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Evaluation of wood characteristics of tropical post-mid rotation plantation *Eucalyptus cloeziana* and *E. pellita*: Part (c) Wood quality and structural properties

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Evaluation of wood characteristics of tropical post-mid rotation plantation *Eucalyptus cloeziana* and *E. pellita*: Part (c) Wood quality and structural properties

Prepared for

Forest and Wood Products Australia

by

H. Bailleres, G.P. Hopewell and R.L. McGavin

Executive summary

A general lack of information about the expected wood quality and structural properties, along with processing characteristics and product suitability of wood harvested from fast-grown hardwood plantations is delaying investment in plantation establishment in Queensland. While several Managed Investment Scheme (MIS) companies are investing in plantation development, the current trend is to focus on pulp wood management practices. The lack of assurances of the likely wood quality outcomes from target species is a significant impediment to being able to invest in management regimes more suited to the production of solid wood and engineered wood products.

Research and development activities are assisting with removing the investment uncertainly however have been hindered by the general absence of plantations of an age, quality and relevant species to facilitate processing, product and wood quality studies, especially that are reflective of expected final harvest age.

In March 2006, Cyclone Larry crossed the north Queensland coast near Innisfail causing substantial damage. The devastation did however provide a unique opportunity to access large plots of quality 15-year-old *Eucalyptus pellita* (red mahogany) and 19-year-old *Eucalyptus cloeziana* (Gympie messmate). Although these plantation areas were destroyed by the cyclone, 42 *E. cloeziana* trees and 32 *E. pellita* trees with minimal or no visible damage were salvaged enabling detailed testing to be undertaken. Testing was conducted to determine wood quality attributes including density, extractive content, unit shrinkage, heartwood proportion and sapwood width. Structural properties testing including small clear and full section strength and stiffness, hardness, joint group, visual grade assessment and natural vibration-based grade assessment were also completed. Included into the testing methodology was the assessment of variation that existed between the inner, intermediate and outer heartwood zones and in limited cases, the variation between provenances.

Measured average basic densities were 588 kg/m^3 and 715 kg/m^3 for *E. pellita* and *E. cloeziana* respectively which are approximately 26% and 12% below the density expected from mature native forest wood of the same species. The density variation that existed from the inner heartwood to the outer heartwood was approximately 100 kg/m^3 for *E. cloeziana* while *E. pellita* varied by approximately 200 kg/m^3. Average extractive contents were 5.55% and 5.16% for *Eucalyptus pellita* and *E. cloeziana* respectively, but varied widely between trees. Both species showed approximately 40% extractive increase from the inner to the outer heartwood. The heartwood proportion was 76% of *E. cloeziana* and 67% for *E. pellita*. These properties were measured from samples sourced from discs that in the majority of cases, were removed from the top of the butt log during merchandising.

The hardness value for *E. cloeziana* was 11 kN which is very close to mature native forest wood. *Eucalyptus pellita* was approximately 30% below that expected from mature native forest wood at 7 kN. There was a trend of increasing hardness from inner to outer heartwood for both species, although the variation was greater for *E. pellita*. Screw and nail withdrawal characteristics for both species followed similar trends with inner and intermediate heartwood having lower value characteristics than the outer heartwood. The fastener withdrawal test resulted in joint groups JD2 and JD4 being assigned to the *E. cloeziana* and *E. pellita* test populations respectively, a lower rating than the JD1 expected for mature native forest wood of both species.

Small clear strength and stiffness (modulus of rupture or MOR and modulus of elasticity or MOE) testing revealed that *E. cloeziana* has the same strength group (SD3) expected from

mature native forest wood. Heartwood zone analysis gave similar results for intermediate and outer heartwood, which both had higher values than those measured for the inner heartwood. *Eucalyptus pellita* satisfied the requirements of SD5, two levels below the SD3 expected from mature native forest timber, and demonstrated an increase from the inner heartwood through to the outer heartwood. This result suggests that this species probably matures more slowly than *E. cloeziana*.

Visual grading for both appearance and structural purposes highlighted the negative impact that heart and heart shakes, as well as knots, have on grade recovery. These defects are characteristic of harvesting relatively young, fast grown trees. Vibration analysis techniques, mainly the resonance method, provided a reliable, practical and simple means of structural grading. Longitudinal vibration measurement could be the simplest way for industry to obtain a consistent and accurate sorting process. The economic benefits could be substantial with reduced cost-adding to low grade and out-of-grade material, by early detection of this wood and diversion to more appropriate product streams.

Static bending tests to confirm MOE and MOR further reinforced the difficulty and inaccuracy of applying visual grading rules developed for mature native forest timber to plantation timber. The average MOE result was 15200 MPa and 13000 MPa and average MOR result was 81.0 MPa and 63.2 MPa for *E. cloeziana* and *E. pellita* respectively. *Eucalyptus pellita* test results were affected by some boards with unusually low MOE and even lower MOR, which is most likely the consequence of brittle heart.

Analysis of genetic impact on wood properties was limited to a preliminary analysis of two provenances of *E. cloeziana*. No significant difference was found between the provenances for MOR and MOE of small clear and full sized samples, distortion, hardness or nail and screw withdrawal. Heartwood proportion, extractive content, basic density and unit shrinkage differed between the provenances.

Overall the wood quality attributes measured for 19 year-old *E. cloeziana* and 15 year-old *E. pellita* plantation material are positioned between those expected of wood from mature native forest trees and those measured in previous studies on younger plantation material of the same species. Compared to mature native forest grown timber of the same species, *E. cloeziana* displays similar overall properties and performance. Unexpectedly, *E. pellita* showed relatively poor wood quality and despite being almost twice the age, showed similar qualities to that measured for eight-year-old plantation material in recent studies. While the plantations were damaged during the cyclone event, there were no obvious visible signs of damage within the wood to indicate that the event had harmed the wood quality or mechanical properties of the selected trees. The results of the study provide encouragement, especially for *E. cloeziana*, that plantations of the species and age tested, should be able to provide wood suitable for a range of high-value solid wood and composite products.

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1 Introduction

1.1 Background

Queensland Government policies for protecting the State's natural heritage and development of a secure and sustainable hardwood timber industry include a commitment to progressively phasing out native forest logging from State lands and industry transition to hardwood plantations. As part of a national trend, private sector forestry companies (mainly Managed Investment Scheme or MIS companies) are procuring land and establishing hardwood plantations. MIS companies want to invest in hardwood plantations but need to a) attract funds and b) invest those funds in locations where they are confident that they can achieve their prospectus targets with selected species. Investment in Queensland is significantly less than other states and key MIS companies suggest that the lack of assurance of likely wood quality outcomes from target species is a significant impediment to being able to invest a greater proportion of funds in Queensland and especially into plantation establishment with solid wood management regimes targeting value added products such engineered wood products. While extensive research programs exist to aid the removal of investment uncertainty, efforts have been hindered by the general absence of plantations of an age, quality and relevant species to facilitate processing, product and wood quality studies, and especially those that reflect the expected final harvest age for solid wood products.

In March 2006, Cyclone Larry crossed the north Queensland coast near Innisfail as a category five cyclone bringing with it wind speeds estimated at 320 km/hr. While the damages bill for primary industries was estimated at $470 million with agricultural crops and forests being devastated over an area of approximately 12,500 square kilometres (Department of Primary Industries and Fisheries 2006), a unique opportunity arose to salvage quality plantation material from large plots of 15-year-old red mahogany (*Eucalyptus pellita*) and 19-year-old Gympie messmate (*Eucalyptus cloeziana*) in the Innisfail area. Although both plots were destroyed by the cyclone, large numbers of stems remained with minimal or no visible damage and which could be salvaged for the purposes of wood quality, processing and product study. While previous studies of tropical plantation hardwoods have occurred with 7- to 9-year-old and >30-year-old plantations, this study was able to focus on critical results for mid-age range or early final crop harvest age material, which is relevant to the prediction of product quality from future plantations.

This research on wood quality and structural properties complements other studies on the *E. pellita* and *E. cloeziana* material and which have been reported independently for plywood mechanical properties (Hopewell *et al*. 2007), accelerated seasoning and grade quality, (Redman and McGavin 2007), and durability (Francis and McGavin 2007).

1.2 Objectives

The aim of this study was to evaluate the wood quality and structural properties of timber sourced from plantation grown 19-year-old Gympie messmate and 15-year-old red mahogany. In addition, the within-tree variation was also investigated by accessing the inner, intermediate and outer heartwood log zones. Both plantations contained two different provenances and where sufficient data permitted, provenance variation was also analysed.

This study provided:

1. Wood properties information:
   - basic density
   - shrinkage

- unit shrinkage
- extractive content
- heartwood proportion and
- sapwood width

2. Mechanical properties information:

- visual grade quality (for structural and appearance products)
- determination of structural properties through natural vibration testing
- modulus of elasticity (for clear wood and full sections)
- modulus of rupture (for clear wood and full sections)
- hardness and
- joint group (via nail and screw withdrawal)

Layout of the report

The report comprises of five sections. Section 2 provides an overview of the sampling strategy adopted for the study, the methodology including wood and mechanical properties testing is outlined in Section 3, while Section 4 presents the results of the testing undertaken along with analysis and discussion. Section 5 completes the report with some concluding comments and recommendations for further research.

2 Material and sampling strategy

2.1 Plantation material

2.1.1 Eucalyptus cloeziana

Eucalyptus cloeziana (Gympie messmate) is a large hardwood tree of scattered occurrence in eastern Queensland from Gympie in the south to the Atherton district in the north. It is usually found in open-forests or woodlands, on soils that are generally well drained, acidic and of low fertility, with an annual rainfall of 550 – 2,300 mm (Boland *et al.* 1984). The timber from *E. cloeziana* has traditionally been used for heavy engineering construction, railway sleepers, mine timber, posts and poles due to its favourable natural durability and strength properties (Boland *et al.* 1984; Bootle 2005). Published wood properties' data for mature *E. cloeziana* wood are summarised in Table 1 below.

Table 1. Properties for mature *Eucalyptus cloeziana* wood.

Air dry density [c]	1010 kg/m^3
Strength groups/ stress grades [c]	green- S2/ F11-F22; seasoned- SD3/ F14-F27
Joint groups [c]	green- J1; seasoned- JD1
Natural durability ratings [c]	above-ground- 1; in-ground- 1
Lyctine susceptibility [c]	not susceptible
Termite resistance [c]	highly resistant
MOR [d]	green- 94 MPa; seasoned- 137 MPa
MOE [d]	green- 14 GPa; seasoned- 17 GPa
Maximum crushing strength [d]	green- 49 MPa; seasoned- 73 GPa
Janka hardness [d]	green- 7.7 kN; seasoned- 12 kN

[a] Perrin 1988 ; [b] Cause *et al.* 1989 ; [c] Hopewell 2006; [d] Bootle 2005 (small clear sample testing).

Due to the combination of desirable wood properties and good growth characteristics, *E. cloeziana* is one of six key species currently grown in Queensland state-owned plantations (Department of Primary Industries and Fisheries 2006) and has been identified as a candidate for establishment in private timber plantation projects, particularly in north Queensland.

Of four similarly aged hardwood species processed in a DPI&F trial in Argentina in 2001, 13- and 14-year-old *E. cloeziana* provided the highest green-off-saw recovery due to superior form of the logs (Hopewell 2002). *Eucalyptus cloeziana* plantation stems have recently been successfully steam bent in their natural round form as part of an investigation into innovative products from traditional non-commercial thinnings presenting opportunities for arched structural products from this emerging resource (Thirion 2007). McGavin *et al.* (2006) and McGavin and Bailleres (2007) also reported extensive wood and mechanical properties testing along with market suitability studies for eight-year-old *E. cloeziana* plantation thinnings showing encouraging potential.

The *E. cloeziana* plantation used for this study was located on Crupi Road, approximately 30 km south of Innisfail. The plantation received extensive damage during the Cyclone Larry event, however, during the salvage assessment it was noted that many of the damaged trees had blown over with the root ball intact with little or no obvious damage to the merchantable bole. At the time of the cyclone, the trees were 19-years-old, representing approximate full rotation age being targeted by plantation managers, providing ideal material for research and development activities. A plantation summary is presented in Table 2.

Table 2. Nineteen-year-old *Eucalyptus cloeziana* plantation summary.

Provenances	Pomona, south Queensland Helenvale, north Queensland
Location	Crupi Rd, approx. 30 km south of Innisfail
Owner	Mr Graham D. Smith
Soil	red podsolic
Rainfall	3340 mm/ annum
Slope	3°
Aspect	south-east
Altitude	40 m asl
Planting date	03/1987
Age at cyclone salvage	19-year-old
Original stocking	1234 stems per hectare (spha)
Espacement	3.0 m x 2.7 m
Site preparation	1. three-furrow disc plough 2. deep rip to 0.4 m 3. offset discing x 3 passes 4. planting holes by motorized soil auger
Silvicultural history	*weed control*- 2 m row maintained until age 2 *fertilisation*- 300 g/tree Crop King Q5 at planting 600 g/tree Crop King Q5 at age 1 yr *pruning*- to 1.5 m at age 1.5 yrs and to 6 m at 3.5 yrs *thinning*- to 400 spha at age 4.5 yrs
General comments	This plantation experienced good growing conditions during the 19 years prior to Cyclone Larry. Pomona provenance material was producing more wood volume through straighter formed and more vigorous stems.

(Source: Dickinson, 2006a.)

2.1.2 Eucalyptus pellita

Eucalyptus pellita (red mahogany) is a species native to tropical north Queensland, Papua New Guinea and Irian Jaya (Indonesia), where it is mainly found on moist sites such as gentle slopes, creek banks and alluvial plains, with an annual rainfall of 900 - 2200 mm (Boland *et al.* 1984; Harwood 1998). The species shares it's standard trade name of red mahogany with *E. resinifera* (Standards Australia 2001), both of which have similar wood properties. Due to its sporadic distribution, *E. pellita* timber has traditionally only been available locally in limited quantities. It is used for flooring, cladding, panelling and general construction (Boland *et al.* 1984; Bootle 2005). Published wood properties' data for mature *E. pellita* wood are summarised in Table 3 below.

Table 3. Properties of mature *Eucalyptus pellita* wood.

Air dry density [c]	995 kg/m^3
Strength Groups/ Stress Grades [c]	green- (S2)/ F11-F22; seasoned- (SD3)/ F14-F27
Joint groups [c]	green- J1; seasoned- JD1
Natural durability ratings [c]	above-ground- 1; in-ground- 2
Lyctine susceptibility [c]	untreated sapwood is susceptible
Termite resistance [c]	highly resistant
MOR [d]	green- 78 MPa; seasoned 140 MPa
MOE [d]	green- 16 GPa; seasoned- 18 GPa
Maximum crushing strength [d]	green- 50 MPa; seasoned- 76 GPa
Janka hardness [d]	green- 9.0 kN; seasoned 12 kN

[a]Perrin 1988 ; [b]Cause *et al.* 1989 ; [c]Hopewell 2006 ; [d] Bootle 2005 (small clear sample testing).

Due to its fast growth, *E. pellita* has been a species of interest in north Queensland for land degradation control and commercial timber plantation establishment (Sun *et al.* in Muneri *et al.* 2001).

In addition to trials established by DPI&F in collaboration with various landholders in the tropical north, private forestry companies are beginning to plant *E. pellita* in the region. ITC Limited report plans to expand their private estate in northern Queensland to approximately 50,000 ha, of which *E. pellita* will be one of probably three or four key species (Larsen 2006). ITC Limited's current 2008 investment prospectus details plans for *E. pellita* plantation establishment with commercial thinning at age seven and clearfall at age 18.

Prior to the Cyclone Larry salvage trials, DPI&F undertook research work on the same *E. pellita* plantation when it was eight years old (Muneri *et al.* 2001). Additional wood products' research has been reported by Hopewell (2002) on 13- and 14-year-old *E. pellita* grown in Argentina. These trials highlighted the species propensity to decay, generally associated with heart and branch wounds, which resulted in relatively low graded recoveries. Nevertheless, the boards recovered from the Argentinean study indicated that by age 14, *E. pellita* displays a good level of red colouration. McGavin *et al.* (2006) reported detailed wood and mechanical properties' information for a small sample of eight-year-old *E. pellita* plantation thinnings along with preliminary utilisation information for veneer, sawn timber and round wood applications.

The logs salvaged for this investigation were sourced from a genetics trial and seed production crop in the cyclone affected zone. In contrast to the *E. cloeziana*, most of the cyclone-damaged *E. pellita* trees broke off above the ground line, possibly due to less intensive site preparation activities, differing soil type, more exposed topography or different rooting characteristics. Although not quantified, general observations suggested that the Papua New Guinea provenance suffered more damage than the Australian provenance. The silvicultural and site data for the sampled plantation is summarised in Table 4.

Table 4. 15-year-old *Eucalyptus pellita* plantation summary.

Provenances	Coen, north Queensland (CSIRO 14339) North Tokwa to Kiriwa, Papua New Guinea (CSIRO 16121)
Location	Dillon property, approx. 20 km N of Innisfail 17°28'S, 145°57'E
Owner	Mr Dennis Dillon
Soil	red ferrosol (krasnozem)
Rainfall	3340 mm/ annum
Slope	1° to 5°
Aspect	easterly
Altitude	80 m a.s.l.
Planting date	05/1991
Age at cyclone/harvest	15-year-old
Original stocking	1143 stems per hectare
Espacement	3.5 m x 2.5 m
Site preparation	1. offset discing, two passes 2. planting holes dug with mattock ('grubber')
Silvicultural history	*weed control*- 2 m row maintained until age 1.5 years *fertilisation*- none recorded *pruning*- to 1.5 m at age 14 months and to 3.5 m at 2.5 yrs *thinning*- 1. to 700 spha at 14 months 2. to 400 spha at 2 yrs 3. to 240 spha at 5 yrs 4. to 150 spha at 8.5 yrs
General comments	Prior to the cyclone, tree growth and health had been very good, with the PNG provenance performing marginally better on average than the north Queensland material.

