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MECHANICAL PROPERTIES OF ROTARY VENEERS RECOVERED FROM EARLY TO MID-ROTATION SUBTROPICAL HARDWOOD PLANTATION LOGS FOR VENEER BASED COMPOSITE APPLICATIONS

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ABSTRACT: This paper experimentally investigates the mechanical properties of rotary veneers peeled from small-diameter hardwood plantation logs, recovered from early to mid-rotation subtropical hardwood plantations. The study aims at providing essential probabilistic data needed to ultimately predict the capacity and reliability of veneered based composites structural products (such as LVL and plywood) from characteristics which can be measured in line during manufacturing. Two species planted for solid timber end-products (Gympie messmate - *Eucalyptus cloeziana* and spotted gum - *Corymbia citriodora*) and one species traditionally grown for pulpwood (southern blue gum - *Eucalyptus globulus*) were studied. The compressive and tensile Modulus of Rupture (MOR) of the veneers, parallel to the grain and for veneer based composite applications, were experimentally investigated. Results show that the compressive MOR for all species typically ranges from 30-50 MPa (for MOE < 12,000 MPa) to 60-90 MPa (for MOE > 22,000 MPa). The tensile MOR is typically lower than or in the range of the compressive MOR for MOE less than 12,000 MPa, while for larger MOE (MOE > 22,000 MPa), tensile MOR greater than 140 MPa were observed. The total knot area ratio (tKAR) of the veneers is also analysed and Weibull distributions were found to provide a good characterisation of the statistical repartition of the tKAR value along the length of a veneer sheet. For each species, equations to best predict a veneer MOR from its measured MOE and tKAR value are derived and fit the experimental results with a coefficient of determination between 0.63 and 0.74. The variability of the MOR of each species was accurately modelled by Weibull distributions, with the distribution parameters determined based on the experimental data. Results shown that southern blue gum and Gympie messmate is the most and least sensitive species to size effects.

KEYWORDS: Hardwood plantations, Veneers, Mechanical properties, Thinning, Pulpwood

INTRODUCTION

Australian hardwood 'commercial plantations' (i.e. established and managed specifically targeting commercial use by the forest products industry) cover about one million hectares and represent about half all Australian plantations. About 84% of these hardwood plantations have been primarily established for pulpwood production, leaving a smaller proportion of these estates established for high quality solid wood markets (Australian Government 2015, Gavran 2013).

The Australian timber industry is rapidly changing and is increasingly relying on plantations as a supplementary resource or as an alternative to native forests (McGavin, et al. 2015a). Yet, to justify continued expansion of Australia's current hardwood plantation estates and to increase the value gained from existing estates, it is becoming necessary to develop high-value end-use products from early to mid-rotation hardwood plantation logs. These logs are usually harvested 12 to 15 years after establishing the plantation, either by clear felling the plantation for pulpwood resources or in a thinning operation for saw log management regimes (Nolan, et al. 2005). With an unfavourable market for pulpwood (McGavin, et al. 2014b) and thinned logs deemed of poor quality, these small diameter (about 15 to 30 cm) logs have currently little to no commercial value in Australia (McGavin, et al. 2006).

For structural applications, these logs yield a poor recovery rate when processed using traditional sawmilling techniques to produce sawn timber. However, the use of spindle-less technology has been demonstrated to be an efficient process by recovering up to 70 % of the logs into rotary veneers (McGavin, et al. 2014a), and therefore offers the possibility to use these resources for Veneer Based Composite (VBC) products.

With this in mind, plywood and LVL products have been manufactured and analysed by Forest Product Innovation team from the Queensland Government (McGavin, et al. 2013). Studies with similar aims have been performed for instance in New-Zealand (Gaunt, et al. 2002), Europe (Rahayu, et al. 2015) and South America (Monteiro de Carvalho, et al. 2004). The results showed that these products can exceed the mechanical properties of similar products manufactured from mature plantation softwood (*e.g. Pinus* species). However and despite proven potential to make attractive structural products, veneer-based composite products manufactured from veneers recovered from early to mid-rotation hardwood plantation logs cannot currently be commercialised as (i) no proper design guidelines exist and (ii) the resources are not recognised as a source of structural timber. Indeed, due to the high proportion of natural defects (knots, gum veins, grain deviation, etc.), the variability in their mechanical properties is not fully understood, and the statistical characteristics of their actual strength needs to be fully investigated to develop probability-based limit state design criteria, similar to that used for traditional wood constructions. Additionally, for hardwood species traditionally used for pulpwood, species selection and breeding have focused on achieving high pulp yield, density and volume, which may adversely affect important mechanical properties for high value-added solid wood products (Bailleres, et al. 1995a, b, Blackburn, et al. 2012, Lenz, et al. 2010).

This paper represents an essential step towards understanding the mechanical properties of veneer-based composites structural products manufactured from veneers recovered from early to mid-rotation hardwood plantation logs by providing essential probabilistic data on the actual mechanical properties of the individual veneers. These data will be ultimately used to numerically investigate the capacity and reliability of LVL and plywood structural products manufactured from the studied resources. The specific objectives of the paper are therefore to (i) experimentally investigate the compressive and tensile Modulus of Rupture (MOR) parallel to the grain of veneers peeled from early to mid-rotation subtropical hardwood plantation logs of three different species, (ii) analytically quantify the relationship between the measured MOR, Modulus of Elasticity (MOE) and total knot area ratio (tKAR) of the veneers, which can be measured in-line during manufacturing, for each analysed species and (iii) statistically characterise the variation of both the MOR (size effect) and tKAR values within each species.

In this effort, the tensile and compressive MOR of veneers peeled from three different subtropical hardwood species are investigated and presented in this paper. Gympie messmate (GMS)

(*Eucalyptus cloeziana*) and spotted gum (SPG) (*Corymbia citriodora*), planted for solid timber end-products, and southern blue gum (SBG) (*Eucalyptus globulus*), traditionally planted for pulpwood, were selected. The total knot area ratio (tKAR) of the tested samples and veneer sheets from which the samples were cut is quantified and reported. The variability in mechanical properties of the veneers is discussed in terms of Weibull distributions and equations are derived to best predict the Modulus of Rupture (MOR) of the veneers from characteristics, Modulus of Elasticity (MOE) and tKAR, which can be measured in line during manufacturing.

MATERIAL AND METHODS

Samples preparation

As part of collaborative projects between industry and the Queensland Government to enhance the value of early to mid-rotation hardwood plantations logs, logs in 1.3 m lengths were rotary peeled to produce veneers with a dried nominal thickness of 2.5 mm at the Salisbury Research Facility, Brisbane, Australia, using a spindle-less lathe. The logs originated from two different sites in Northern New South Wales and one site in South East Queensland for the spotted gum logs, three different sites in Victoria for the southern blue gum logs, and one site in South-east Queensland for the Gympie messmate logs (McGavin, et al. 2015a). The trees were 10 to 12, 13 to 16 and 12 to 15 years old, and had an average diameter at breast height over bark (DBHOB) of 20.6, 30.6 and 31.9 cm, for the spotted gum, southern blue gum and Gympie messmate logs, respectively. Details of the overall resources peeled during these projects can be found in McGavin, et al. (2015a), (2015b).

In this research, 90 veneer sheets of nominal 1.2 m width (and 1.2 m long) out of all peeled logs were selected per species. The sheets were selected to best represent the range of MOE encountered for each species. The sheets were peeled from 44, 43 and 20 different trees for the SPG, SBG and GMS plantations, respectively. Table 1 details the number of trees selected for each growing site.

