7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Timber properties from regrowth and plantation blackbutt timber were measured by conducting drying experiments using conventional kiln drying. The sample size chosen for each assessment was based on the sample size used in previous work that has studied timber properties within and between trees, given the desirability of using the largest sample sizes possible for the best statistical estimates of variability, while maintaining a realistic time frame for this project. The timber properties measured consisted of the basic density, initial moisture contents, diffusion coefficients, failure strain, failure stress, modulus of elasticity and shrinkage. Correlations between the mentioned parameters have been assessed. The properties of regrowth timber were then compared with the timber properties of plantation timber.

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. Plantation blackbutt samples had significantly 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 tests 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.

The modulus of elasticity (MOE) 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, possibly large microfibril angle, and low basic density.

Most timber properties for regrowth and plantation blackbutt timber were distributed normally on a linear scale when being assessed using 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 the 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 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 the within—tree variability and between—trees variability of regrowth blackbutt timber 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 the within—tree variability test of regrowth blackbutt timber were taken from separate sites, while all twelve trees for the between—trees test of regrowth blackbutt 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. A different result was obtained for plantation blackbutt. The basic structural parameters, the diffusion coefficient, the shrinkage and the stiffness were similar for both the within—tree and between—trees variabilities of plantation balckbutt, according to the significance test at a 0.05 significance level. 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.

A *t* significance test was also 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 potential differences in microfibril angle may have affected these timber properties in plantation blackbutt timber.

A principal components analysis (PCA) presented the possibility that there was a strong correlation between the basic density, the initial moisture content, the diffusion coefficient, and the green modulus of elasticity (MOE). The results of the PCA showed that the principal component for the within—tree and between—trees test accounted for 93% and 94% (for regrowth), and 92% and 90% (for plantation), respectively, of the total amount of variation giving some support for the mentioned correlation between the parameters. Boards with low basic densities have low green MOEs, high diffusion coefficients, and high initial moisture contents. In addition, basic density may be the link between the MOE and the diffusion coefficient.

The results of the *F* significance test showed there was no significant difference between the within—tree and between—trees variability of plantation blackbutt timber. However, the other significance tests showed that there was a significant difference between the within—tree and between—trees variability of regrowth blackbutt timber, the within—tree variabilities of regrowth and plantation blackbutt timber, and the between—trees variability of regrowth and plantation blackbutt timber. The results suggest that the variability of the timber properties was affected by boards taken from logs felled at different locations. Overall, the empirical equations can be used to estimate important drying properties of other regrowth and plantation blackbutt samples, such as the diffusion coefficients, using easily measured properties, like the initial moisture content and the basic density, as long as the boards were taken from the same age group (i.e. regrowth or plantation) and the same location. Boards can then be segregated in groups based on their respective diffusion coefficient, hence a suitable drying schedule can be chosen for each group. Collapse was not significant for the blackbutt samples studied in this thesis, and possibly this timber species in general, but it may be significant for other eucalyptus species such as collapse-prone *Eucalyptus regnans* F. Muell (mountain ash) (Chafe *et al*., 1992; Innes, 1996). This potential limitation means that care is needed in applying the relationships found in this thesis to collapse—prone species.

The effects of different drying schedules and the potential correlations between the diffusion coefficient, the green MOE, the shrinkage coefficient (calculated from the tangential shrinkage), and the initial moisture content on the variability of the final moisture contents, when the average moisture content within a stack of timber reached 15%, were predicted using the same drying model. The results of the investigation suggested that, within a piece of timber (internal), as the external temperatures increase, the diffusion coefficient will increase for the following reasons. The internal average temperature increases and the internal resistance to mass transfer decreases, which leads to the moisture content gradient decreasing, even though the drying rate may slightly increase. This decreases both the drying time and the maximum strain reached. There are limitations, however, associated when using high temperatures in kiln drying, such as collapse and timber discolouration, which need to be accounted for when applying the results of this work to other species.

The total drying time of the optimized drying schedule of plantation blackbutt timber was longer (an additional 168 hours, i.e. 472 hours) compared with the total drying time of the optimized drying schedule of regrowth blackbutt timber (304 hours). Due to the greater variability present in plantation blackbutt, slower drying is required. Moreover, the total drying times from the ‘regrowth blackbutt’ optimization and the ‘plantation blackbutt’ optimization (which both accounted for variability) were shorter compared with the total drying time of the original drying schedule for 28 mm—thick mixed—sawn blackbutt boards, i.e. 504 hours. On the other hand, the total drying times of the optimized drying schedules of regrowth and plantation blackbutt timber were greater than the total drying time (152 hours) predicted by Pordage’s (2006) optimized drying schedule accounting for the variability of *Eucalyptus paniculata* (grey ironbark). He had limited information on the variability of the parameters of grey ironbark and thus used an estimate from another eucalyptus species, *Eucalyptus obliqua* (messmate), whereas in this thesis, the variabilities for regrowth and plantation blackbutt used for the optimization technique were measured and part of the scope for this study. Overall, a typical application of the data obtained in this thesis to the optimization of drying schedules was conducted.

7.2 Recommendations

1. The concept of fracture mechanics makes it possible to assess the propagation of cracks along an expected crack path. Daudeville’s (1999) study of fracture in spruce (softwood) compared simulation results based on Linear Elastic Fracture Mechanics (LEFM) model, and experimental results of the three point bending test, showed that LEFM could predict the load—displacement curve of the specimen. Additionally, a simplified approach of Damage Mechanics for the

analysis of cracking has been shown, in the literature to correctly predict the load-deflection curve (Daudeville, 1999). The fracture energy, which is the dissipated energy per unit crack area, was also found to be the major parameter that governs fracture propagation in linear or in non—linear fracture studies. The concept of fracture mechanics is yet to be applied for predicting failure behaviour in hardwoods, in this case, for blackbutt timber. The study of fracture mechanics as a failure criterion may be a useful way to determine a better failure criterion for timber during drying than the current criterion of maximum strain.

2. Actual measurements of the microfibril angle of blackbutt timber need to be further investigated. The purpose for this is to investigate the correlation of the MOE, microfibril angle, and the diffusion coefficient, since literature suggests that microfibril angle is possibly a better indicator of stiffness and strength than density.

3. Measure the amount of variability of collapse—prone eucalyptus species such as *Eucalyptus regnans* F. Muell (mountain ash). The purpose for this is to assess if the relationships found in this thesis are applicable to collapse—prone species.

4. It is possible that the difference in the values of variability of timber properties caused the difference in the total drying time, i.e. the initial moisture content, reference diffusion coefficient or the shrinkage coefficient. Therefore, a sensitivity study should be conducted to determine which parameter had the greatest influence in the result of the optimization.

5. The predicted optimized drying schedules for regrowth and plantation blackbutt timber in this thesis require further testing by conducting actual timber drying experiments to validate that the drying schedules produce high quality dried boards at both laboratory and commercial scales.