Source: Dickinson 2006b; Muneri *et al.* 2001

2.2 Tree selection and harvesting

The damage caused to the plantation area by the cyclone influenced decisions about choosing suitable trees for the study. It was estimated that for each specie, 40 butt logs, each six metres in length and 15 top (or second) logs of three metres were required for the study. Based on earlier site investigations, it was expected that this quantity of material should be available from trees that suffered minimal or no damage to the merchantable log section.

The *E. cloeziana* plantation presented few problems in achieving the desired volume of quality logs. While the plantation was destroyed by the cyclone, many of the trees were blown over with the root ball still intact with minimal or no apparent damage to the merchantable bole. The *E. pellita* plantation received substantially more damage and many trees had snapped along the merchantable bole. In total, 42 *E. cloeziana* trees and 32 *E. pellita* trees were used to provide material for the study.

Harvested study trees were merchandised with the intention of maintaining long lengths suitable for long distance road haulage. The target lengths were six metre butt logs and three metre secondary logs, although there were some six metre secondary logs. After preliminary merchandising, logs were end sealed with a proprietary brush-on end sealer treatment and then transported to the Salisbury Research Centre[1] for final merchandising, allocation and testing.

2.3 Sample distribution

Once logs arrived at the Salisbury Research Centre, they were measured accurately and merchandised for final distribution. Merchandising included allocating veneer billets, sawlogs, seasoning sawlogs and wood quality discs. Figure 1 provides a generalised schematic of the flow of material showing how the logs were sampled for this wood quality and structural properties study, the accelerated seasoning study, veneer and plywood study and durability study.

[1] Salisbury Research Centre in Brisbane is managed by DPI&F as a forest products processing research facility.

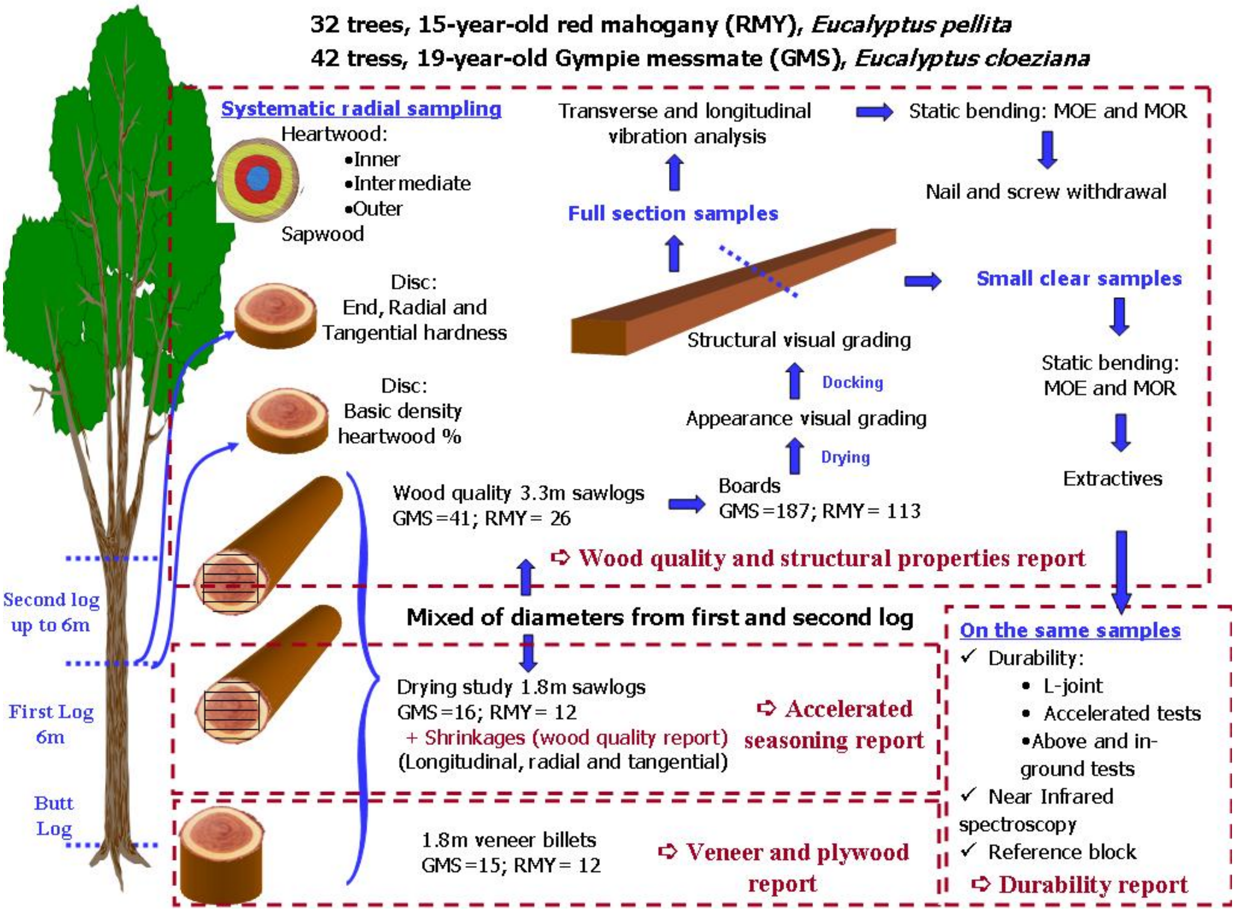


Figure 1. Generalised schematic of material flow showing how logs were sampled for the four separate studies.

2.3.1 Veneer billets

The allocation of veneer billets received the highest priority given the need for large diameter and high quality billets. The allocation method used was to rank each log by large end diameter and direct the first, third, fifth, etc largest logs to provide 15 billets from each species batch for the veneer and plywood trials. The rationale for selecting each second log was to ensure that a sample of large diameter logs was also available for solid wood processing trials. A 1.8 metre section was removed for the veneer billet with the balance being returned for further allocation. Additional information regarding the billets used for the veneer and plywood trials have been reported independently by Hopewell *et al.* (2007).

2.3.2 Sawlogs

Sawlogs were used to provide many of the wood quality and mechanical properties samples and were the second priority during final merchandising and allocation of logs. The target sawlog length was 3.3 metres although some variation existed and shorter logs were included to increase the sample size where necessary. A total of 41 *E. cloeziana* logs and 26 *E. pellita* logs were allocated as sawlogs (Table 5 and Table 6). All sawlogs were processed at the Salisbury Research Centre.

Table 5. *Eucalyptus cloeziana* sawlog summary.

N=41	Small end diameter (mm)	Large end diameter (mm)	Log length (m)	Log volume[1] (m^3)
Mean	287	335	3.45	0.260
Standard deviation	62	63	0.02	0.104
Maximum	429	457	3.49	0.486
Minimum	193	231	3.40	0.122

[1]Note: Huber's formula used to estimate sawlog volume.

Table 6. *Eucalyptus pellita* sawlog summary.

N=26	Small end diameter (mm)	Large end diameter (mm)	Log length (m)	Log volume[1] (m^3)
Mean	271	315	3.33	0.217
Standard deviation	52	60	0.27	0.090
Maximum	377	454	3.52	0.424
Minimum	194	230	2.64	0.099

[1]Note: Huber's formula used to estimate sawlog volume.

2.3.3 Seasoning sawlogs

Sixteen *E. cloeziana* and 12 *E. pellita* logs approximately 1.8 m in length were allocated for assessing the accelerated seasoning behaviour of the plantation sawn wood. Shrinkage and unit shrinkage samples were also sourced from these logs during processing and aside from the results of these tests, the seasoning component of the study has been reported independently by Redman and McGavin (2007).

2.3.4 Discs

One wood quality sample disc per tree was collected to facilitate the following tests:

- heartwood proportion
- sapwood width
- density

These discs were generally removed from the top of the butt (or first) log after final merchandising was completed and resulted in the majority removed from 1.8 m to 4.2 m from the large (or stump) end of the butt log. In limited cases, the disc was removed from the butt end of the butt log, but only where at least 300 mm was first removed. This discarded section combined with the height of the tree stump after harvesting meant that the disc was sourced at least 600 mm above the ground line. This strategy was implemented to minimise any influence of unusual wood properties that may exist close to ground line.

In addition to the wood quality sample disc, one other disc was removed from 12 randomly selected *E. cloeziana* trees and 11 randomly selected *E. pellita* trees for the purposes of hardness testing. These discs were not necessarily removed from any specific part of the logs.

2.3.5 Sawn timber

Sawlogs were painted on the small (top) end with differing colours that reflected the inner (blue), intermediate (red) and outer heartwood (yellow) areas (Plate 1). The zone boundaries were determined by dividing the total heartwood radius into three equal distances. The sapwood zone remained uncoloured.

Plate 1. Painted log ends identify inner (blue), intermediate (red) and outer (yellow) heartwood zones.

Sawlog processing aimed to retrieve 100 mm wide and 38 mm thick boards only. To be identified as originating from a specific heartwood zone, each board needed to show at least 75% of the representative paint colour. The target was to cut five boards from each sawlog: two boards from each of the intermediate and outer heartwood zones and one board from the inner heartwood zone. In general, these originated from the centre cant component of the log. The inner heartwood target board either contained or was sawn along the pith. Plate 2 illustrates processing the centre cant to remove target boards.

Plate 2. Processing the centre cant to remove target boards.

Sawlog size and quality influenced the success in achieving these target boards. For example, a smaller diameter log may have only yielded one inner, one intermediate and two outer heartwood boards. In this example, the second intermediate heartwood board was targeted from one of the side wing boards to achieve the five target boards. While only five boards were targeted, the remainder of the log was processed with the aim of cutting boards from within the differing zones to provide spare boards if required at a later date. Despite this plan, in some cases, not all five target boards could be gathered from each sawlog due to log size and/or log and board quality.

In addition to the five target boards from each sawlog (i.e. one inner heartwood and two from each of the intermediate and outer heartwood zones), an additional 60 'spare' sawn boards of *E. cloeziana* (30 intermediate and 30 outer heartwood) were selected randomly and directed towards specific natural vibration analysis and static testing. Of the 60 boards, all had natural vibration measurements recorded in the unseasoned condition prior to static testing to establish unseasoned modulus of elasticity (MOE). Half (i.e. 30 in total comprising 15 intermediate and 15 outer heartwood) were then selected randomly to establish unseasoned modulus of rupture (MOR) by destructive static testing. The remaining 30 boards were seasoned to approximately 12% moisture content prior to recording seasoned natural vibration measurements and static testing for MOE and MOR.

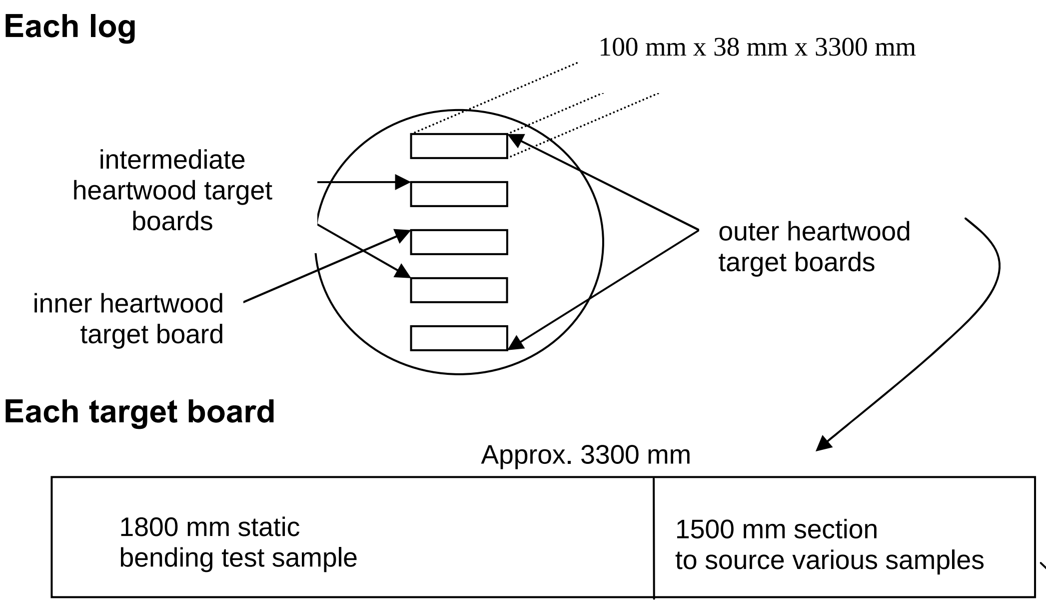
The unconventional sawing pattern aimed at producing boards from specific parts of the log rather than maximising sawn recovery. This approach was chosen to ensure representation of the three heartwood zones for the majority of the wood quality and mechanical properties testing reported here as well as the durability testing reported independently by Francis *et al.* (2007).

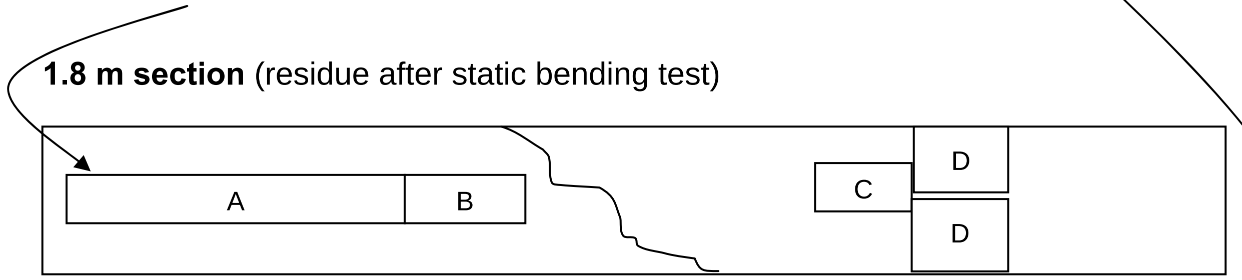
Sawn boards were seasoned using a conservative approach of air drying followed by solar kiln drying to a target moisture content of 12%. The five target boards from each log then underwent a non-destructive mechanical properties test using natural vibration prior to a docking process to remove a 1.8 m and 1.5 m long section from each board.

The 1.8 m long board underwent further natural vibration analysis before being used for destructive full section static bending tests to accurately determine strength and stiffness properties (i.e. MOR and MOE). Some durability test samples including in-ground durability stake, durability reference block and a ground proximity test block were prepared from the residual pieces after destructive strength and stiffness testing (Figure 2). Two joint group samples (i.e. nail and screw withdrawal) were also removed from the residual pieces.

The remaining 1.5 m long board was used to source an above-ground natural durability L-joint sample, extractive content samples, an accelerated decay test sample, a durability reference block, near-infrared[2] spectroscopy (NIRS) sample and a small clear strength and stiffness sample. Figure 2 illustrates the flow of test sample preparation and while this figure shows all samples being removed neatly and in line, in reality, the samples were taken as close to each other as possible, avoiding defects such as knots and sloping grain.

[2] While near infrared spectroscopy samples were removed, the testing and results were not included in this study.





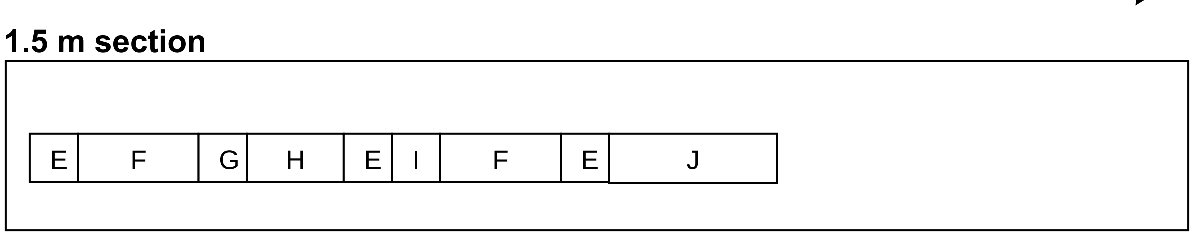
Sample description:

A – in-ground durability stake (20 mm x 20 mm x 500 mm).

B – durability reference block (20 mm x 20 mm x 250 mm).

C – ground proximity test block (75 mm x 25 mm x125 mm).

D – joint group samples (2 pieces 50 mm x 35 mm x 140 mm).



Sample description:

E – extractive content samples (3 pieces 35 mm x 35 mm x 30 mm).

F – above-ground durability L-joint sample (35 mm x 35 mm x 300 mm and 35 mm x 35 mm x 200 mm).

G – accelerated decay test (35 mm x 35 mm x 30 mm).

H – durability reference block (35 mm x 35 mm x 150 mm).

I – near-infrared sample (35 mm x 35 mm x 30 mm). Note: testing and results not included in this study.

J – small clear strength and stiffness sample (20 mm x 20 mm x 300 mm).

Figure 2. Schematic of the sample preparation methodology to remove test samples from sawn target boards.

3 Methods for wood and mechanical quality characterisation

3.1 Data analysis: box plot

Box plots were used to illustrate the data for wood and mechanical properties. A box plot is a chart that indicates the central tendency of the values, their variability, the symmetry of the distribution, and the presence of outliers (i.e. values very different from the others). Box plots are often used to compare several sets of data.

There are several ways to display a box plot, however, this report uses the following format:

- the box itself contains the middle 50% of the data
- the upper end of the box indicates the 75th percentile of the data set
- the lower end indicates the 25th percentile
- the distance between the upper and lower edges of the box is known as the inter-quartile range
- the black horizontal line represents the median
- the red cross represents the average.

If the median line within the box plot is not equidistant from the ends of the vertical line, then the data is skewed.

The ends of the vertical lines indicate the minimum and maximum data values, unless outliers are present in which case the vertical line extends to a maximum of 1.5 times the inter-quartile range.