Each veneer sheet was then cut parallel to the grain into three 400 mm wide × 1.2 m long strips. Each strip was photographed for image analysis as outlined in Section “Knot area ratio”.

Additionally, the dynamic MOE of each veneer strip was determined using a non-destructive acoustic method by recording the longitudinal natural frequency of the strip and analysing it using the software BING® (Beam Identification by Non-destructive Grading) (CIRAD 2012). Dimensions and mass of each veneer were measured and used as input into the software BING®. Density is automatically calculated by the software. Figure 1 shows the acoustic test set-up.

The three strips per veneer sheet were then glued together in a LVL configuration (i.e. all veneer grain aligned in the same direction) using standard gluing procedures and a readily available commercial Phenol-Formaldehyde adhesive system (Momentive Specialty Chemical PP1158). To ensure defects were randomised, the middle strip was glued upside-down and the other two strips were glued with their tight side (i.e. is the one not in contact with the knife as the log is being peeled) as the outer faces of the LVL. The overall configuration aims at capturing the average properties of each veneer sheet, including the effects of both hot pressing the sheets and the glue used during the manufacturing process. After manufacture, the obtained 3-Ply LVLs were sawn into one 630 mm long × 100 mm wide sample for compression testing and one 1,130 mm long × 150 mm wide sample for tension testing. While these samples were not standard sizes for LVL testing (different to the test sample dimensions required in the Australian/New Zealand standard AS/NZS 4357.2 (AS/NZS, 2006) for instance), they correspond to large samples relative to the overall size of the manufactured 3-ply LVLs. Each 3-Ply LVL was cut following the same cutting pattern enabling to locate the actual location of the compression and tension samples on the photos of the veneer strips.

The samples were conditioned at 20°C and 65% relative humidity before testing following the recommendations in the Australian standard AS/NZS 4357.2 (AS/NZS, 2006), targeting a sample nominal moisture content of 12%.

Material testing

Compression tests

The 630 mm long samples (90 samples per species) were tested in compression using a 500 kN universal MTS testing machine, at a stroke rate of 0.8 mm/min, to reach failure between 3 and 5 minutes. A similar method to the one recommend for plywood in Clause 7.5 of the Australian and New Zealand standard AS/NZS 2269.1 (AS/NZS 2012) was applied with the samples prevented from lateral buckling every 55 mm by rollers. The samples were tested between platens, both mounted on a half sphere bearing, which could rotate, so as to provide full contact between the platens and the specimens. Before testing, the ends of the samples were cut with a high quality fine cut circular saw blade to ensure a uniform contact pressure between the samples and the platens. Figure 2 shows the test set-up.

The compressive MOR (MOR_c) of the samples is calculated as,

$$MOR_c = \frac{F_{\max}}{wt} \quad (1)$$

where F_{max} is the maximum recorded force, and t and w are the measured thickness and width, respectively, of the samples.

Immediately after testing, pieces were cut from selected samples (5 to 10% of all tested samples) to determine the samples' moisture content (MC) at the time of testing. Specifically, the weight of the pieces was recorded and the pieces were later left in an oven at 103^{o}C until they reached constant mass. Sample moisture content was calculated in accordance to the Australian and New Zealand standard AS/NZS 1080.1 (AS/NZS 2012).

Tension tests

The 1,130 mm long samples (90 samples per species) were tested in tension in a custom built 600 kN testing machine, at a load rate of 30 kN/min, targeting failure between 3 and 5 mins. The samples were clamped between curved and knurled jaws, leaving a testing length of 500 mm between the jaws. The curved jaws aimed at minimising stress concentration at clamping and ensuring failure between jaws. Figure 3 shows the test set-up.

The tensile MOR (MOR_t) of the samples is calculated using the same equation as Eq. (1). Similar to the compression samples, pieces were cut from selected samples, immediately after testing, to determine the moisture content of the tested specimens at the time of testing.

Veneer grading

Veneers are classified in this study into three grades, referred to as “Low”, “Medium” and “High”, based on their dynamic MOE value. For each species, the grades divide veneers into three bins of an equal number of veneers and mimic a simple way an industrialist could divide the veneers using the veneer MOE value as the sole grading indicator. The industrialist could hypothetically either manufacture three qualities of LVL and plywood structural products with no veneer wastage or use the data provided in this study to optimise the use of the veneers to target various qualities of its final products. How the veneers are divided into bins varies with both the final structural products and the specific strategy adopted by an industrialist, the three grades above were arbitrary chosen in this study for simplicity.

Cut-off MOE values for each grade are based on the expected distribution of MOE encountered for the studied veneered resources and quantified by McGavin, et al. (2015a). In total, McGavin, et al. (2015a) analysed and peeled 215, 120 and 223 logs for the SPG, SBG and GMS species, respectively. The cut-off MOE (rounded to the nearest hundred) for each grade and each species are reported in Table 2.

Knot area ratio

Knots or groups of knots create weak zones in the timber in which failure usually initiates (Gibson and Ashby 1999). The total knot area ratio (tKAR) is often used as an indicator to characterise the influence of knots on the timber properties and is considered to be an efficient approach (Fink and

Kohler 2014). It is defined as the ratio of the sum of the projected area of all knots within a timber piece length of 150 mm to the total cross-sectional area of the piece (Isaksson 1999). Other types of knot area ratios can be found in Isaksson (1999). Considering both the tKAR value and the timber MOE has been found to improve the strength predictability of timber structural elements (Fink and Kohler 2014, Johansson 2003). This approach is used in this study and detailed hereafter.

Tension and compression samples

The maximum value of the tKAR ($tKAR_{max}$) of each compression and tension sample over their testing length was calculated from the known position of the samples on the photos taken of each veneer strip. While for lumbers, edge knots influence the strength of timber differently to centre knots (Johansson 2003, Lepper and Keenan 1986), no distinction was made herein between the two types of knots as for LVL the difference in strength reduction between an edge and centre knot would be less significant than for lumbers. In a lumber in tension, the edge knot creates an out-of-plane bending moment and therefore a higher strength reduction than a centre knot (Foschi and Barrett 1980). In a LVL, an edge knot would only be present on one (or few) ply and the associated out-of-plane bending moment would be significantly prevented by the adjacent ply with no knot. Significant improvement of the veneer strength prediction considering the total knot area ratio was achieved, as discussed in the subsection “Tension tests” in the results section.

For each photo of the veneer strips constituting the 3-Ply LVLs, nodes larger than 5 mm in diameter were manually marked with black spots. For image processing purpose, the photos were then converted into black and white pictures, only showing the location of the knots. A script in python language was then written to calculate the maximum tKAR value for each tension and compression sample. Figure 4 shows the original photo of a spotted gum veneer strip (Figure 4 (a)), the knots marked in black (Figure 4 (b)) and the black and white picture showing the location of the compression and tension samples determined from the gluing and sawing sequences (Figure 4 (c)).

Veneer sheets

The tKAR values of each full veneer sheet (based on the reconstituted photo of the entire sheet from the three photographed strips, see Section "Samples preparation") were calculated every 150 mm, providing eight values per 1.2 m long sheet. These data were used to statistically determine the lengthwise variability of the knot area ratio of the studied veneered resources,

Due to the logs being rotary peeled, the occurrence of knots across the sheet width is periodic and therefore the maximum tKAR value of large VBC samples would be similar to the one of the entire sheet. For narrow samples, the previous may not be true. Nevertheless, the distribution of knots along the sheet length can be used as an indicator of the tKAR variability within VBC samples in future studies.

