scale based on the W test, both within and between—trees. On the other hand, some timber properties showed a better fit with the three—parameter lognormal distribution, such as the diffusion coefficient and the green failure strain for within—tree variability of regrowth timber. The means and standard deviations of these distributions were further analysed by applying significance tests at a 0.05 level.

For regrowth blackbutt, the data for the initial moisture content, the basic density, the diffusion coefficient, and shrinkage showed no significant differences, comparing the cases within and between—trees. The mechanical behaviour, however, was significantly different between each group and suggested that the two regrowth trees used for the within—tree test were stiffer than the 12 trees used for the between—trees test. It was possible that the mechanical properties were dependent on the geographic location where the tree was felled, and the heartwood content of each log.

On the other hand, since all the plantation logs used for the within and between—trees tests were taken from one location, the mechanical properties were not significantly different within the plantation sample. The silviculture and the age of all the plantation trees were the same, which might have contributed to the small variation of the timber properties between the within—tree and between—trees cases for plantation material.

Lastly, a significance test was conducted to compare the properties of regrowth and plantation blackbutt timber. Most timber properties (except for the initial moisture content) were significantly different between regrowth and plantation blackbutt. Plantation blackbutt timber had a lower basic density, higher diffusion coefficient and shrinkage, and the modulus of elasticity (both in its green and dried states) was lower compared with regrowth blackbutt timber. In addition to geographic location, heartwood/juvenile content, maturity (age), and differences in microfibril angle may have affected these timber properties in plantation blackbutt timber.