The outliers are represented as circles which are filled in when the values are more than 3 times the inter-quartile range, and are empty if they are within the 1.5 to 3 times inter-quartile range interval.

3.2 Small clear wood properties

3.2.1 Heartwood proportion and sapwood width

The proportion of heartwood and the sapwood width within a log can have utilisation and processing implications, particularly in lyctine susceptible species or where durability and appearance properties are required.

Heartwood proportion and sapwood width were measured and calculated from the discs removed from each sample tree. The disc samples were sprayed with a dimethyl yellow solution to stain and demarcate the heartwood zone (Plate 3). The sapwood and heartwood dimensions were measured in a radial direction at four points across each disc. Sapwood was recorded as a measure of width (in a radial direction) while the heartwood proportion was calculated as a percentage of disc basal area under-bark.

Plate 3. Example of disc with coloured staining showing heartwood (pink) and sapwood boundary[3].

3.2.2 Extractive content

Wood contains small amounts of extraneous components which do not form part of the cell wall structure, but are probably present, at least in part, as cell contents. Consequently, they can often be extracted from the wood by means of a suitable solvent (organic solvents or sometimes water) without destroying the structure of the wood, and therefore are termed extractives.

Extractives are extremely varied in their chemical nature and embrace many different classes of organic compounds, including tannins, resins, essential oils, fats, terpenes, flavanoids, quinones, carbohydrates, glycosides and alkaloids (Farmer 1967). These components are responsible for some of the characteristic features of individual timbers such as odour, colour and durability.

Using a test method derived by TAPPI (2001), the extractive content of the samples removed from the three heartwood zones of each species was measured using both water and dichloromethane as solvents. For sample preparation, the three extractive sections collected from each board (Figure 2) were combined and ground into a granular consistency. From the particle mix, one test sample was removed and the rest discarded. The same process was repeated to obtain an extractives value for each target board.

3.2.3 Basic density

Basic density is the measurement of the actual wood mass (with all moisture removed) and is calculated as the oven-dry mass of a timber section divided by its green (saturated) volume.

[3] Note that wedges have been removed from the disc for other testing purposes.

Basic density is a useful indicator for characteristics such as hardness, strength, workability and pulping properties.

Two wedges were removed from each disc. The heartwood zones of each wedge were divided into three equal segments (measured in a radial direction) representing inner, intermediate and outer heartwood. The sapwood segments from each wedge were also included (Figure 3).

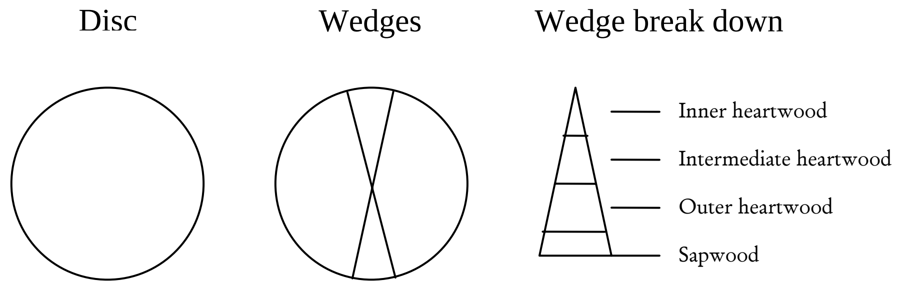


Figure 3. Basic density sample preparation.

Basic density was determined in accordance with Australian and New Zealand Standard *AS/NZ 1080.3:2000 Timber –Method of test –Method 3: Density* (Standards Australia 2000). Green volumes were determined by water displacement before oven-drying to a consistent weight. Basic density was then calculated from the equation:

Basic density (kg/m^3) = oven-dry weight /green volume.

3.2.4 Hardness

The hardness of a timber indicates its ability to resist indentation and ease of working with tools and machinery. Traditionally, hardness has been used to determine species' suitability for applications typically subjected to indentation pressure, such as flooring. Hardness is closely related to a capacity to resist abrasion (i.e. wearing), which is another important property to consider when selecting species for flooring, bench tops and other specialist components where sound wearing properties are necessary.

Hardness was measured by the Janka hardness test in accordance with British Standard *BS373:1957 Methods of testing small clear specimens of timber* (British Standards Association 1957), which requires a steel ball with a diameter of 11.28 mm to be pressed into a test piece until the ball has penetrated to a depth equal to half its diameter.

The disc removed for hardness testing was prepared in a manner that enabled radial, tangential and longitudinal (or end grain) hardness within the inner, intermediate and outer heartwood and sapwood zones (Plate 4). The maximum force necessary to press the ball to the required depth is measured in kiloNewtons (kN) and is recorded as the hardness of the timber.

Plate 4. Hardness sample preparation enabled testing to be conducted on the inner, intermediate and outer heartwood and sapwood zones.

3.2.5 Unit Shrinkage

Shrinkage will occur in wood after the moisture content falls below a particular level, called the 'fibre saturation point'. At this point, the wood cell cavities are empty of free water, but the cell walls are still saturated with chemically bound water. As moisture is removed from the cell walls, the timber shrinks until it reaches the local equilibrium moisture content (EMC), where the moisture content of the wood stabilises to that of the surrounding air. A measurement of the shrinkage that will occur in timber as it dries (or seasons) provides processors with an indication of the dimensions that must be sawn from green timber (necessary extent of over-cutting) to ensure that seasoned timber will be available in the required dimensions. Different species have different rates of shrinkage.

Unit shrinkage is another important measure that provides an indication of the dimensional change that can be expected with seasonal variations, where timber will either increase or decrease in moisture content (and therefore dimension) as the temperature and humidity of the surrounding air fluctuate. Unit shrinkage is expressed as the percentage of dimensional change per one percent change in moisture content and can be applied between about 5% and 25% moisture content where the relationship is linear.

The test method adopted was as described by Kingston and Risdon (1961). Test pieces were cut to the standard size for shrinkage testing (100 mm x 25 mm x 25 mm) and had true radial and tangential faces with length parallel to the grain (Kelsey and Kingston 1957). After the green moisture contents of the samples were determined in accordance with Australian and New Zealand Standard *AS/NZS1080.1:1997 Timber –Method of Test –Method 1: Moisture content* (Standards Australia 1997), the samples were weighed and had length, width and thickness measurements made at regular intervals, until approximately 12% moisture content had been reached. Samples were then reconditioned and redried with measurements taken at about 12% and 5% moisture content before the samples were oven dried to a constant dry weight. The measured unit shrinkage of the test piece is presented as the percentage change in dimension with each one percent change in moisture content.

3.2.6 Nail and screw withdrawal

Nail and screw withdrawal tests were conducted in accordance with Australian Standard *AS1649: 2001 Timber - methods of test for mechanical fasteners and connectors - Basic working loads and characteristic strengths* (Standards Australia 2001). Two samples were prepared from each target board enabling both nail and screw withdrawal to occur with representation across each of the heartwood zones. Test fasteners were 50 mm plain shank nails 2.5 mm in diameter, while screws were 38 mm no. 6 steel wood screws. For each fastener type, four fasteners were inserted in each test piece to the depth specified in *AS1649: 2001*. A Universal Test Machine was used to record the withdrawal load (Plate 5).

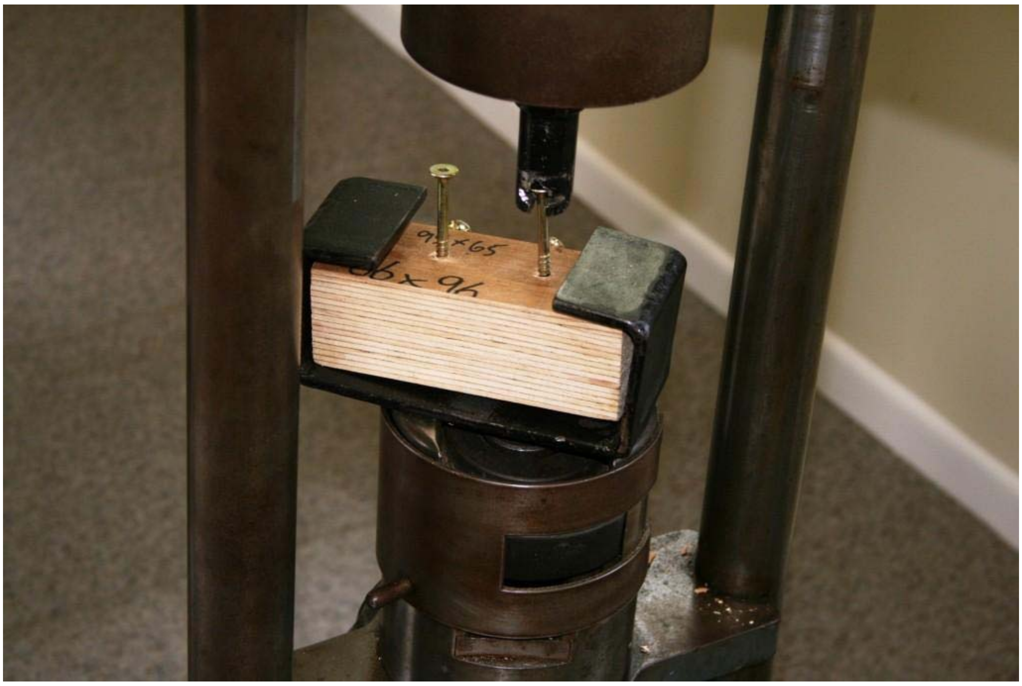


Plate 5. Universal test machine set up for the nail and screw withdrawal test.

Data were analysed as detailed in *AS1649:2001,* which in summary included:

- The determinations for each of the four fasteners per sample were averaged.
- A log transformation was applied to the data to correct for skewness.
- The mean and standard deviation were calculated from the transformed data.
- The fifth percentile for withdrawal load was estimated from the mean and standard deviation.
- The fifth percentile was back-transformed to the original units (Newtons or N).
- The fifth percentile was divided by the fastener penetration to bring the statistic to a per mm penetration basis (R_{5th}, N/mm).
- The basic working load in withdrawal R_{bwl} and characteristic load capacity R_k in N/mm were calculated using the following formulas:

$$R_{bwl} = R_{5th} \div 2.2$$
$$R_k = R_{bwl} \times 1.7$$

The value of R_k was compared with Tables 4.2b and 4.6b of Australian Standard *AS1720.1:1997 Timber structures. Part 1: Design methods* (Standards Australia 1997) to allocate the test population to a dry joint group (JD) for nails and screws respectively.

3.2.7 Static bending – MOE and MOR

The modulus of elasticity (MOE) is a measure of the ability of timber to resist deflection under loads, i.e. its stiffness. Stiffness is measured to enable or determine structure serviceability. For example, a lintel over a door must be sufficiently stiff to prevent excessive deflection. If large deflections occurred, the door would jam due to the 'sag' in the lintel.

The modulus of rupture (MOR), or bending strength, is a measure of the ultimate short-term load carrying capacity (breaking point). This measure of bending strength indicates the maximum load that can be applied to a timber section without resulting in ultimate failure (breakage).

The small clear strength testing was conducted as described in Mack (1979). Small clear timber samples with a dimension of 20 mm x 20 mm and 300 mm in length were conditioned to approximately 12% moisture content prior to being centre-point loaded. The magnitude of deflection for given loads was recorded for MOE and the force required to break the sample recorded for MOR.

Average MOE and MOR values for each batch were compared with the limiting values for standard seasoned strength group ratings described in Australian and New Zealand Standard *AS/NZS2878:2000 Timbers - Classification into strength groups* (Standards Australia 2000), which are reproduced in Table 7.

Table 7. Strength group ratings for seasoned timber (*AS/NZS2878:2000*).

	Strength group							
	SD1	**SD2**	**SD3**	**SD4**	**SD5**	**SD6**	**SD7**	**SD8**
MOR (MPa)	150	130	110	94	78	65	55	45
MOE (MPa)	21500	18500	16000	14000	12100	10500	9100	7900

3.3 Full section characteristics: grade determination and structural properties

3.3.1 Visual grading – appearance purposes

Visual grading was conducted to determine the recovery that could be achieved for appearance type products and the variation that may exist between the different heartwood zones. Visual grading was completed on all available target boards in accordance with Australian Standard *AS2796:1999 Timber – Hardwood – Sawn and milled products* (Standards Australia 1999).

Conformance with the distortion limitations (e.g. twist, spring and bow) was undertaken assuming a product category of strip flooring.

Grade quality was assessed against the standard's grade quality criteria to determine whether each full length target board satisfied the criteria of select grade (highest grade), medium feature grade or high feature grade. Boards that failed to meet any of these grade criteria were rejected. Once the full length grade was determined, a hypothetical docking process was undertaken to evaluate whether the original grade quality could be improved by reducing the board length to remove grade limiting defects or imperfections. A minimum length of 1.2 m was set.

3.3.2 Visual stress grading – structural purposes

Visual stress grading for structural purposes was undertaken in accordance with Australian Standard *AS2082:2000 Timber –Hardwood -Visually stress-graded for structural purposes* (Standards Australia 2000). This standard categorises timber pieces of a particular visual quality into structural grades from one to four, with structural grade one containing the highest structural properties (Table 8). For this study, grading was conducted on full length boards and no further re-sawing was considered. Only the most obvious grade limiting characteristic was recorded.

The species strength group which is derived from small clear strength testing (see section 3.2.7) can then be used in combination with the structural grade obtained from visual grading to allow a stress grade (F-grade) to be determined for each piece (Table 8). Specific timber stress grades are used in structural designs and building plans to specify required strengths for construction.

Table 8. Stress grade (F-grade) determination for seasoned timber (AS2082:2000).

Strength group	**Stress grade (F-grade)**			
	No. 1 structural	**No. 2 structural**	**No. 3 structural**	**No. 4 structural**
SD1	F43	F34	F27	F22
SD2	F34	F27	F22	F17
SD3	F27	F22	F17	F14
SD4	F22	F17	F14	F11
SD5	F17	F14	F11	F8
SD6	F14	F11	F8	F7

3.3.3 Full section static stiffness and strength testing

Traditionally, small clear strength testing has been used to establish a species strength group and visual grading used to determine the structural grade of an individual piece of structural timber. Combined, these two attributes have been used to assign a stress or F grade (see section 3.3.2 for further explanation). While this has worked effectively for many years, with the changing nature of the forest resource (e.g. from mature native forest to regrowth and young fast grown plantations), there is a need to better understand the strength properties of timber sections and to more accurately define their potential for final products. Strength testing full section pieces (in-grade testing) aids in this process by determining the modulus of elasticity (MOE) and modulus of rupture (MOR) for each individual piece of timber in a form intended for final use and therefore more accurately characterises the resource.

Each of the target boards was visually graded against current appearance and structural grade quality standards Natural vibration analysis measurements were recorded (see sections 3.3.1, 3.3.2 and 3.4 respectively) prior to destructive static testing to establish accurate MOE and MOR values. Testing was conducted in accordance with Australian and New Zealand Standard *AS/NZS4063:1992 Timber – Stress-graded – In-grade strength and stiffness evaluation* (Standards Australia 1992).

3.4 Non-destructive structural properties assessment by natural vibration analysis (resonance method)

Wood is a highly variable material and can only be characterised accurately on a case-by-case basis, which is further complicated by the wide range of different industrial and non-industrial uses. Vibration analysis is a simple and efficient way of characterising the elastic properties of wood. This analytical technique is being used to an increasing extent in wood sciences and the principles are used in industrial grading machines.

Vibration tests were performed on each sawlog prior to processing, each target board in the full length seasoned condition and the 1.8 m section once docked from the target board. Vibration tests were also performed on 60 spare boards as explained in 2.3.5. Testing used a BING system[4] with results collected for longitudinal and transverse vibrations (Figure 4). Each test specimen was placed on elastic supports so as to generate free vibrations when possible. Then an exciting impulse was made by lightly striking the specimen with a hammer at the opposite side of the acoustic microphone. The output signals were transmitted via a low-pass filter (cut-off frequency 20 KHz) to an acquisition card (sampling frequency 82 KHz for longitudinal and 20 KHz for transverse) on a computer and recorded. The signal was analysed by a Fast Fourier Transform (FFT) in order to extract one or several harmonics used to feed mechanical models described by Brancheriau and Bailleres (2002).

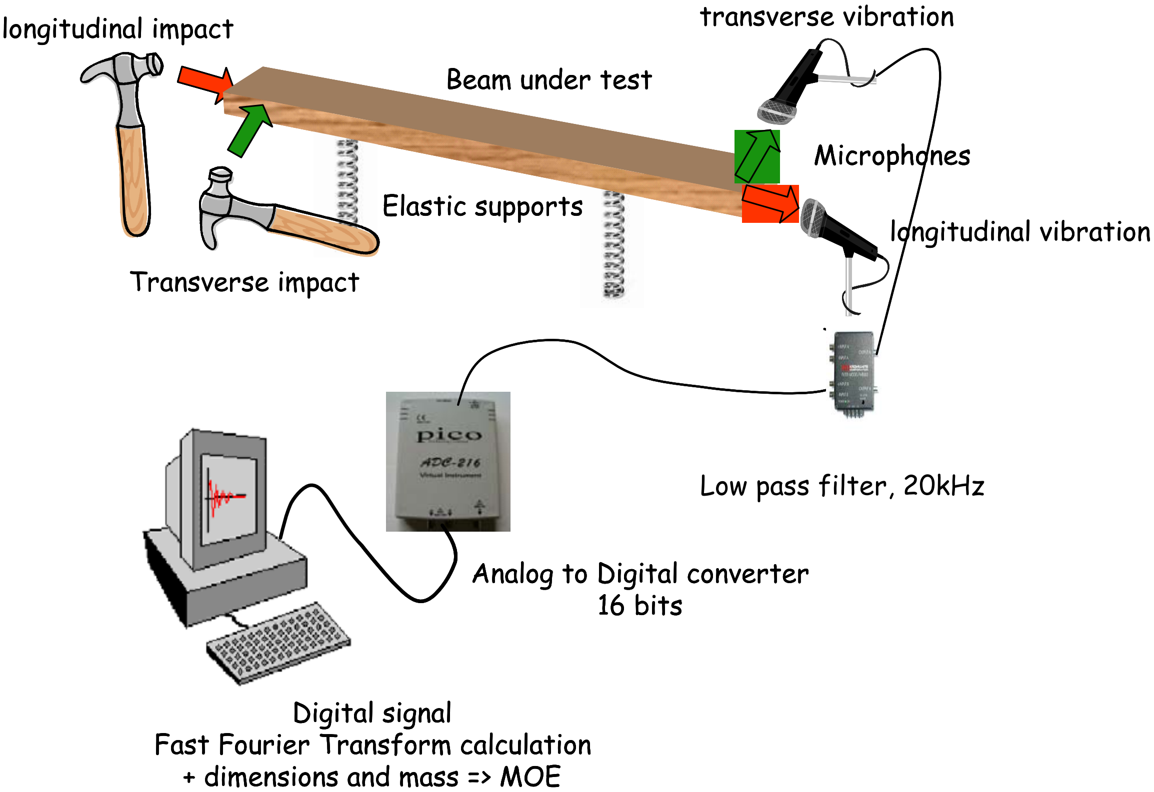


Figure 4. Experimental setup for the vibrational tests using BING.