Veneer sheets with low MOE values are usually peeled closer towards the pith of the tree, where they encounter a higher proportion of knots along with less mature wood properties (e.g. lower wood density) compared with sheets recovered from towards the log periphery, which generally yield higher MOE (McGavin, et al. 2015a). Consequently, the knot area ratio for each species is quantified, analysed and reported in the study per veneer grade.

Statistical analyses

Non-linear models have been applied to fit the tKAR and MOE data using TableCurve 2D version 5.01 (Systat software INC 2002a) and TableCurve 3D version 4.0 (Systat software INC 2002b) software. TableCurve uses the Levenberg-Marquardt algorithm for fitting the non-linear equations and minimises the sum of the squares of the residuals. The software determines effective starting estimates of the equation parameters during a pre-scan procedure of the input data. The algorithm considers convergence when the fractional error in the minimisation reaches 10^{-6}, which represents a coefficient of determination goodness value unchanged through six significant figures for five iterations (Systat software INC 2002a, b).

RESULTS AND DISCUSSION

Moisture content

The oven dry moisture content of the samples is reported in Table 3 for each species and testing method. The coefficients of variation (CoV) between recorded samples per species and test type are also reported in Table 3. The moisture content of all samples is of the same order of magnitude, with an average moisture content of 10.4% and CoV between all samples of 5.7%.

Compression tests

Figure 5 gives the relationship between the average measured dynamic MOE of the veneer strips and compressive MOR of the 3-ply LVL samples for all investigated species.

The relationship between the compressive *MOR* and *MOE* is usually best represented by a power equation and this relationship is used herein. Additionally, the influence of the knots on the compressive MOR is considered further herein in the form,

$$MOR_C = \alpha \cdot MOE^{\beta}(1 - \gamma \cdot tKAR) \quad (2)$$

where the first term of the equation (power relationship) represents the strength of the wood itself and the second term (in brackets) represents a reduction in cross-sectional area due to the presence of the knots. The coefficient γ in Eq. (2) represents the influence of the knots in reducing the strength, including the grain deviation around the knots, and is typically higher in tension than in compression due to the presence of knots having less influence on the compressive MOR than on the tensile one (Kollmann 1968). Table 4 gives the coefficients α, β and γ in Eq. (2) obtained by performing a non-linear regression on the compression test results. The coefficients of determination R^2 are also given in Table 4 and are relatively high, ranging between 0.63 (GMS) to 0.74 (SPG). Considering the knot area ratio significantly improves the compressive strength prediction as ignoring it in Eq. (2) reduces the coefficient of determination R^2 by 12% on average (based on the results in Gilbert, et al. (2016) where the tKAR value of the samples was ignored in the prediction).

The curves provided using Eq. (2), using the average maximum tKAR value of the compression samples for each grade, are also plotted in Figure 5. Figure 5 shows a large variation in the compressive strength, which ranges from about 30-50 MPa for MOE less than 12,000 MPa to 90 MPa for MOE greater than 22,000 MPa. At 12% moisture content, plantation softwood species for structural purposes (sawn timber or veneer based products) typically have MOE in the order of 10,000 to 15,000 MPa and compressive strength ranging from 30 to 60 MPa (Carter Holt Harvey Woodproducts 2015, Hyne timber 2016, Kretschmann 2010). Therefore, in its lower MOE range, the analysed veneers would be comparable to plantation softwood in terms of mechanical properties. Yet, as veneer MOE greater than 12,000 MPa represent more than 80% of the veneers recovered from the analysed species (McGavin, et al. 2015a), early to mid-rotation hardwood plantation logs would produce a large proportion of veneers with MOE and MOR higher, i.e. of superior quality, than the ones typically encountered in softwood species for structural applications.

Tension tests

The relationship between the average measured MOE of the veneer strips and tensile MOR of the 3-ply LVL samples is plotted in Figure 6 for all investigated species. Eq. (2) is also used to best fit the MOR of the tension samples as,

$$MOR_t = \alpha \cdot MOE^{\beta}(1-\gamma \cdot tKAR) \tag{3}$$

Similarly to Figure 5, the curves provided using Eq. (3), using the average maximum tKAR value of the tension samples for each grade, are also plotted in Figure 6. Table 4 gives the coefficients *α, β* and γ in Eq. (3) obtained by performing a non-linear regression on the tension test results. The coefficients of determination R^2 are also given in Table 4 and, similar to the results in compression, are relatively high, ranging from 0.64 (GMS) to 0.72 (SPG). Considering the knot area ratio in Eq. (3) improves the accuracy of the equation and the coefficient of determination R^2 increases by

20.6% on average when compared to the results published in Gilbert, et al. (2016), where predictions were made without considering the tKAR value of the samples.

Figure 6 shows a larger range variation of the tensile strength when compared to the compressive strength. The MOR ranges from about 30-60 MPa for MOE less than 12,000 MPa to above 140 MPa for high MOE greater than 22,000 MPa.

At 12% moisture content, plantation softwood species for structural purposes, i.e. with the lower graded timber of MOE less than about 10,000 MPa not considered, typically have tensile strength ranging between 60 and 90 MPa (Kretschmann 2010). Therefore, in its lower MOE range, the analysed veneers encounter lower MOR than plantation softwood. However, similar to the compressive strength and due to the analysed resources having MOE significantly higher than typical softwood MOE, the analysed species would recover a large proportion of veneers with higher MOE and MOR than those typically observed in plantation softwood species.

Comparison between species

To simply compare and clearly visualise the strength of all species, Figure 7 plots the best fit prediction using Eqs. (2-3) and the average maximum tKAR values of the compression and tension samples for each grade.

As discussed in previous sections, Figure 7 shows that for veneer MOE less than about 12,000 MPa, the tensile strength tends to be equal to or lower than the compressive strength. As discussed previously, for this range of MOE, a large proportion of knots are usually observed. These defects have a larger influence on the tensile strength than on the compressive strength (Kollmann 1968), explaining this phenomenon. For higher MOE veneers, greater than 22,000 MPa, less natural defects are observed and the tensile strength is 40% to 80% larger than the compressive strength. The larger difference is encountered for the southern blue gum species.

As shown in Figure 7, the tensile strength of the two species planted for sawn timber (SPG and GMS) tends to be similar, except for low MOE veneers where the tensile strength of the SPG samples is about 20% lower than the GMS samples. On the other hand, the tensile strength of the species traditionally planted for pulpwood (SBG) is between 5% and 30% greater the other two species. The compressive strength of the SBG samples is up to 23% lower than the other two species, with the difference being more significant for veneers with MOE greater than 15,000 MPa. Despite being a species traditionally planted for pulpwood, SBG samples still have high mechanical properties, especially in tension. In all tests performed, the three samples with the highest tensile MOR were SBG (see Figure 6).

Weibull distribution (size effect)

For brittle materials, such as timber in tension, the Weibull distribution (Weibull 1939) is commonly used to characterise the size effect and variability in the material properties. While the Weibull strength theory has been developed for isotropic and homogeneous material (Fonselius 1997), its use for timber products is well accepted (Gibson and Ashby 1999, Madsen and Buchanan 1986). Moreover, despite timber not experiencing brittle failure in compression, the Weibull strength theory still applies in compression as failure occurs in the weakest cross-section (Madsen and Buchanan 1986).