A lateral or an axial percussion at one end of a beam set up on elastic supports produces bending or longitudinal vibrations. Considering the hypothesis of the homogeneity of geometrical and mechanical properties of the beam, basic dynamics theorems can be applied to obtain the motion equations of longitudinal and transverse vibrations. The resolution of the

[4] http://www.indexld.com/bing/eng/presentation_bing.html

differential equation for transverse motion leads to a search for solutions to the frequency equation in order to extract the modulus of elasticity (MOE) in different configurations.

Other parameters extracted from the digital signal for each beam and vibration mode include:

- Spectral centre of gravity (SCGravity) = Mean frequency
- Spectral span = Scattering around mean
- Spectral slope = Envelope decay
- Sub band energy 1 [0 Hz; 200 Hz] before mode 1.
- Sub band energy 2 [200 Hz; 3000 Hz] between mode 1 and mode 4.
- For the first 4 resonance frequencies = frequencies, associated MOE, temporal damping and quality factor of extraction.

In all, 25 parameters were extracted from the signal to explore MOR and MOE prediction improvements.

4 Results

4.1 Small Clear Wood Properties

4.1.1 Heartwood proportion and sapwood width

Results for heartwood proportion and sapwood width are summarised as box plots within Figure 5 and Figure 6 respectively. Average heartwood proportions were 76% for *E. cloeziana* and 67% for *E. pellita*, with average sapwood widths of 20 mm and 26 mm respectively.

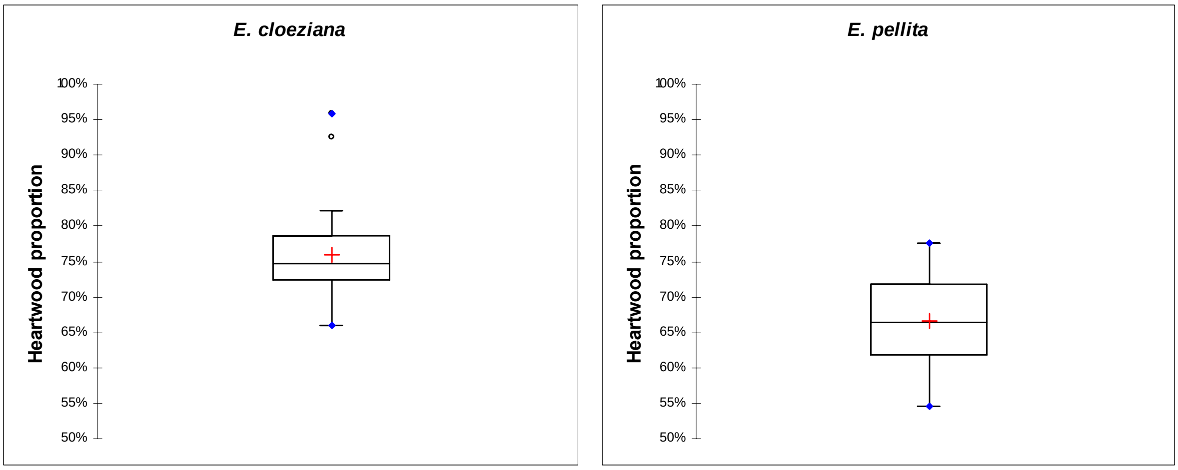


Figure 5. Box plots showing heartwood proportion (N = 40 for *E. cloeziana* and N = 31 for *E. pellita*).

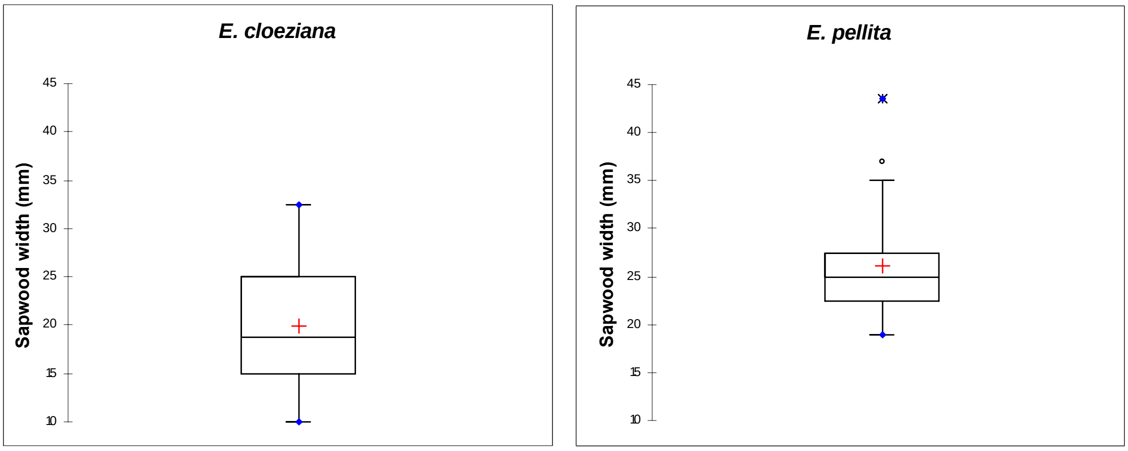


Figure 6. Box plots showing sapwood width in mm (N = 40 each for *E. cloeziana* and N = 31 for *E. pellita*).

The average sapwood width measured for *E. cloeziana* was greater than the 15 mm, 16 mm and 12 mm widths reported by Muneri *et al.* (1998) for 11, 17 and 46-year-old plantation *E. cloeziana* respectively. For the same material, the average heartwood proportion reported was 65%, 69% and 87% respectively. McGavin *et al.* (2006 and 2007) measured an average heartwood proportion of 50% and 44 % along with 29 mm and 25 mm sapwood width for two different eight-year-old *E. cloeziana* plantations. The average heartwood proportion found during this study is logically placed on an asymptotic curve (Zobel and Sprague 1998) with age versus heartwood proportion, which should stabilize close to 90% between 25 and 35 years old. Sapwood width follows the same inverse trend but tends to fluctuate more.

Bhat *et al.* (1987) found a heartwood proportion of 25-28 % on 3-year-old *E. pellita* trees in India. The heartwood percentage reported by Norton and Muneri (2002) and McGavin *et al.* (2006) was around 70 % for 8.5-year-old plantation *E. pellita* and is similar to the heartwood proportion results for the 15-year-old material measured in this study.

4.1.2 Extractive content

Average total extractive contents were 5.55 % for *E. pellita* and 5.74% for *E. cloeziana.* These are relatively low compared with the values commonly reported in the literature for mature wood of the same genus (Hillis 1987). This is attributed to the extraction procedure used for this study which was based on extraction from large particle size pieces (around 1-2 mm nominal) which produces lower extraction yields.

In both species the relative increase of extractive content from inner heartwood to outer heartwood was 10 to 20% (Figure 7 and Figure 8). This radial variation is common in hardwood species (Hillis 1987). Potential consequences of this variation include better natural durability, deeper colour and lower sorption rates towards the outer heartwood. In some cases, the low extractive content (around 30% less), lower density and high proportion of natural defects (e.g. knots, veins, shakes) in the inner heartwood zone might have encouraged standing tree fungal attack in the stem centre.

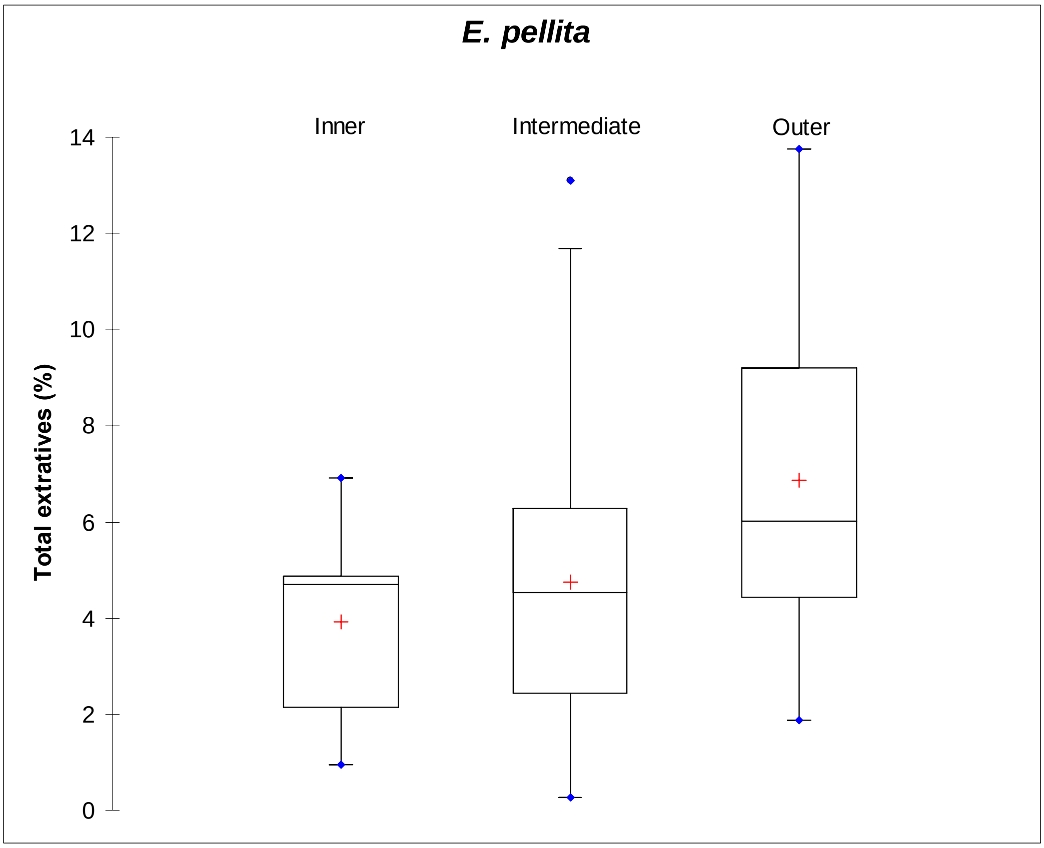


Figure 7. Box plot showing radial total extractive content variation for inner, intermediate and outer heartwood zones for *E. pellita* (N=13 for inner, N=47 for intermediate, N=45 for outer heartwood).

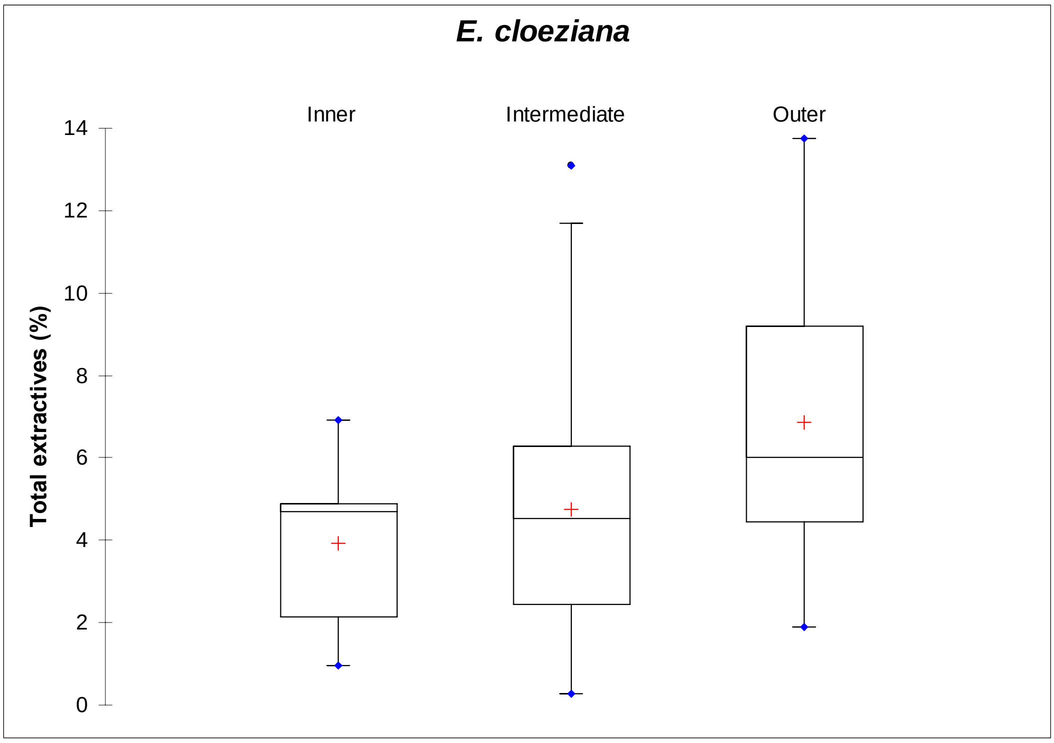


Figure 8. Box plot showing radial total extractive content variation for inner, intermediate and outer heartwood zones for *E. cloeziana* (N=25 for inner, N=74 for intermediate, N=79 for outer heartwood).

There is a large variation in total extractive content between trees as shown in Figure 9 and Figure 10. Understanding and identifying this variation could be advantageous to tree improvement strategies given that extractive content directly influences several key wood qualities and in-service product performance.

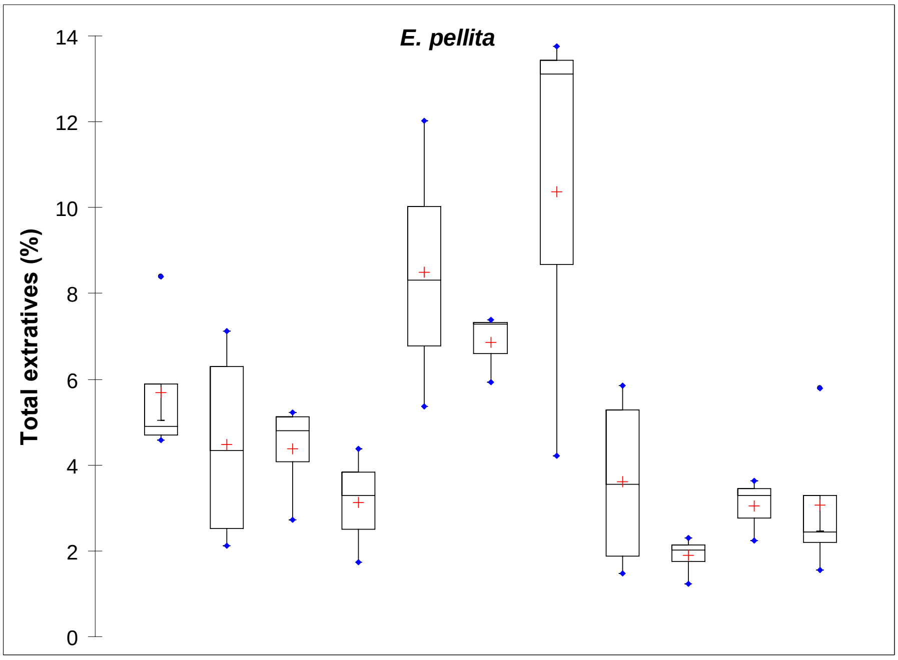


Figure 9. Variation in total extractive content (%) between a sub-sample of 11 *E. pellita* trees.

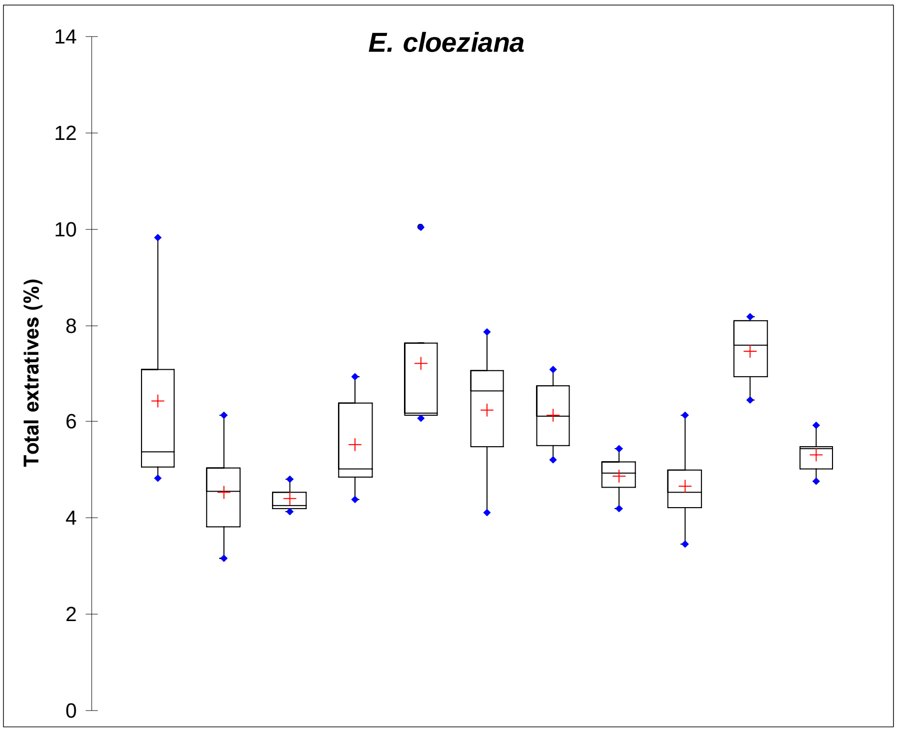


Figure 10. Variation in total extractive content (%) between a sub-sample of 11 *E. cloeziana* trees.

4.1.3 Basic density

The results of the basic density testing are presented in Figure 11 and Figure 12. Average basic densities were 588 kg/m^3 for *E. pellita* and 715 kg/m^3 for *E. cloeziana*. These are approximately 26% and 12% less than the 790 kg/m^3 and 810 kg/m^3 reported by Bootle (2005), respectively, for wood sourced from mature natural grown trees. These results demonstrate the influence of juvenile wood and the impact that plantation age has on wood density. The difference between average densities of the study material compared with mature wood is greater for *E. pellita* and is expected to have been influenced by the younger age of the plantation.

Sapwood is less dense than the outer heartwood because it contains a smaller quantity of extractives. A simple calculation shows that the extractive content explains the difference of basic density between sapwood and outer heartwood.

Basic density increased from the inner heartwood to the outer heartwood and then decreased slightly in the sapwood in both species. This trend is similar to that found in previous studies on younger (eight-year-old) plantation hardwood thinnings of the same species (McGavin *et al.* 2006 and 2007). The variation between the three heartwood zones ranged from 450 to 650 kg/m^3 for *E. pellita* and from 650 to 750 kg/m^3 for *E. cloeziana*. This increase is expected to stabilise between the ages of approximately 25 to 30 years. *Eucalyptus pellita* displayed a greater variation due to the larger proportion of lower density juvenile wood when compared to *E. cloeziana*. This greater variation in *E. pellita* is a disadvantage in terms of wood property performance when compared to *E. cloeziana* for some applications. As the material used for this study was sourced from only one site, complementary studies should be performed to assess the impact of site and genetic origin in order to optimize the wood quality produced in future plantings.

The average basic density of the test material (around 600 kg/m^3) was similar to or greater than the basic density expected from final harvest Queensland grown plantation softwoods.

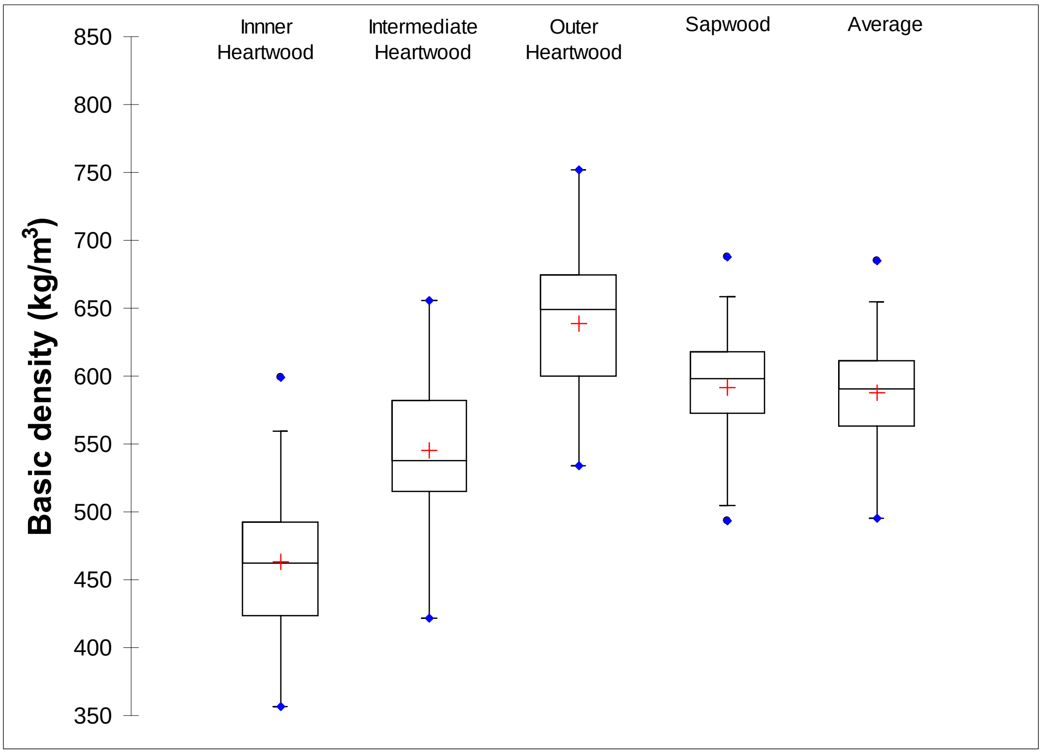


Figure 11. Box plot showing basic density radial variation for *E. pellita.*

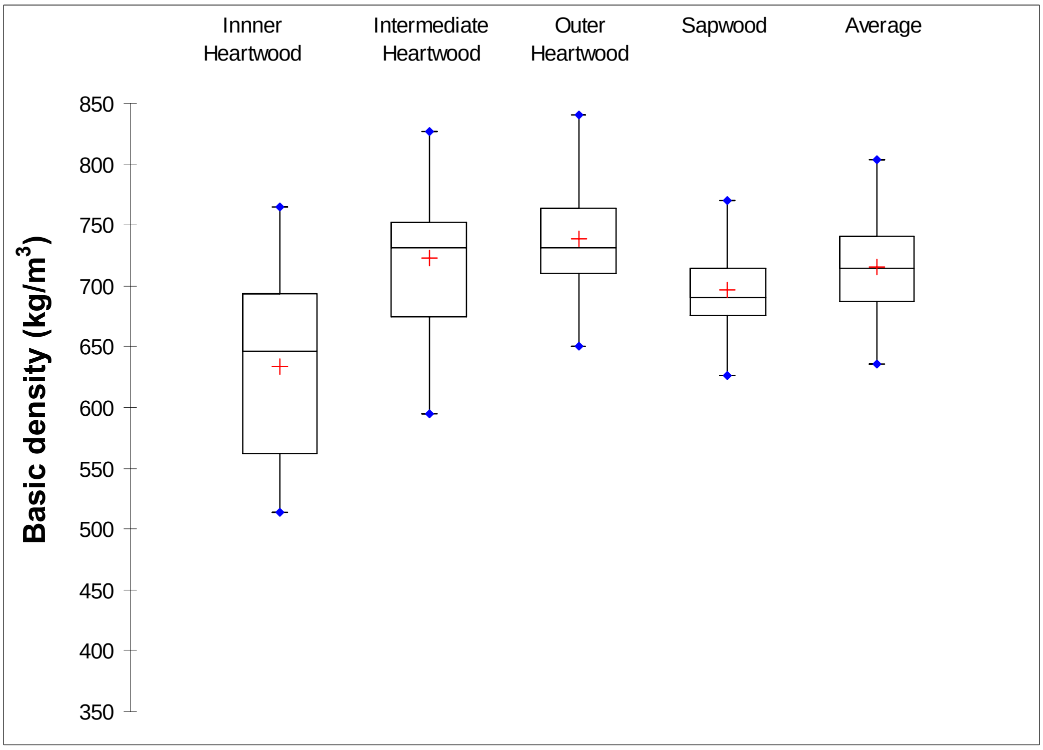


Figure 12. Box plot showing basic density radial variation for *E. cloeziana.*

4.1.4 Hardness

Average transverse (average of radial and tangential) hardness was 11 kN for *E. cloeziana* and 7 kN for *E. pellita* and values for radial, tangential and end plane hardness are given in Figure 13. Transverse hardness for wood from mature native forest trees is 12kN for both species (Bootle 2005). Average hardness for *E. cloeziana* was similar to that expected for mature wood but average hardness for *E. pellita* was 30% below that expected for mature wood. (Figure 13). *Eucalyptus cloeziana* was approximately 35% harder than *E. pellita*, which is consistent with the density results.

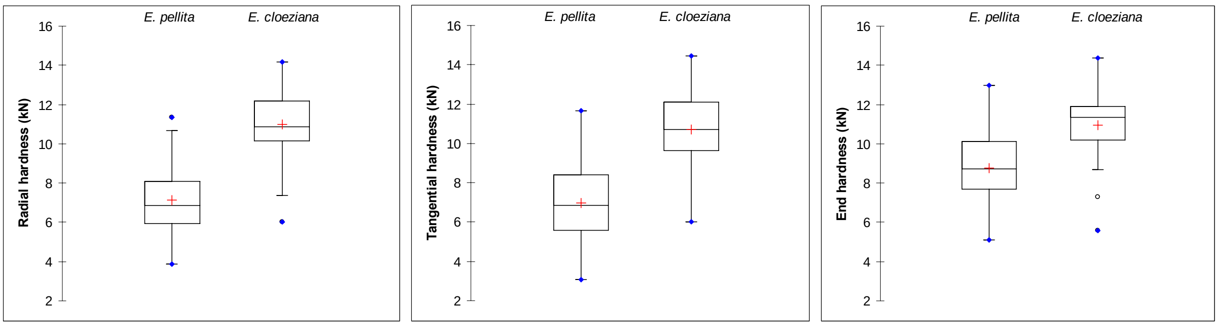


Figure 13. Box plot showing radial (RL plane), tangential (TL plane) and end (RT plane) hardness (kN) for *E. pellita* and *E. cloeziana*.

The pith to bark variation of radial, tangential and end hardness followed the same trend as density with a significant increase of about 37% for *E. pellita* and 17% for *E. cloeziana* (Figure 14 and Figure 15). *Eucalyptus cloeziana* displayed a lower gradient for hardness on the radius when compared to *E. pellita*. It was interesting to note that the juvenile wood had minimal impact on the hardness of *E. cloeziana* whereas the impact with *E. pellita* was more evident.

Interestingly, the tangential hardness of the outer heartwood was greater than the hardness of sapwood and was probably due to extractive deposits, which reinforce the cellular structure of wood by filling the pores. By comparison, radial hardness varied only slightly between the outer heartwood and sapwood zones, probably due to the influence of ray parenchyma which acts as a stiff reinforcement.

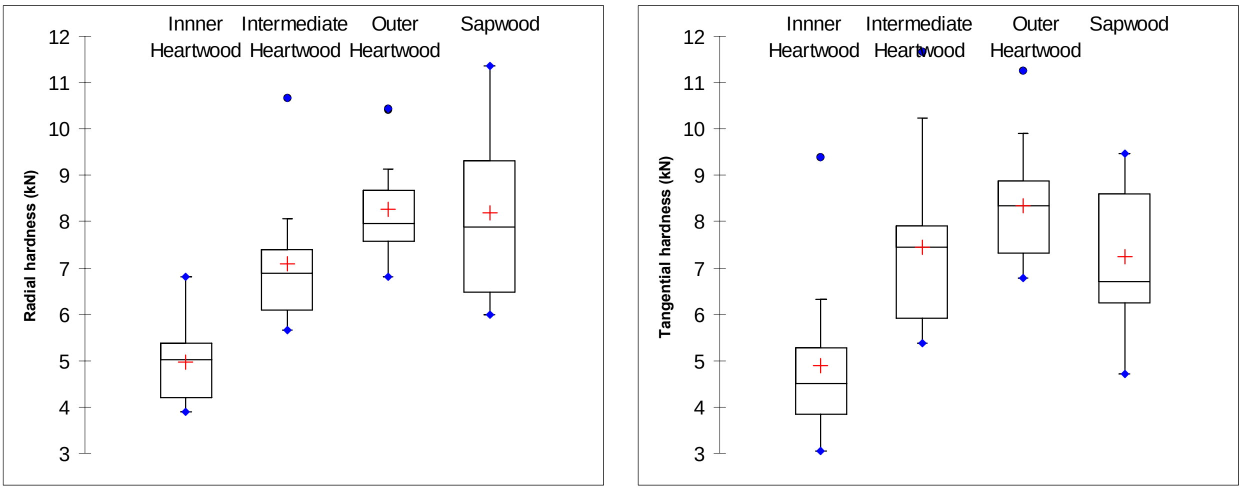


Figure 14. Box plots showing pith to bark variation of radial and tangential hardness for *E. pellita*.

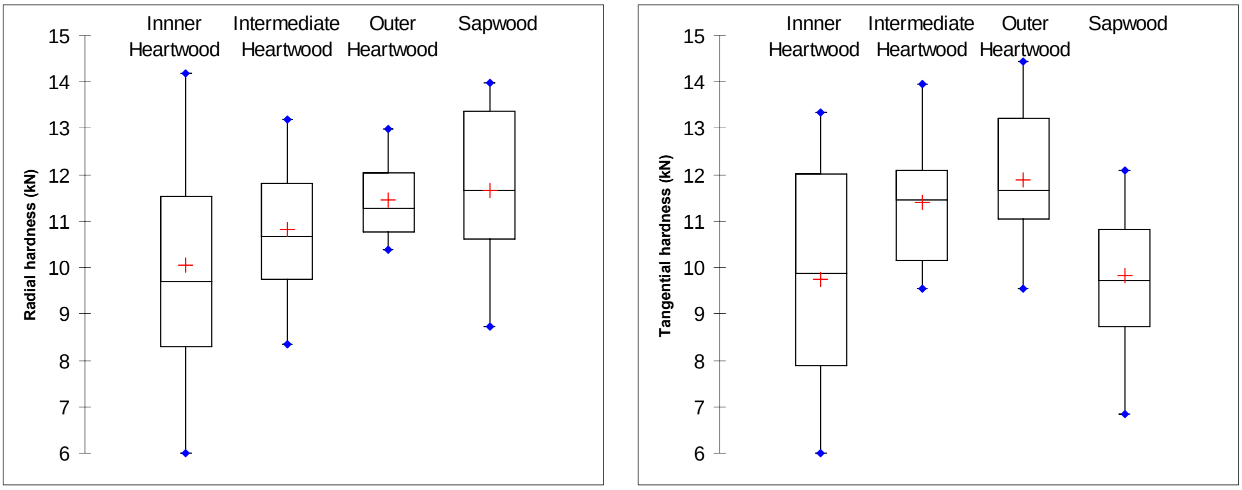


Figure 15. Box plots showing pith to bark variation of radial and tangential hardness for *E. cloeziana*.

4.1.5 Unit Shrinkage

Unit shrinkages in all directions were comparable for both species (Table 9). The average unit shrinkage values obtained during this study were 0.29% tangential and 0.24% radial for *E. cloeziana*, and 0.30% tangential and 0.22% radial for *E. pellita*.

Table 9. Heartwood unit shrinkages statistics for *E. cloeziana* and *E. pellita*

		E. cloeziana			***E. pellita***	
Statistic	**Radial**	**Tangential**	**Longitudinal**	**Radial**	**Tangential**	**longitudinal**
No. of observations	60	60	60	60	60	60
Minimum	0.04	0.11	0.00	0.12	0.18	0.00
Maximum	0.54	0.43	0.02	0.34	0.42	0.03
Range	0.50	0.32	0.02	0.22	0.24	0.03
Mean	**0.24**	**0.29**	**0.01**	**0.22**	**0.30**	**0.01**
Standard deviation	0.09	0.09	0.00	0.05	0.06	0.00
Variation coefficient	0.37	0.29	0.40	0.24	0.18	0.44

Published values for tangential and radial unit shrinkage for *E. cloeziana* include 0.39 and 0.30 respectively for 35-year-old plantation grown timber and 0.40 and 0.20 respectively for mature natural grown timber (Department of Primary Industries and Fisheries 2005); 0.26 and 0.18 respectively for 8-year-old plantation grown timber (McGavin *et al.* 2006) and 0.25 and 0.12 respectively for 4-year-old plantation grown timber (Muneri and Leggate 2000).

Published values for *E. pellita* follow a similar trend with 0.34 and 0.27 for tangential and radial unit shrinkage respectively for mature natural grown timber (Kynaston *et al.* 1994)[5] and 0.28 and 0.17 respectively for 8.5-year-old trees (Muneri *et al.* 2000).

Results from this study suggest an increase of transverse shrinkages with cambial age which follows a similar trend for other properties such as density (Figure 16). Conversely, as seen in Figure 17, the longitudinal unit shrinkage decreased with increasing radial position in the heartwood. This variation is probably explained by the higher proportion of tension wood in the vicinity of the pith (see Washusen 2002, for example) and by the evolution of ultrastructure and

[5] Kynaston *et al.* (1994) reports pooled values for both *E. pellita* and *E. resinifera*.

variation in composition of the cell wall (e.g. microfibril angle, lignin content, cellulose content) during the juvenile phase. Higher extractives content in outer heartwood may explain the slight decrease in transverse shrinkage observed in this zone.