The probability of failure P_f of a volume V at an applied stress σ is given by the two-parameter Weibull distribution as,

$$P_f = 1 - e^{-\frac{1}{V_0}\int_V \left(\frac{\sigma}{m}\right)^k dV} \tag{4}$$

where V_0 is the reference volume, m the scale parameter and k the shape factor. k reflects the size effect and, for the same probability of failure, the relationship between the tensile or compressive strength MOR_1 of a volume V_1 is given relative to the reference strength MOR_0 of volume V_0 as,

$$\frac{MOR_1}{MOR_0} = \left(\frac{V_0}{V_1}\right)^{1/k} \tag{5}$$

As the Weibull parameters are usually dependant on the grade of the material, they should be estimated based on tests performed on timber products of the same grade. Assuming a constant shape factor *k*, it is also possible to follow a similar approach to Foschi and Barrett (1980) by normalising the strength using its best prediction given in Eq. (2). Eq. (4) therefore becomes,

$$P_f = 1 - e^{-\frac{1}{V_0}\int_V \left(\frac{MOR}{M\alpha \cdot MOE^{\beta}(1-\gamma tKAR)}\right)^k dV} \tag{6}$$

where the new scale parameter *M* is a constant. The strength can then be expressed in terms of the failure probability P_f by rearranging Eq. (6) as,

$$MOR_{c,t} = M\alpha \cdot MOE^{\beta}(1-\gamma \cdot tKAR)\left[-\frac{V_0}{V}\ln(1-P_f)\right]^{1/k} \tag{7}$$

In timber, the size effect is different for tension and compression failure and the factor *k* also usually varies with specimen dimensions (width, thickness and length). The shape factors associated with each dimension are best found using the slope method, where specimens from the same batch, from which one dimension varies, are tested (Fonselius 1997). However, as the tests reported herein are performed at a constant volume, the shape factor *k* in Eq (7) is assessed in this paper using the shape parameter method (Fonselius 1997), consisting of finding the Weibull parameters that best fit the cumulative distribution function of the MOR.

Figure 8 shows the cumulative probability distribution of the ratio $MOR_c/\alpha.MOE^{\beta}(1\text{-}\gamma.tKAR)$ and $MOR_t/\alpha.MOE^{\beta}(1\text{-}\gamma.tKAR)$ for both compression and tension tests, respectively, and for all investigated species. The scale parameters *M* and shape factors *k* obtained by performing a regression analysis on all curves in Figure 8 are reported in Table 5. The corresponding two-parameter Weibull distributions are also plotted in Figure 8 for comparison. Consistent with the literature (Barrett, et al. 1995, Madsen 1990), Table 5 shows that the shape factors for tension failure are less than the shape factors for compression failure. The ratio between the compression shape factor and the tension one for all species ranges between 1.8 (SBG) to 2.1 (SPG) which is similar to the ratio for softwood lumbers of about 2.1 found in Madsen (1990), where shape factors are reported for both tension and compression. Gympie messmate was found to have the highest shape factor to all investigated species and is therefore less sensitive to size effect. On the other hand, southern blue gum was found to be the species the more sensitive to size effect with a shape factor in compression 1.37 lower than the one of Gympie messmate.

Total knot area ratios of veneer sheets

A two-parameter Weibull distribution (Weibull 1939), based on the weakest link theory, provided good characterisation of the total knot area ratio distribution for each grade, with a low Kolmogorov-Smirnov test result of less than 0.08. It is assumed that no correlation exists between two consecutive tKAR values within a veneer sheet and therefore the maximum tKAR value of a sheet of length *l* can be probabilistically assessed using the Weibull distribution and the reference length l_{ref} = 150 mm. As Weibull distributions are based on the weakest link theory, the value 1-*tKAR* must be used instead of *tKAR* in the distribution as,

$$P_f = 1 - e^{-\frac{l}{l_{ref}}\left(\frac{1-tKAR}{m_{tKAR}}\right)^{k_{tKAR}}} \tag{8}$$

In Eq. (8), P_f is the probability of having a knot area ratio greater than *tKAR* in a *l* long sheet, m_{tKAR} is the scale parameter and k_{tKAR} the shape factor.

Figure 9 plots the cumulative distribution of the tKAR values for all species, for $l = lref$, and for each grade. The two-parameter Weibull distributions are also shown in Figure 9 with the best fit values of the scale parameters m_{tKAR} and shape factors k_{tKAR} given in Table 6.

For veneer with no defects, i.e. $tKAR = 0$, Eq. (8) leads to 1-*tKAR* values greater than 1.0 (See Figure 9). As a tKAR value is greater than or equal to zero, the actual maximum knot area ratio *tKAR* of a sheet of length *l* is calculated from P_f as,

$$\begin{cases} \text{if } P_f \leq 1 - e^{-\frac{l}{l_{ref}}\left(\frac{1}{m_{tKAR}}\right)^{k_{tKAR}}} \text{ then } tKAR = 1 - m_{tKAR}\left(-\frac{l_{ref}}{l}\ln\left(1 - P_f\right)\right)^{\frac{1}{k_{tKAR}}} \\ \text{else } tKAR = 0 \end{cases} \tag{9}$$

Figure 9 and Table 6 show that SPG and GMS have the highest and lowest proportion of knots, respectively, of the three studied species. In Figure 9, at the 50th percentile, the tKAR values of the SPG veneers are equal to 0.15, 0.09 and 0.04 for the "Low", "Medium" and "High" grades, respectively, and are 4.4, 6.0 and 6.0 times higher than the tKAR values of the GMS veneers for the "Low", "Medium" and "High" grades, respectively. Additionally, Figure 9 confirms that veneers with lower MOE ("Low" grade) have a higher probability of encountering knots than veneers with high MOE ("High" grade). In Figure 9, at the 50th percentile, the tKAR value of the "Low" grade veneers is 3.6, 2.4 and 4.7 times higher than the one of the "High" grade veneers for the SPG, SBG and GMS species, respectively.

To study the influence of the knots on the tensile and compressive MOR between veneers of different lengths, the Weibull shape factor k_{tKAR} can be calculated by using 1-$\gamma.tKAR$ instead of 1-$tKAR$ in Eq. (8), where γ (see Eq. (2)) is defined in previous subsections "Compression tests" and "Tension tests". Values of k_{tKAR} for the Weibull distributions of 1-$\gamma.tKAR$ and for all values of γ reported in Table 4 are given in Table 7.

Overall results

While the current work focussed on three species, it can be easily extended to other species, both softwood and hardwood, juvenile and mature trees. The simplicity of Eqs. (2-3) can be used as a simple way to grade veneers. Additionally, while the size effect has been quantified herein as the overall volume shape factor (See Section "Weibull distribution (size effect)" and (Fonselius 1997)), the actual size effect factors in the directions parallel and perpendicular to the grain need to further quantified, outside the scope of this paper.

CONCLUSIONS

This paper showed that both the tensile and compressive strength of veneers, in a veneer based composite applications, are in the range of 30-50 MPa for MOE less than 12,000 MPa. However, for higher MOE, greater than 22,000 MPa, the tensile strength is 40% to 80% higher than the compressive strength and can reach a value higher than 140 MPa. Despite being traditionally established for pulpwood end-use, the southern blue gum veneers show higher tensile strength (between 5% and 30%) and lower compressive strength (up to 23%) than the other two species. The equations proposed in the paper estimate the tensile and compressive strength of the three analysed species, in terms of the dynamic MOE and knot area ratios, with a coefficient of determination ranging between 0.63 and 0.74. Weibull distributions were found to accurately estimate the variation of (i) the tensile and compressive strength and (ii) the tKAR along the length of the veneer sheets. The shape factor of the tension strength is about half the one of the compressive strength, with southern blue gum and Gympie messmate being the species the more and least sensitive to size effects, respectively. In terms of the tKAR, results showed that spotted gum has a larger proportion of knots than the other two species. For all species, the occurrence of knots is higher for low MOE than high MOE. The results in this study will be used to numerically analyse the strength variability of LVL and plywood structural products manufactured with early to mid-rotation hardwood plantation veneers.