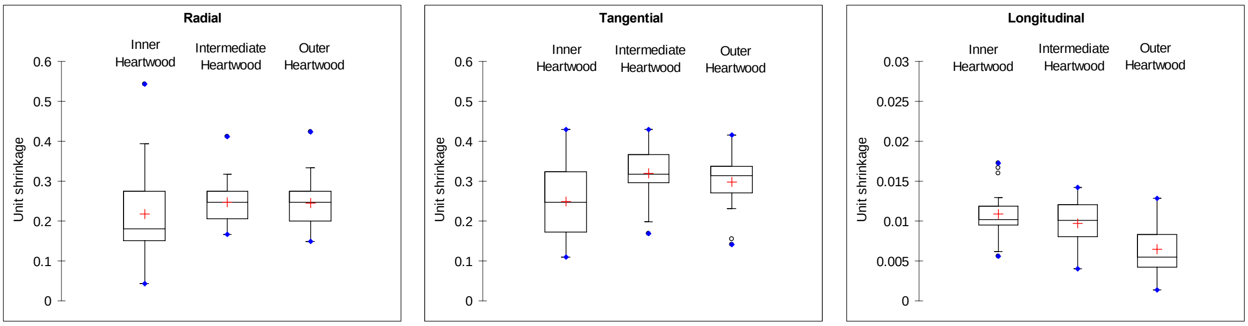


Figure 16. Box plots showing heartwood pith to bark variation of unit shrinkage for E. cloeziana.

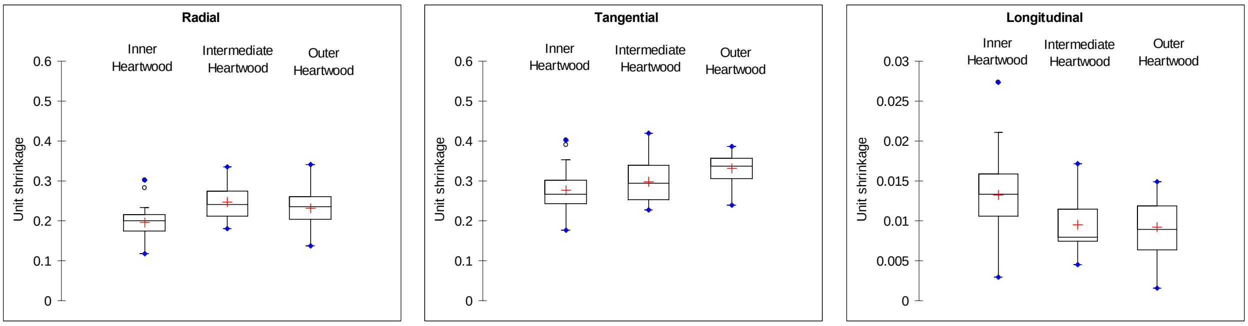


Figure 17. Box plots showing heartwood pith to bark variation of unit shrinkage for *E. pellita*.

4.1.6 Nail and screw withdrawal

The nail and screw withdrawal characteristics for mature *E. pellita* and *E. cloeziana* natural grown timber when load is applied perpendicular to the grain results in a JD1 joint group classification being applied to both species, which is the highest joint group grade (Hopewell, G. ed. 2006). The combined result of nail and screw withdrawal for plantation grown *E. pellita* and *E. cloeziana* was JD4 and JD2 respectively.

Characteristic capacity for nail withdrawal

Eucalyptus pellita pooled test results gave an overall JD3 rating for nail withdrawal characteristics. Inner and intermediate heartwood had significantly lower nail withdrawal capacity (JD3) than the outer heartwood, which attained a JD1 classification (Table 10). These results suggest further negative influence of the juvenile phase of this species on wood quality when compared to natural grown, mature grown timber.

Table 10. Nail withdrawal maximal load (Pmax), characteristic load capacity (Rk) and joint group classification for *E. pellita*.

Sample type	**number of samples**	**Mean Pmax (N)**	**Rk (N/mm)**	Joint group
Tangential and radial	43	811	18.7	**JD3**

Tangential	43	753	17.4	**JD3**
Radial	43	857	18.2	**JD3**
Outer heartwood	15	1004	29.5	**JD1**
Intermediate heartwood	13	807	18.9	**JD3**
Inner heartwood	**15**	**649**	**13.7**	**JD3**

The overall nail withdrawal characteristics of *E. cloeziana* samples tested fall within JD1, the best possible rating (Table 11). Unlike *E. pellita*, the inner heartwood of *E. cloeziana* seems to be less affected by the juvenile phase and, despite the four years age difference, it is suggested that the difference in performance is not only attributable to age.

Table 11. Nail withdrawal maximal load (Pmax), characteristic load capacity (Rk) and joint group classification for *E. cloeziana.*

Sample type	**number of samples**	**Mean Pmax (N)**	**Rk**	Joint group
Tangential and radial	44	1115	29.2	**JD1**
Tangential	44	1034	25.7	**JD2**
Radial	43	1173	27.9	**JD2**
Outer heartwood	15	1192	29.4	**JD1**
Intermediate heartwood	15	1168	31.6	**JD1**
Inner heartwood	**14**	**1004**	**24.4**	**JD2**

Characteristics capacity for screw withdrawal

Overall screw withdrawal capacity for *E. pellita* was JD4 while *E. cloeziana* attained a JD2 rating. The screw withdrawal tests followed similar trends to the nail withdrawal characteristics in both species (Table 12 and Table 13). Consequently, similar conclusions were drawn.

Table 12. Screw withdrawal maximal load (Pmax), characteristic load capacity (Rk) and joint group classification for *E. pellita*.

Sample type	**number of samples**	**Mean Pmax (N)**	**Rk**	Joint group
Tangential and radial	39	34.2	58.2	**JD4**
Tangential	39	30.7	52.2	**JD4**
Radial	39	32.7	55.6	**JD4**
Outer heartwood	12	49.5	84.1	**JD2**
Intermediate heartwood	13	40.7	69.2	**JD3**
Inner heartwood	**14**	**28.6**	**48.6**	**JD4**

Table 13. Screw withdrawal maximal load (Pmax), characteristic load capacity (Rk) and joint group classification for *E. cloeziana.*

Sample type	**number of samples**	**Mean Pmax (N)**	**Rk**	Joint group
Tangential and radial	46	3.23	94.1	**JD2**
Tangential	46	3.24	93.5	**JD2**
Radial	46	3.22	87.2	**JD2**
Outer heartwood	17	3.26	105	**JD1**
Intermediate heartwood	15	3.24	101	**JD1**
Inner heartwood	**14**	**3.19**	**82.7**	**JD2**

4.1.7 Static bending – MOE and MOR

Figure 18 summarises the modulus of elasticity (MOE) and modulus of rupture (MOR) resulting from the bending tests carried out on *E. cloeziana* and *E. pellita* small clear samples.

Eucalyptus cloeziana displayed higher mechanical properties than *E. pellita* which can be explained partly by its four years greater maturity.

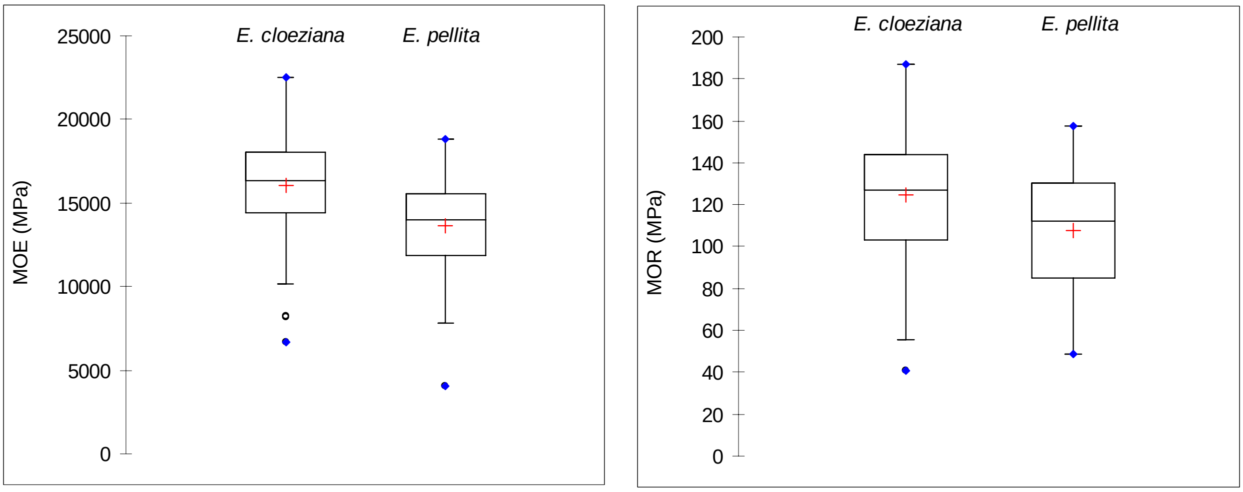


Figure 18. Small clear wood bending MOE and MOR in MPa (N= 177 for *E. cloeziana* and N=103 for *E. pellita*).

Table 14 provides MOE and MOR properties for mature native forest and a reference study on eight-year-old *E. cloeziana* and *E. pellita*. This comparison confirms that the trees from young plantations have inferior mechanical properties. This result could be expected because of the lower density values of the plantation resource (see Figure 11 and Figure 12). Although the mechanical properties test results gave lower values than timber from mature native forests, they are higher than the mechanical properties achieved by common softwood plantation species grown in the same area. Logically the MOE and MOR values obtained during this study are between the younger plantation results reported by McGavin *et al.* (2006) and mature natural grown timber.

The testing undertaken shows that the mechanical properties of the 19 year old *E. cloeziana* were very close to that of mature natural grown timber, while the mechanical properties of the 15 year old *E. pellita* was closer to that of the eight year old plantation material. Despite the age variation of the test material (i.e. *E. pellita* being four years younger than the *E. cloeziana*), the result is not in accord with expected maturation effects on mechanical properties. Even at 15 years old, it would be expected that the properties of the *E. pellita* would be closer to those of mature natural grown timber. As the sample size and modalities are limited, a complementary study should go further into site and genetic effect in order to provide reliable information on wood properties variation of this species and the influence of plantation age.

Table 14. Seasoned MOE and MOR properties from this study, from McGavin *et al.* (2006) for eight year old plantation and from native stands (extracted from Bootle 2005).

	MOE (MPa)			MOR (MPa)		
Species	**Bootle (2005)**	**This study**	**McGavin *et al.* (2006)**	**Bootle (2005)**	**This study**	**McGavin *et al.* (2006)**
E. cloeziana	17000	16100	11800	139	125	106
E. pellita	18000	13600	12700	140	108	99

In accordance with Australian and New Zealand Standard *AS/NZS2878:2000 Timber – Classification into strength groups* (Standards Australia 2000), the *E. cloeziana* test population satisfied the requirements of SD3 for MOE and SD2 for MOR. Applying the procedure of Table 2.3 of *AS/NZS2878:2000*, an overall strength group of SD3 is achieved. Mature natural grown *E. cloeziana* timber is also classified as SD3.

The *E. pellita* test population satisfies the requirements of SD5 for MOE and SD4 for MOR, for an overall strength group of SD5. Mature natural grown timber is classified as SD3, two steps above this strength group.

The variation in MOE and MOR from inner to outer heartwood for both species is presented in Figure 19 and Figure 20. A comparison of radial increase patterns for MOE and MOR between species confirms the difference of ontogenetic behaviour regarding cell wall maturation. Like basic density and hardness, mechanical properties values seemed to stabilise between intermediate and outer heartwood in *E. cloeziana* while a significant increase was observed between intermediate and outer heartwood in *E. pellita*. These results suggest *E. cloeziana* acquires mature characteristics earlier than *E. pellita*. It is recommended that this result should be further investigated in plantation material with different environmental or genetic origins.

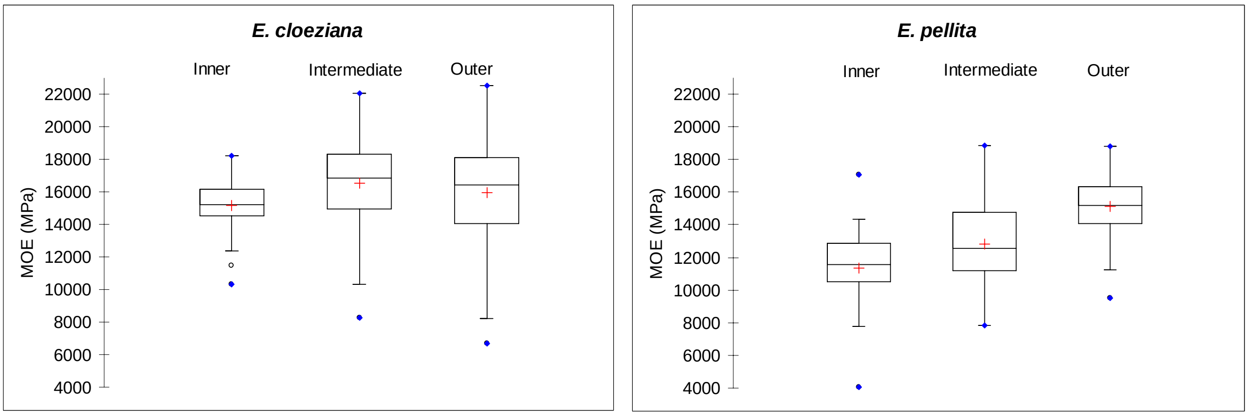


Figure 19. Heartwood MOE variation from pith to bark for *E. cloeziana* and *E. pellita*.

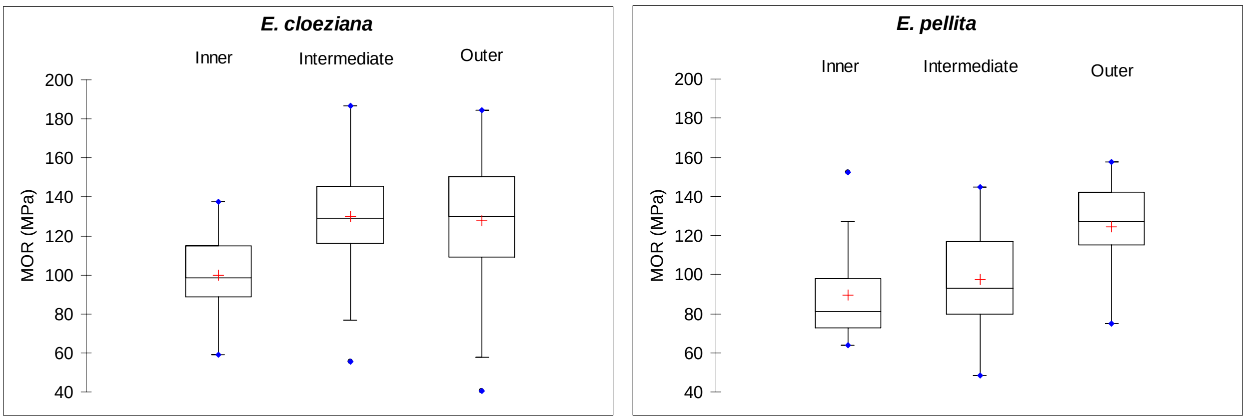


Figure 20. Heartwood MOR variation from pith to bark for *E. cloeziana* and *E. pellita*.

4.2 Full section characteristics: grade determination and structural properties

For appearance and structural grading, a total of 2.42 m^3 (187 boards) of *E. cloeziana* and 1.46 m^3 (113 boards) of *E. pellita* were available.

4.2.1 Appearance grade recovery

A first grading approach focused on distortion characteristics with each target board being evaluated for spring, bow and twist and the measurements compared with the permissible limits outlined for strip flooring within Australian Standard *AS2796.1:1999 Timber – Hardwood – Sawn and milled products Part 1: Product Specification* (Australian Standards 1999).

The proportion of boards rejected due to excessive distortion was 22% for *E. pellita* and 19% for *E. cloeziana* (Table 15). Twist was the main reason for rejection, accounting for around 75% of the rejected boards, with bow being responsible for the balance. The proportion of rejected boards was similar across each zone. The observed grain deviation was negligible for both species and did not explain the cause of distortion. The significant proportion of rejected boards may have been influenced by the unconventional sawing strategy chosen to satisfy sampling design which favours unbalanced relief of growth stresses and consequently increases distortion. In addition, the boards were not 'dressed' or profiled prior to grading. Profiling would be expected to remove some level of distortion and therefore produce marginally better grading results.

Table 15. Proportion of rejected boards due to excessive distortion according to *AS2796.1:1999* Appendix C (Strip flooring).

	Grading characteristics	Inner	Intermediate	Outer	Total
	Number of boards	29	78	80	187
E. cloeziana	**Reject out of total volume (%)**	**3**	**9**	**8**	**19**
	Reject out of heartwood zone volume (%)	17	21	19	
	Number of boards	15	47	51	113
E. pellita	**Reject out of total volume (%)**	**4**	**10**	**9**	**22**
	Reject out of heartwood zone volume (%)	27	23	20	

In a separate process, each target board was also evaluated for grade quality. Each board was evaluated in its original full length and then regraded after hypothetical docking if the removal of defects could increase the grade quality. A minimum board length of 1.2 m was applied. The percentage of rejected full length boards due to defects or imperfections was higher for *E. pellita* (60%) than for *E. cloeziana* (37%). This difference also had a direct consequence on the recovery of select grade boards which was also lower for *E. pellita*. The recovery of medium feature and high feature grades were similar for both species.

Table 16. Grade recovery of full length and docked boards.

	E. cloeziana		***E. pellita***	
Grade	**Full length**	**After docking**	**Full length**	**After docking**
Select	53	69	32	50
Medium feature	4	1	1	1
High feature	6	8	7	12
Reject	37	22	60	37

The primary reasons (excluding distortion) for full length boards failing to meet the allowances set by *AS2796:1999* are presented in Figure 21 and Figure 22. The presence of heart shakes was the primary cause for rejecting boards in both species and accounted for nearly 80% of the rejected boards. The inner heartwood boards were obviously the worst affected by heart shakes as they were sawn very close to or included the pith. Heart shakes are a very common occurrence in hardwoods and especially in eucalypts where boards are sawn close to the pith. Heart shakes were also the largest cause of rejection within the intermediate heartwood boards, which indicates either the influence of deviating pith and/or that boards sawn close to the pith are often affected by heart shakes or decay. The second most important cause of rejection was the presence of knot related defects which accounted for only 15 to 20% of the rejected boards.