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Table 1: *Number of trees per site from which veneer sheets were selected for the three investigated species*

	Number of trees sampled		
Species	1st site[(1)]	2nd site[(2)]	3rd site[(3)]
SPG	9	10	25
SBG	16	11	16
GMS	20	--	--

[(1)]1st site: SPG = Lismore (NSW), SBG = Deans Marsh (VIC) and GMS = Beerburrum (QLD)
[(2)]2nd site: SPG = Kingaroy (QLD) and SBG = Orford (VIC)
[(3)]3rd site: SPG = Urbenville (NSW) and SBG = Mumbannar (VIC)

Table 2*: MOE cut-off values for each grade based on results in McGavin, et al. (2015a) for the three investigated species*

Species	Low grade (MPa)	Medium grade (MPa)	High grade (MPa)
SPG	MOE < 14,000	14,000 ≤ MOE < 17,900	MOE ≥ 17,900
SBG	MOE < 14,100	14,100 ≤ MOE < 18,000	MOE ≥ 18,000
GMS	MOE < 14,600	14,600 ≤ MOE < 18,200	MOE ≥ 18,200

Table 3: *Average moisture content (MC) and associated Coefficient of Variation (CoV) of tested samples for the three investigated species*

	Compression samples			Tension samples		
Species	MC (%)	nb pieces	CoV (%)	MC (%)	nb pieces	CoV (%)
SPG	10.5	10	3.6	10.0	11	4.2
SBG	11.0	6	2.6	10.9	4	1.1
GMS	11.0	5	4.1	9.7	7	4.0

Table 4: *Coefficients α, β and γ in Eq. (2-3) between MOR and average MOE for the three investigated species*

	Compressive tests				Tension tests			
Species	α	β	γ	R^2	α	β	γ	R^2
SPG	0.490	0.506	0.437	0.74	0.025	0.842	1.110	0.72
SBG	0.810	0.437	0.246	0.64	0.117	0.694	1.575	0.69
GMS	0.680	0.474	0.388	0.63	0.013	0.896	1.211	0.64

Table 5: *Two-parameter Weibull scale parameters and shape factors for tensile and compressive MOR for the three investigated species*

	Compressive tests		Tensile tests	
Species	k	$M(V_0/V)^{1/k}$	k	$M(V_0/V)^{1/k}$
SPG	15.60	5.53	7.38	38.59
SBG	11.74	9.63	6.47	63.83
GMS	16.09	5.23	8.48	23.80

Table 6: *Two-parameter Weibull distributions scale parameters and scale factors for knot area ratios (1-tKAR) for the three investigated species*

	Low grade		Medium grade		High grade	
Species	m_{tKAR}	k_{tKAR}	m_{tKAR}	k_{tKAR}	m_{tKAR}	k_{tKAR}
SPG	0.885	10.43	0.939	13.35	0.981	17.74
SBG	0.948	22.67	0.974	25.39	0.980	43.13
GMS	0.977	30.02	0.991	46.99	0.998	63.86

Table 7: *Two-parameter Weibull distributions scale factors k_{tKAR} for knot area ratios (1-γ.tKAR) for the three investigated species*

	Low grade		Medium grade		High grade	
Species	Comp.	Tension	Comp.	Tension	Comp.	Tension
SPG	26.27	9.21	33.26	11.88	48.37	15.87
SBG	13.78	97.55	15.68	107.15	26.90	179.77
GMS	79.41	24.56	122.79	38.62	166.26	52.55

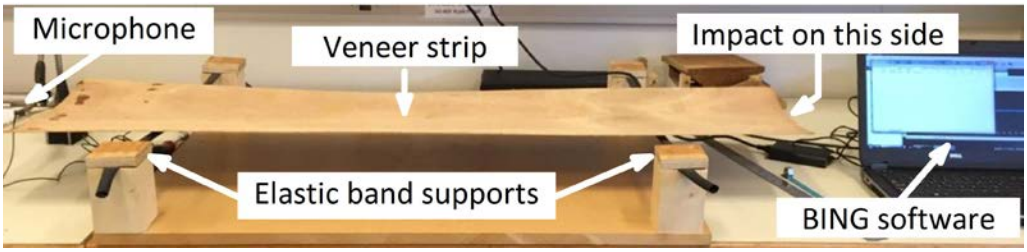


Figure 1: *MOE determination test set-up*

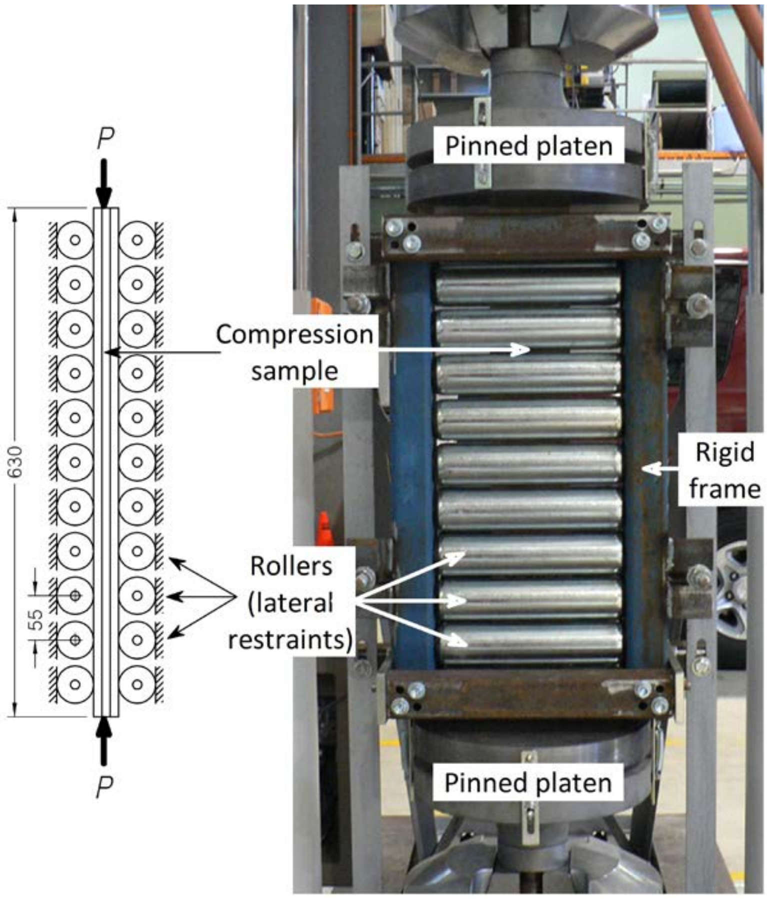


Figure 2: *Compression test set-up (schematic and actual)*

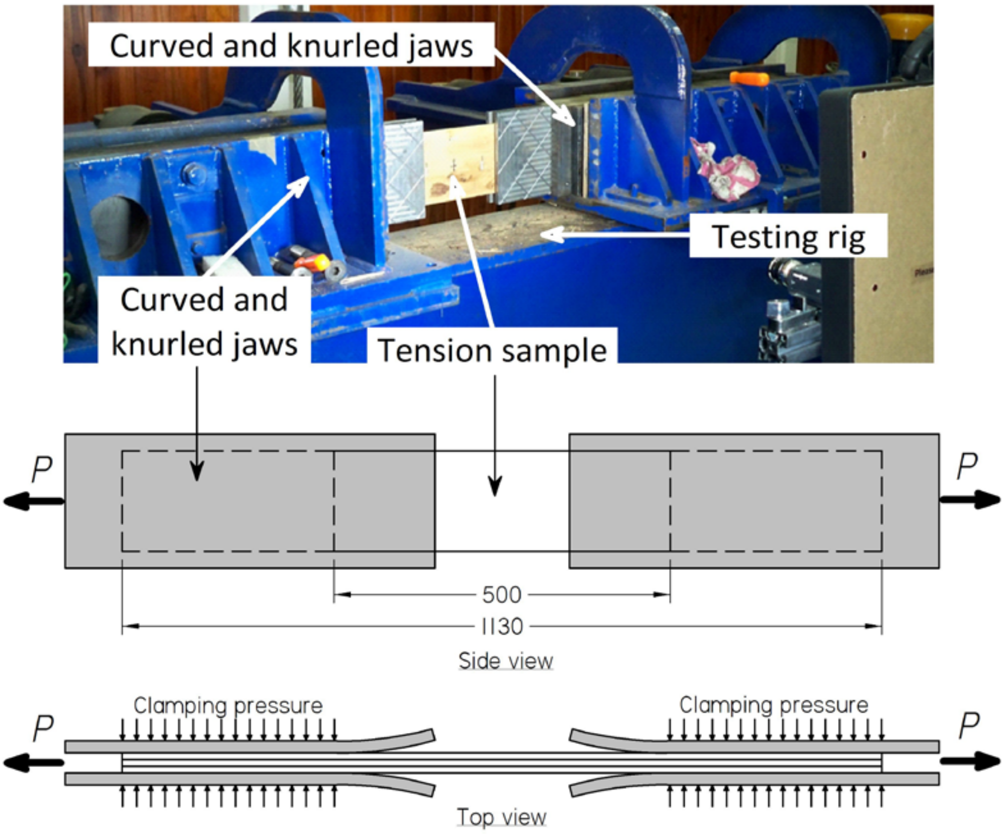
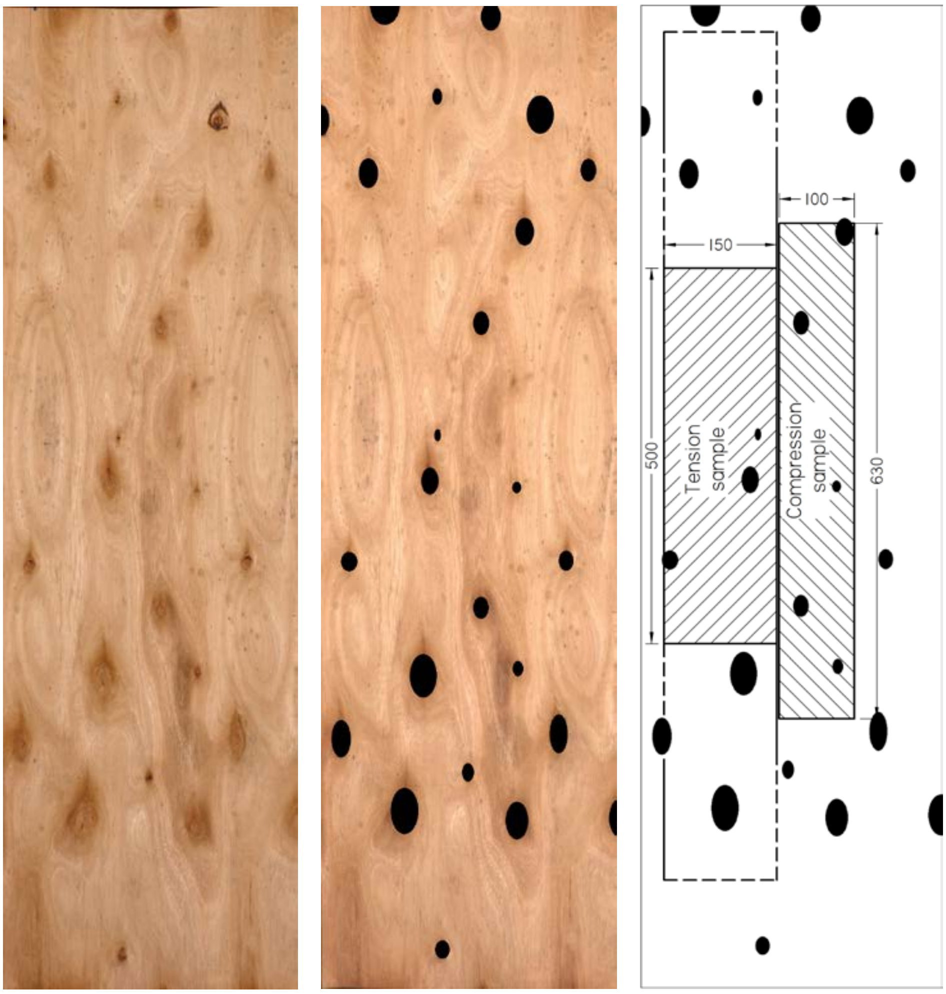
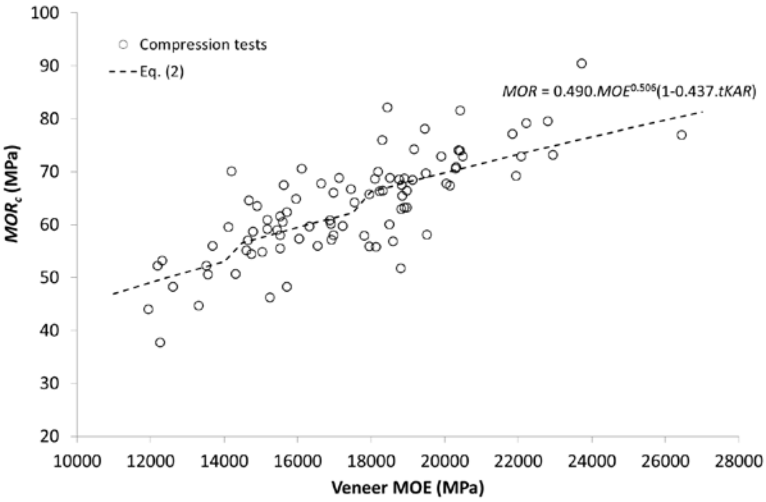