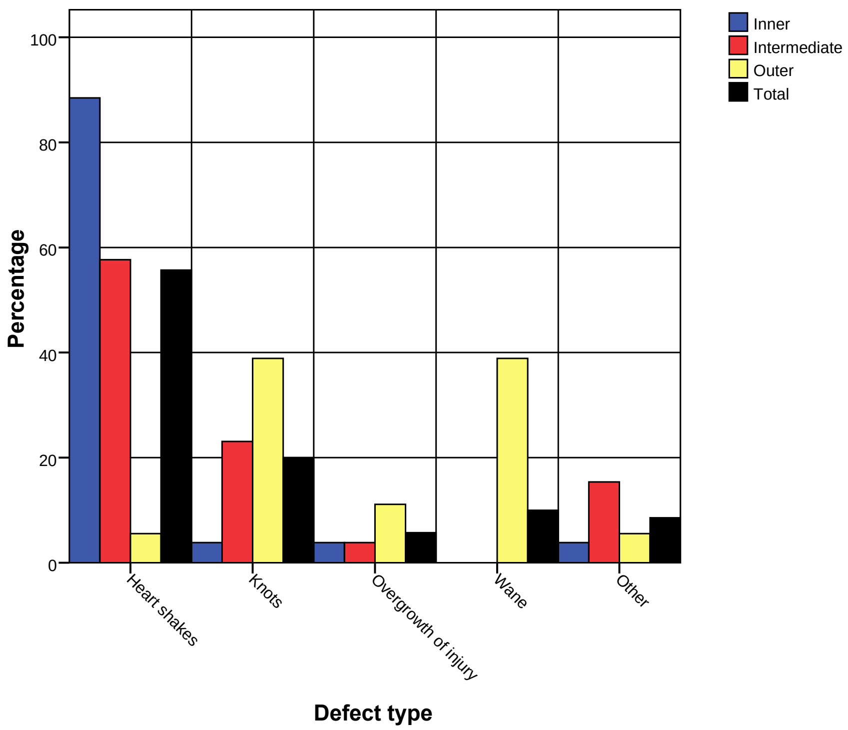


Figure 21. Reasons for rejection for full length *E. cloeziana* boards.

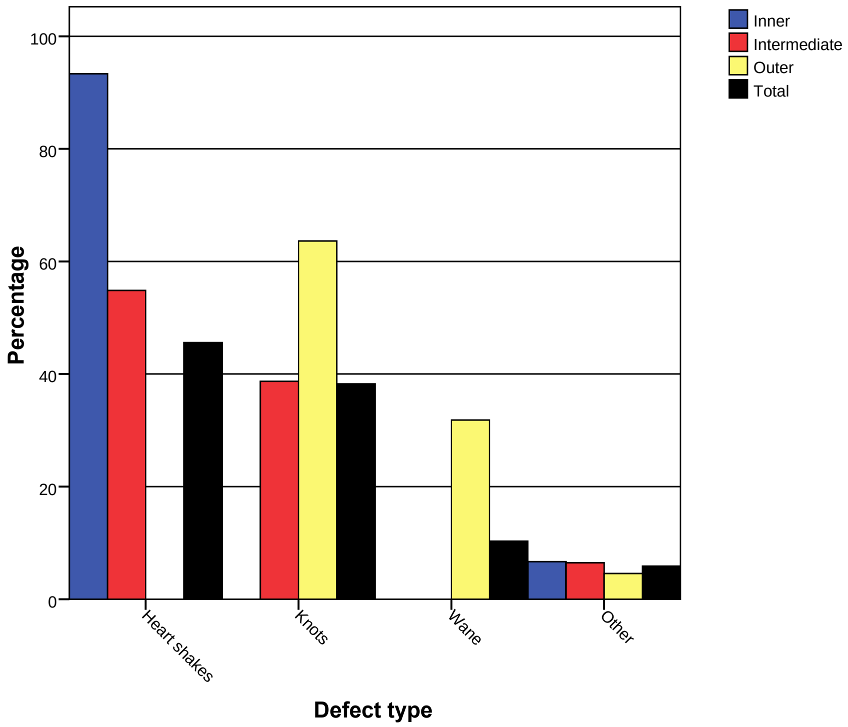


Figure 22. Reasons for rejection for full length *E. pellita* boards.

The docking process improves the appearance grade recovery appreciably as displayed in Figure 23 and Figure 24. Knots were the main defect removed. Approximately 40% of the rejected boards could be upgraded from reject to select grade after docking. The main benefit of docking is to improve the grade quality (and potentially the product value) by removing the defect responsible for reducing the grade. However the negative implication is that board volume and therefore saleable volume are reduced.

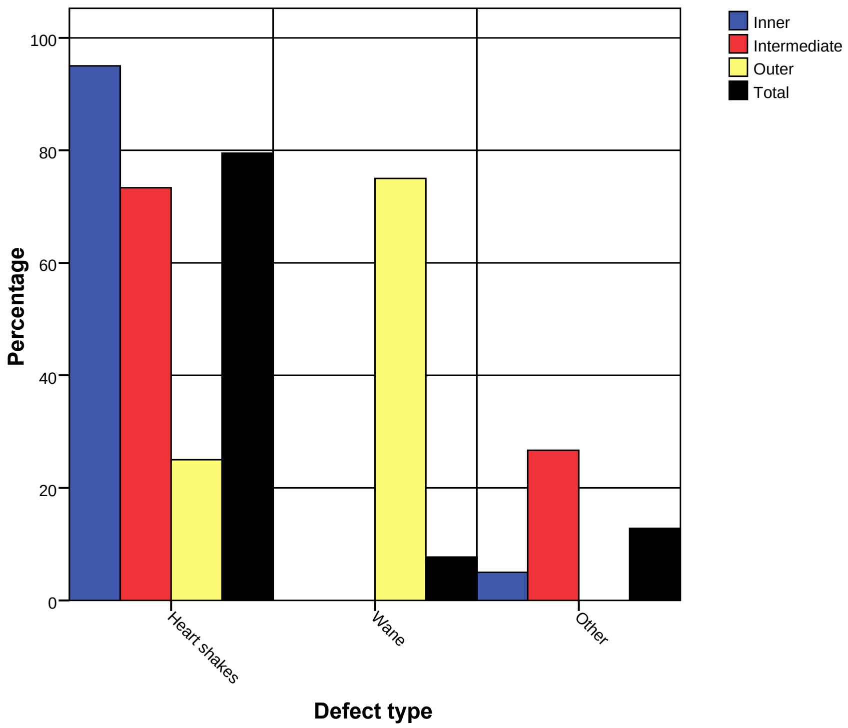


Figure 23. Reason for *E. cloeziana* boards being rejected even after docking.

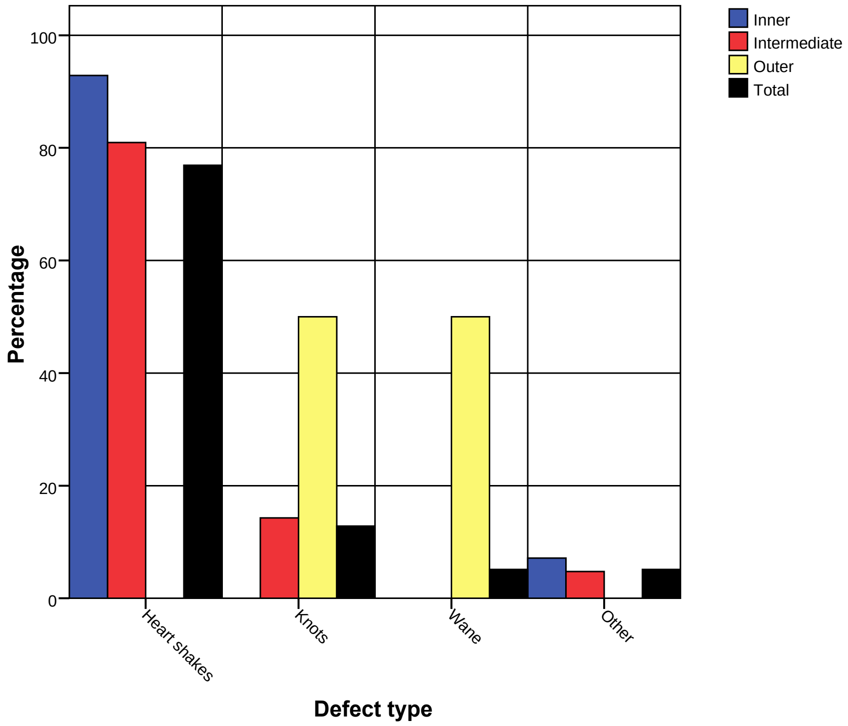


Figure 24. Reason for *E. pellita* boards being rejected even after docking.

4.2.2 Structural grade recovery

As with the appearance grading process, both distortion and grade quality were evaluated. For distortion, each target board was evaluated for spring, bow and twist with measurements being compared against the permissible limits outlined within Australian Standard *AS2082:2000 Timber – Hardwood – Visually stress-graded for structural purposes* (Australian Standards 2000). The results indicate that 25 % of *E. pellita* and 18% of *E. cloeziana* boards had distortion measurements outside the Standard's permissible limits (Table 17). As with appearance grading, the application of visual stress grading rules revealed that *E. pellita* had an increased occurrence of distortion compared with *E. cloeziana*, however the main reason for downgrade was spring in the inner heartwood. This could be explained by a higher longitudinal shrinkage and shrinkage variation in inner heartwood as demonstrated in Figure 16 and Figure 17.

Table 17. Proportion of rejected boards due to excessive distortion.

	Grading characteristics	Inner	Intermediate	Outer	Total
	Number of boards	29	78	80	187
E. cloeziana	**Reject out of total volume (%)**	**4**	**7**	**6**	**18**
	Reject out of heartwood zone volume (%)	28	18	15	
	Number of boards	13	37	41	91
E. pellita	**Reject out of total volume (%)**	**4**	**13**	**8**	**25**
	Reject out of heartwood zone volume (%)	31	32	17	

To determine grade quality, each board was assessed for defects or imperfections and structurally graded in accordance with *AS2082:2000*. Wood from the inner and intermediate zones was most affected by defects and directly impacted on the proportion of rejected boards.

The primary reasons for full length boards failing to make any structural grade quality (i.e. reject boards) are displayed in Figure 25 and Figure 26 for *E. pellita* and *E. cloeziana* respectively. The resulting distributions of grade qualities for both species are presented in Figure 27. The main reason for rejection was the presence of heart which was expected, given the small diameter of the plantation logs.

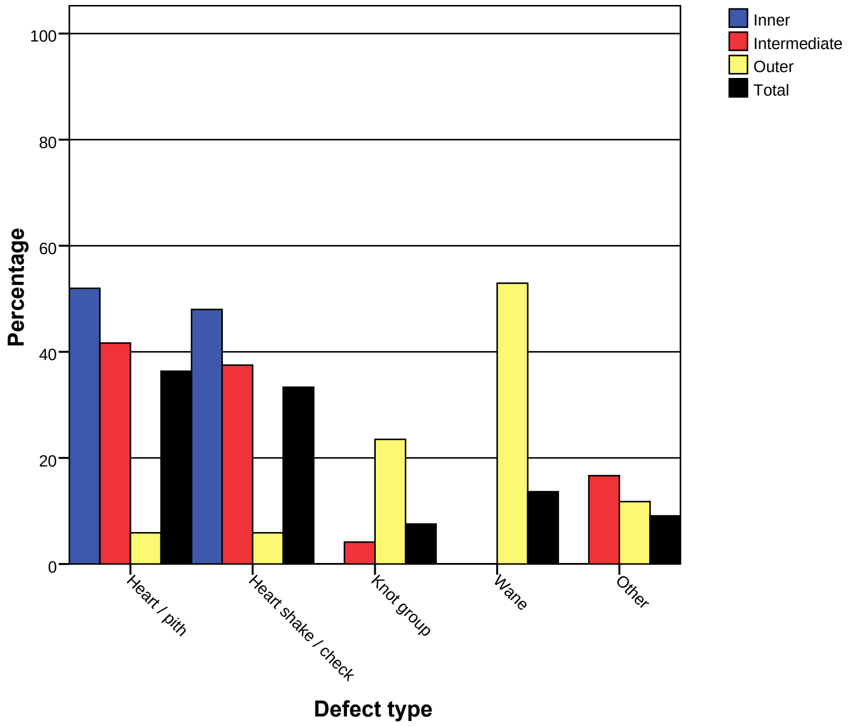


Figure 25. Reason for full length *E. pellita* boards being rejected.

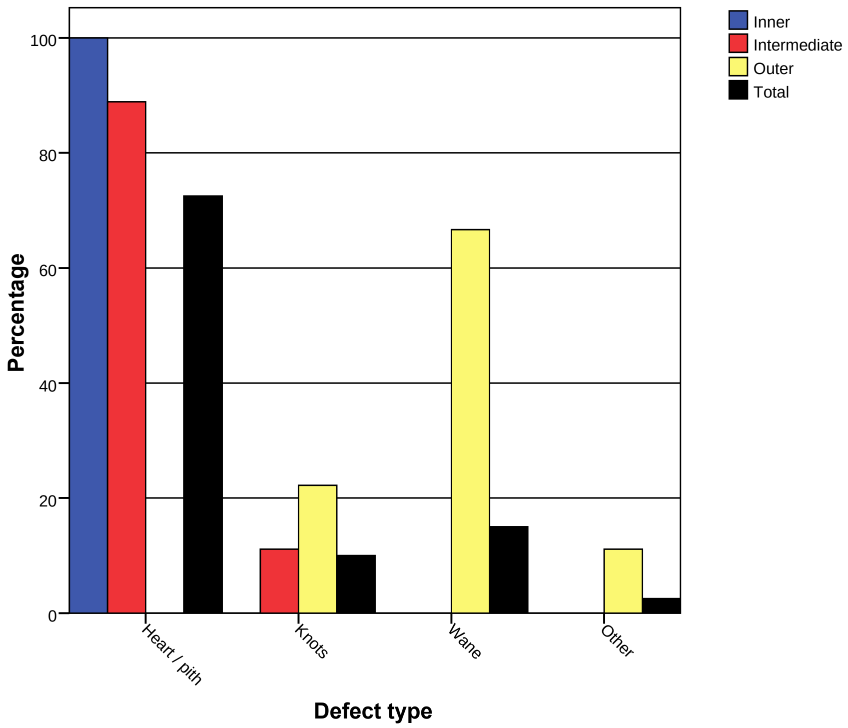


Figure 26. Reason for full length *E. cloeziana* boards being rejected.

Inferior clear wood mechanical properties and high proportion of defects of *E. pellita* compared to *E. cloeziana* obviously lead to a less favourable grading distribution. *Eucalyptus cloeziana* provides mostly F27 stress grade whereas *E. pellita* is shared out between four stress grades from F8 to F17 (Figure 27).

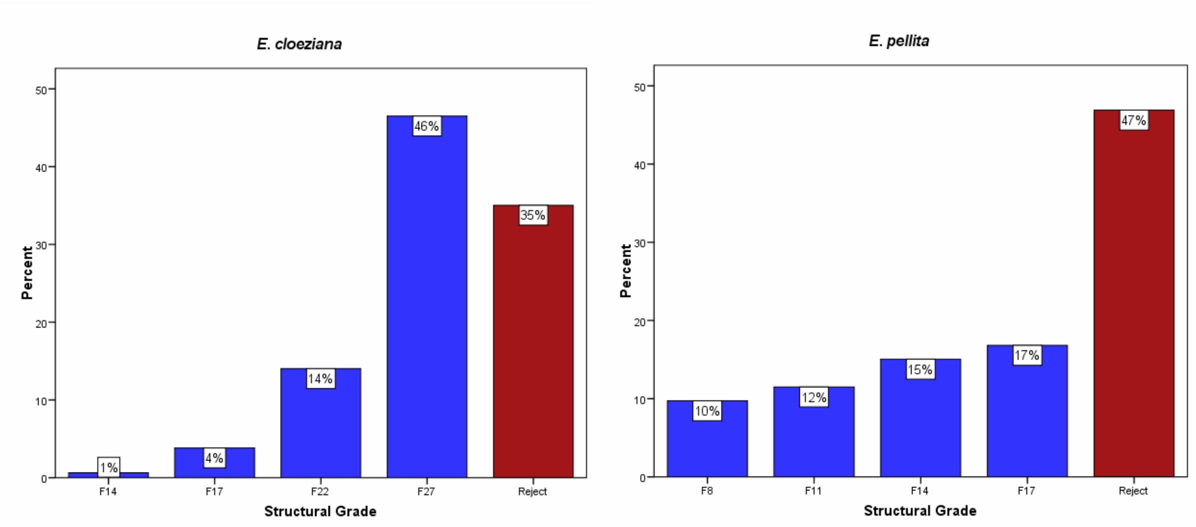


Figure 27. Structural grade quality distributions for *E. cloeziana* and *E. pellita*.

4.2.3 Full section static stiffness and strength testing

The mechanical properties obtained from the static bending tests are displayed in Table 18. They confirm the lower mechanical properties of *E. pellita* in comparison to *E. cloeziana*.

Table 18. Static bending test summary

		Modulus of elasticity (MPa)			Modulus of rupture (MPa)		
	Data origin and tree age	***This study 19 & 15***	***McGavin et al. (2007) 8***	***McGavin et al. (2006) 8 & 8.5***	***This study 19 & 15***	***McGavin et al. (2007) 8***	***McGavin et al. (2006) 8 & 8.5***
E. cloeziana	Number of samples	187	131	102	187	131	102
	Mean	**15200**	12009	11600	**81.0**	70.5	61.0
	Standard deviation	2710	2750	2600	23	28.8	23.9
E. pellita	Number of samples	113	-	54	113	-	54
	Mean	**13000**	**-**	11100	**63.2**	-	70.3
	Standard deviation	2350	-	3100	23.6	-	15.5

The mean static bending modulus of elasticity (MOE) results for both species are better than the data obtained by McGavin *et al.* (2006) for younger aged material of the same species. The mean static bending modulus of rupture (MOR) results of *E. cloeziana* are also better than the data obtained by McGavin *et al.* (2006) for younger aged material. Unexpectedly, the testing of *E. pellita* produced a lower mean static bending MOR than the data obtained by McGavin *et al.* (2006) despite the *E. pellita* of this study being almost twice the age.