Figure 3: *Tension test set-up (schematic and actual)*

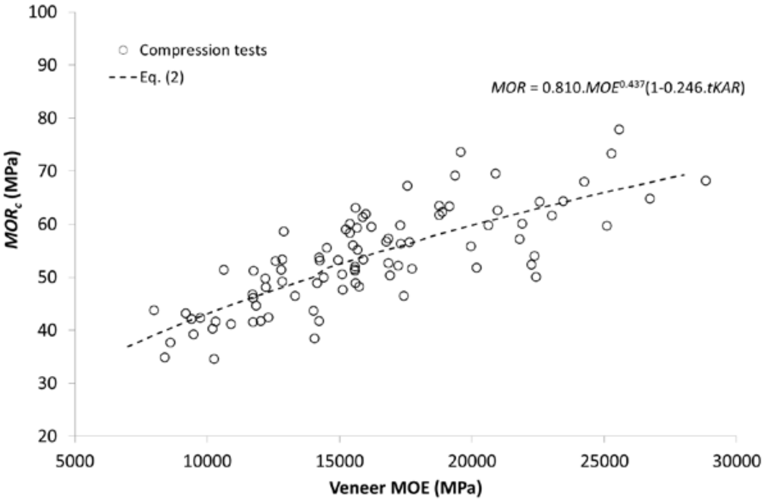


(a) *(b)* *(c)*

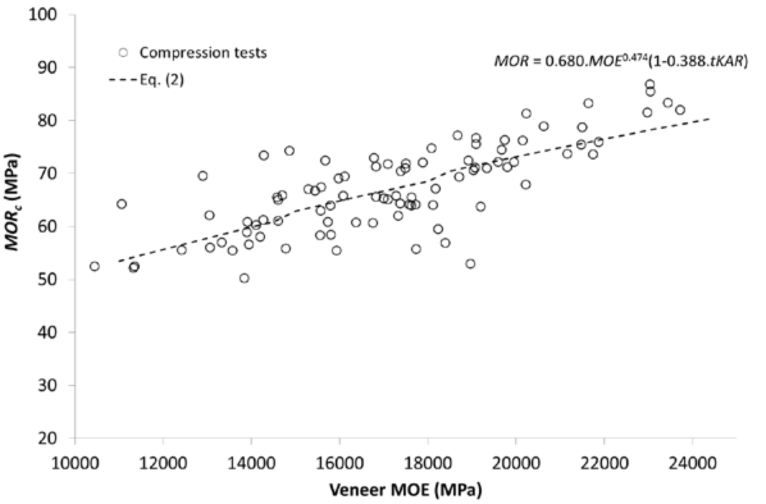
Figure 4: *Finding knot area ratio, (a) original veneer strip (1.2 m × 0.4 m), (b) knots visually marked and (c) black and white picture for image processing with compression and tension samples shown*



(a) Spotted gum

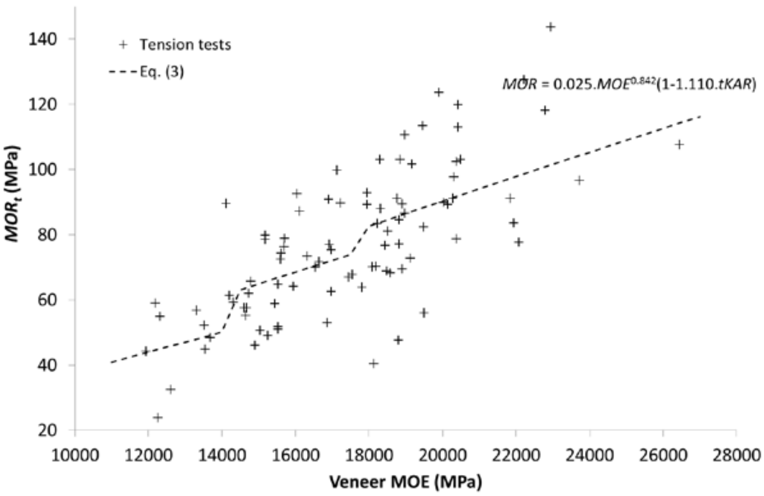


(b) Southern blue gum

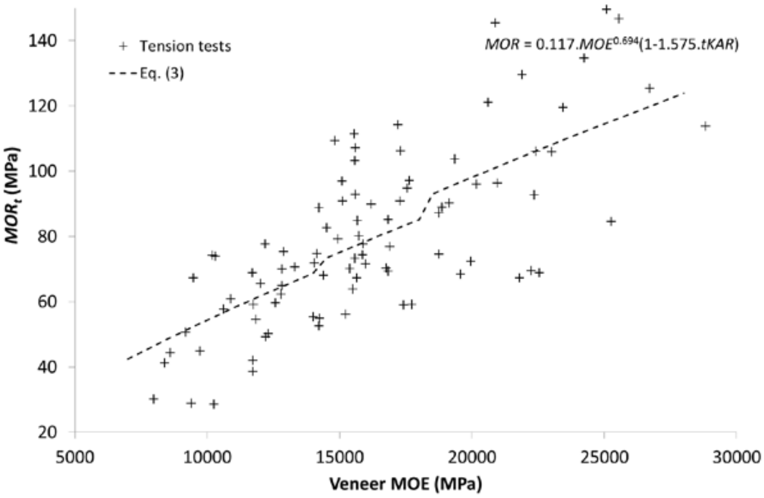


(c) Gympie messmate

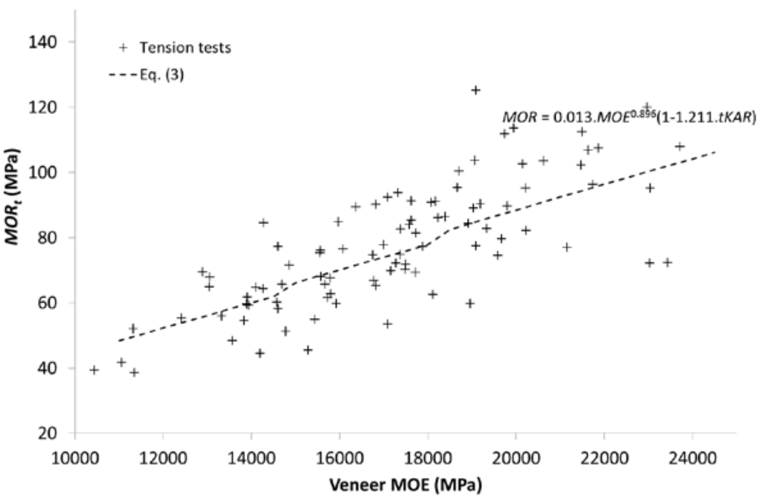
Figure 5: *Relationship between the measured compressive MOR and veneer dynamic MOE for the three investigated species*



(a) Spotted gum



(b) Southern blue gum



(c) Gympie messmate

Figure 6: *Relationship between the measured tensile MOR and veneer dynamic MOE for the three investigated species*

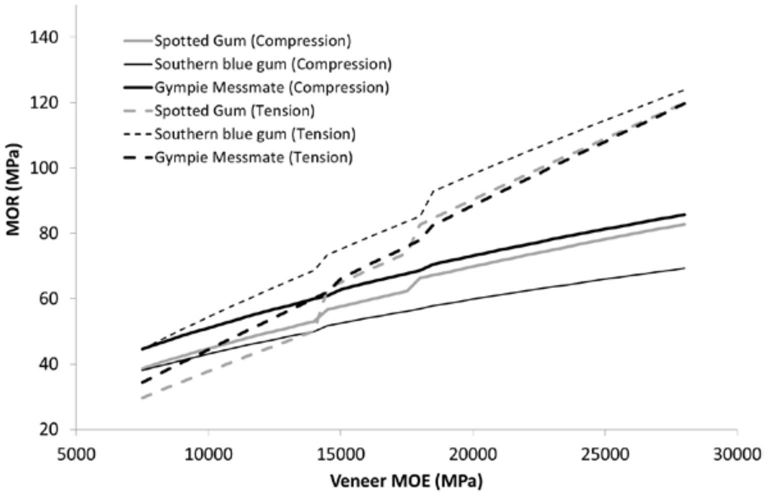
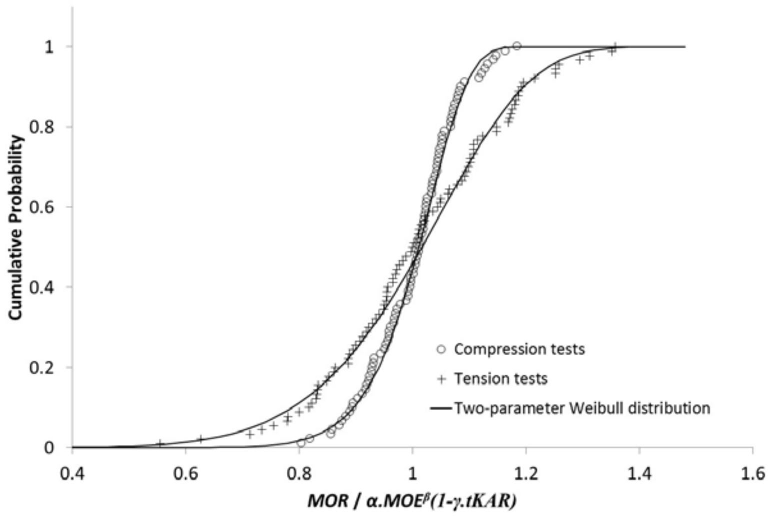
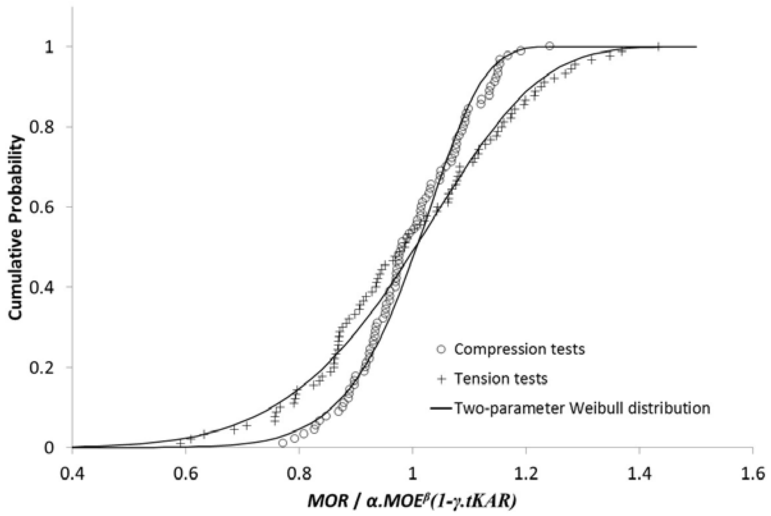


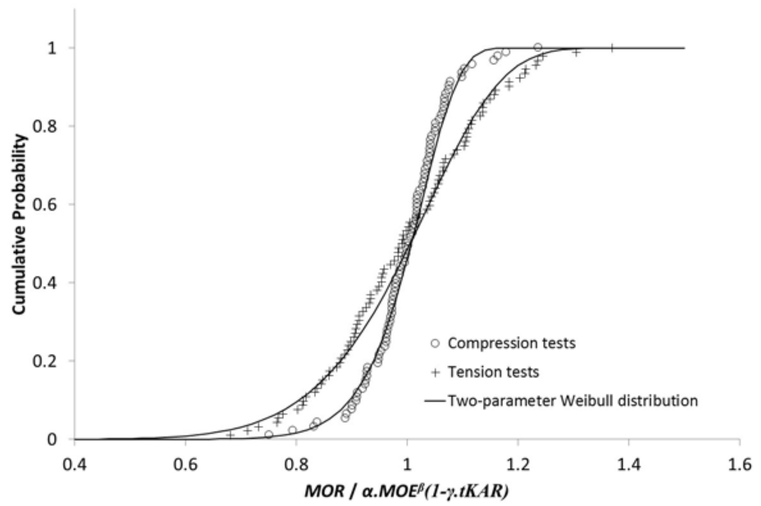
Figure 7: *Best predicted compressive and tensile MOR vs veneer MOE for all species*



(a) Spotted gum

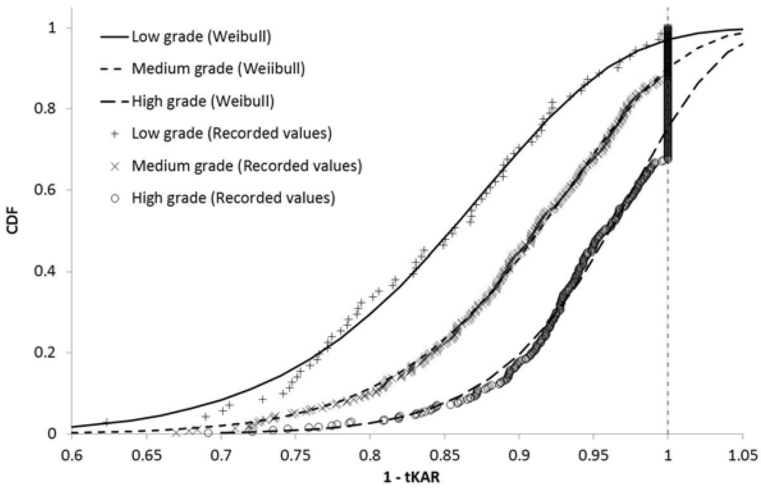


(b) Southern blue gum

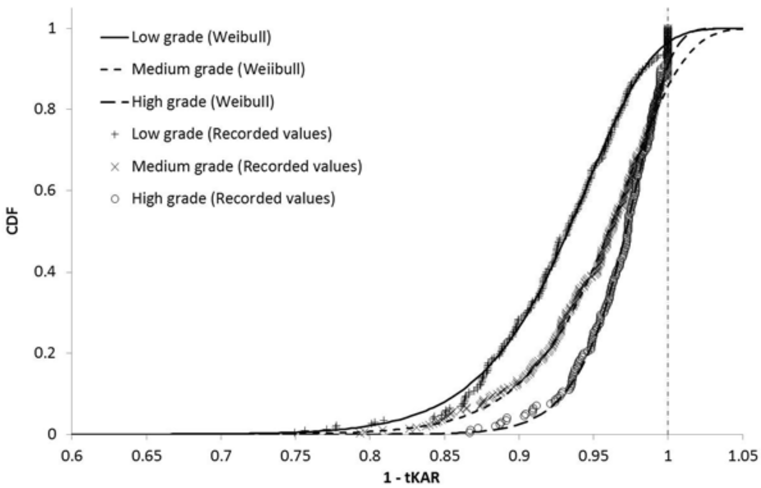


(c) Gympie messmate

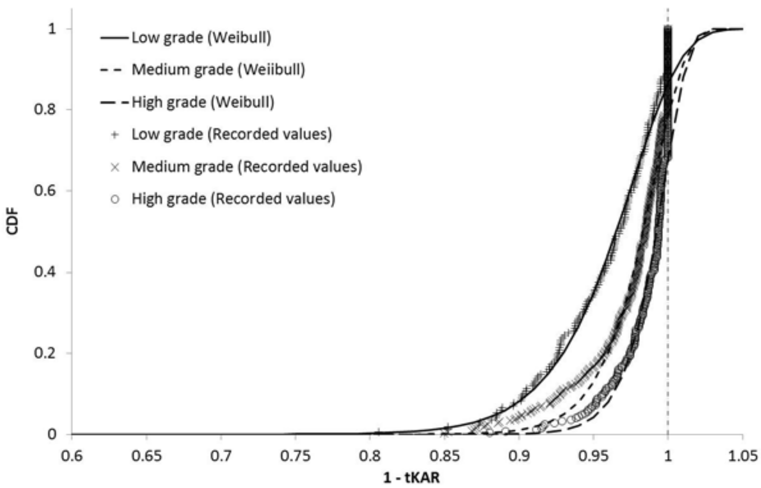
Figure 8: *Cumulative distribution test results for all investigated species*



(a) Spotted gum



(b) Southern blue gum



(c) Gympie messmate

Figure 9: *Total knot area ratio distribution for* $l = l_{ref}$