Figure 28 demonstrates the difference in MOR distribution of both species and while *E. cloeziana* displays normally distributed values as expected, the *E. pellita* displays a more even or uniform distribution. This uniformity seems to be heavily influenced by a larger than expected proportion of low MOR values and is most likely the consequence of brittle heart.

This also results in a higher proportion of low MOE and lower MOR values than expected when compared to the average MOE/MOR ratio. This effect is demonstrated within Figure 29 where *E. pellita* displays a weaker correlation than *E. cloeziana* because of a group of boards from inner and intermediate heartwood which are outliers. There was no visible evidence of direct mechanical damage due to cyclone.

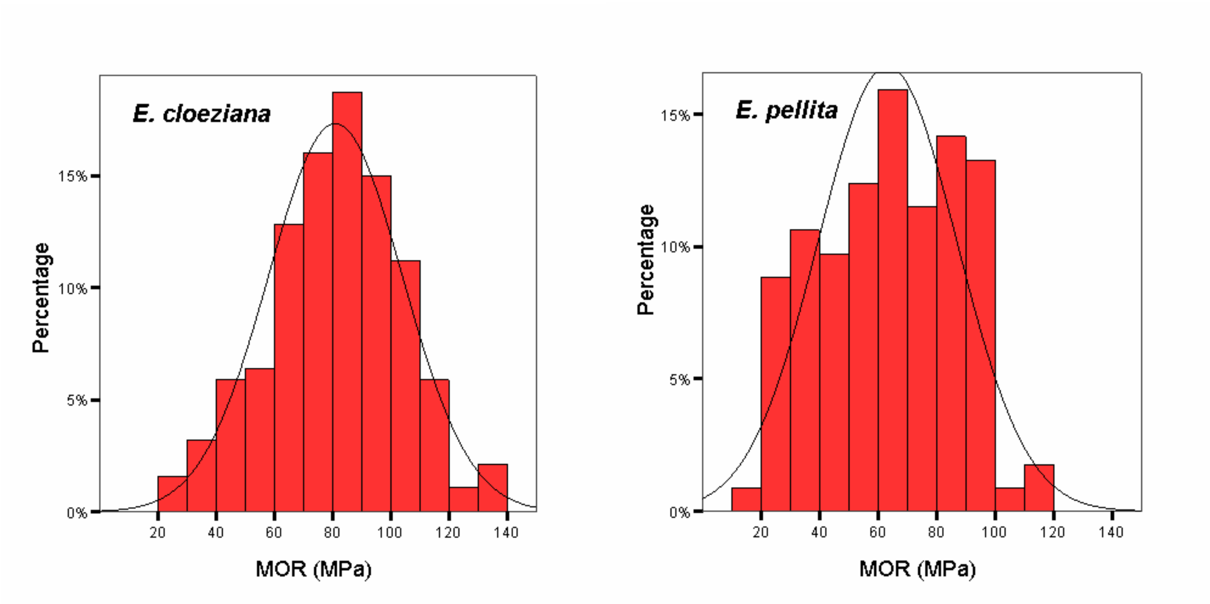


Figure 28. Histogram of static bending MOR

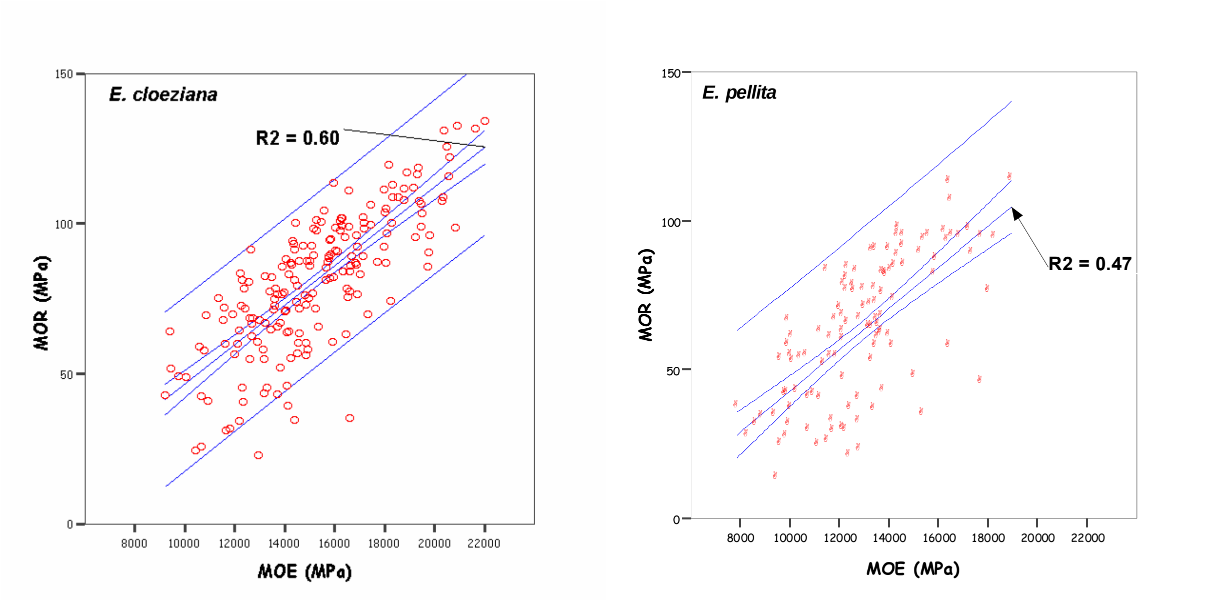


Figure 29. Correlations between static bending MOE and MOR. Blue lines represent regression lines, 95% individual and mean confidence intervals.

The F-grade distribution extrapolated from static testing results is presented in Figure 30. While the visual stress-grading approach provides a high proportion of rejected boards (around 30%) for both species, by comparison, the mechanical stress-grading approach doesn't generate reject boards but a range of grades, mostly between F14 and F27 for *E. cloeziana* and between F8 and F22 for *E. pellita*. It should be noted that structural boards from mature natural forest are generally visually graded with the lowest marketable grade being F14. The visual grading clearly disadvantages young plantation wood despite their valuable mechanical properties.

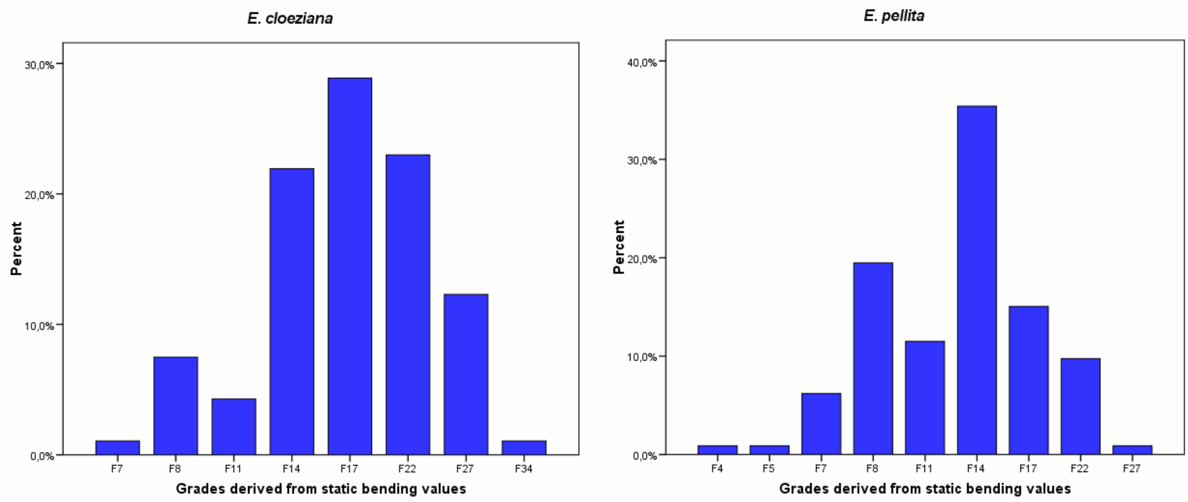


Figure 30. Proportion of stress-graded boards from static bending test.

4.3 Provenance effect

While the original project plan didn't include analysis of the provenance effects of wood characteristics, limited opportunity was available to undertake partial analysis and has therefore been included. For *E. cloeziana*, 19 trees from Helenvale provenance and 23 trees from Pomona provenance were included in the study allowing limited analysis to be undertaken. The *E. pellita* sample contained only three trees from one provenance compared to 29 of the other, consequently analysis of any provenance effect on property variation for this species was not conducted. As the experiment design did not originally cater for provenance effect analysis, and the resulting sample size was small and repetition limited, interpretation of the results should be made cautiously.

Statistical analysis shows that there was no significant difference between the two *E. cloeziana* provenances for MOR and MOE for small clear and full size samples, distortion, hardness or nail and screw withdrawal.

The mean heartwood proportion, basic density, extractives content and unit shrinkages between the two provenances is statistically different. For all these characteristics, the Pomona provenance displayed lower means than Helenvale provenance however there was no statistical difference for variance (Figure 31, Figure 32, Figure 33 and Figure 34).

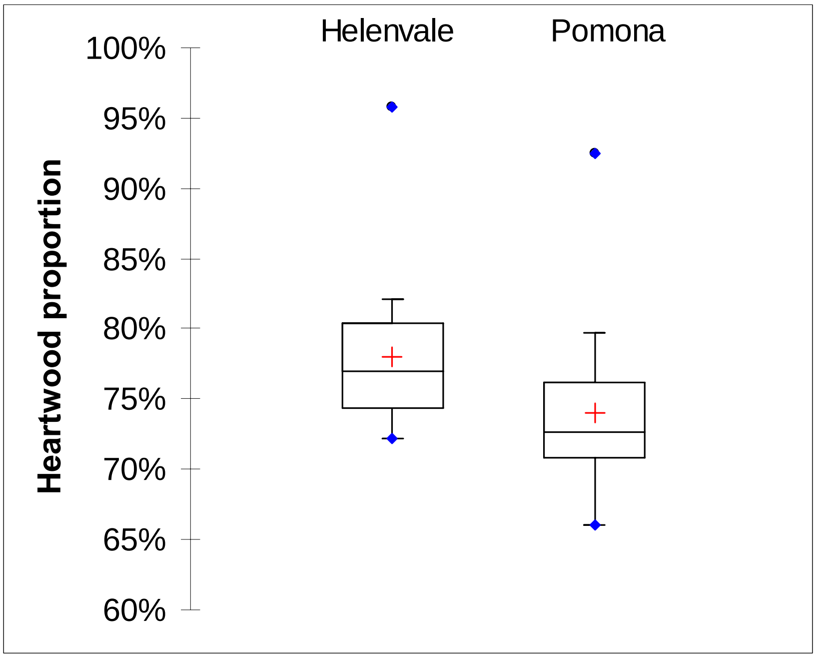


Figure 31. Box plot showing heartwood proportion for *E. cloeziana* Helenvale and Pomona provenances.

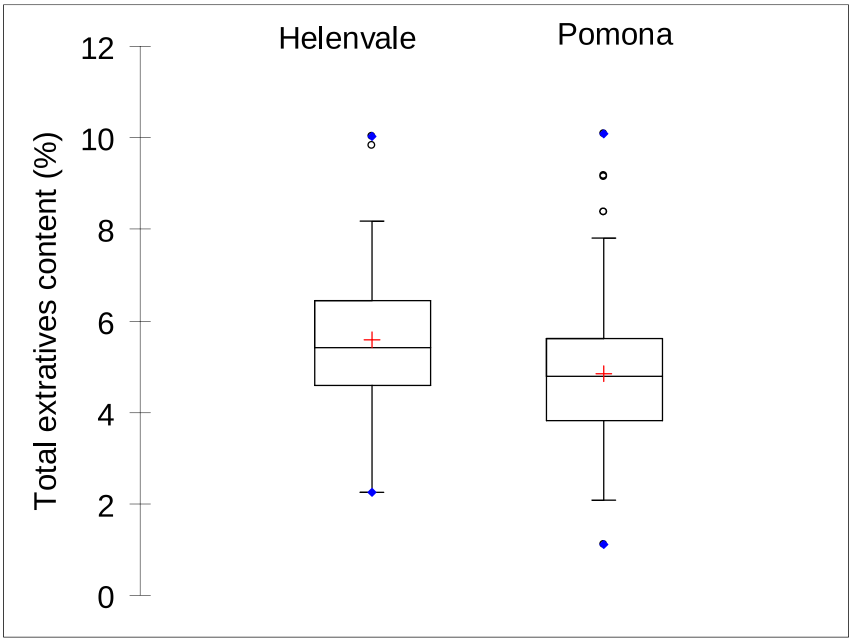


Figure 32. Box plot showing total extractives content for *E. cloeziana* Helenvale and Pomona provenances.

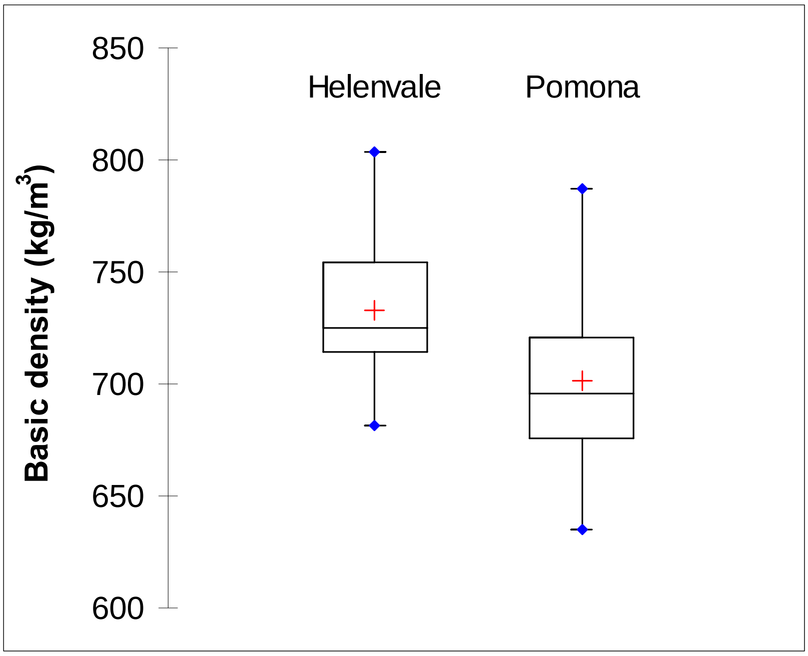


Figure 33. Basic density for *E. cloeziana* Helenvale and Pomona provenances.

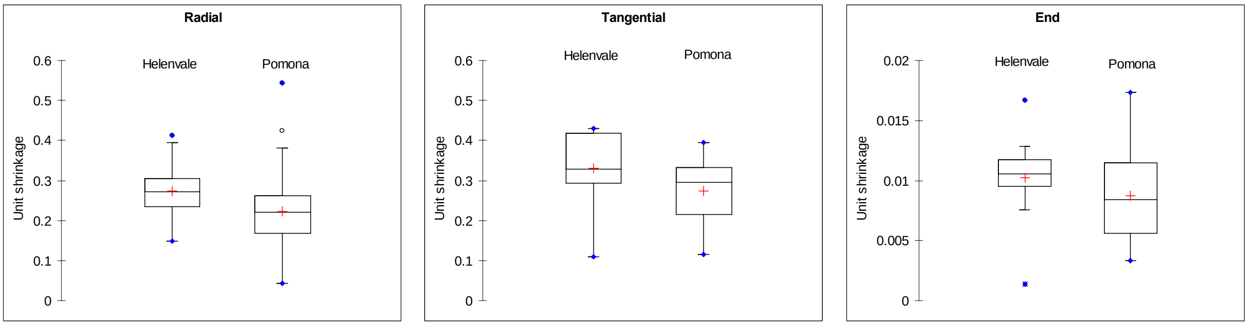


Figure 34. Box plots showing unit shrinkages for *E. cloeziana* Helenvale and Pomona provenances.

Heartwood proportion results and total extractives content were 78% and 5.58% respectively for the Helenvale provenance compared with 74% and 4.85% respectively for Pomona provenance. These differences may explain the dissimilarity observed with the basic density results which were 733kg/m^3 for Helenvale and 701 kg/m^3 for Pomona. A lower heartwood proportion decreases the recovery of high quality timber while extractive content would be expected to improve stability, colour and natural durability.

Despite its lower extractive content, Pomona unit shrinkages were lower than Helensvale (Figure 34). Shrinkage is a complex wood property which can also be related to several material parameters. In particular Pomona's lower basic density could explain its lower shrinkage than Helenvale.

Obviously other parameters such as the interaction environment by genetics effects could also explain the differences observed. Further investigations on several provenances across various sites would be necessary to further understand these variations.

4.4 Structural properties prediction by natural vibration analysis

4.4.1 Logs vibration measurements versus dry boards static bending

The *E. cloeziana* log vibration MOE varied from approximately 10,000 MPa to 20,000 MPa. This wide variability would not normally be expected from mature native forest logs and suggests that good process management will be required to match plantation logs efficiently with target products.

The vibration MOE calculated from longitudinal vibration of logs provided a reasonable estimation (R^2=0.59) of the average seasoned board static MOE (Figure 35). This correlation is strong even though only a sub-sample of boards sawn from the log was included in the testing.

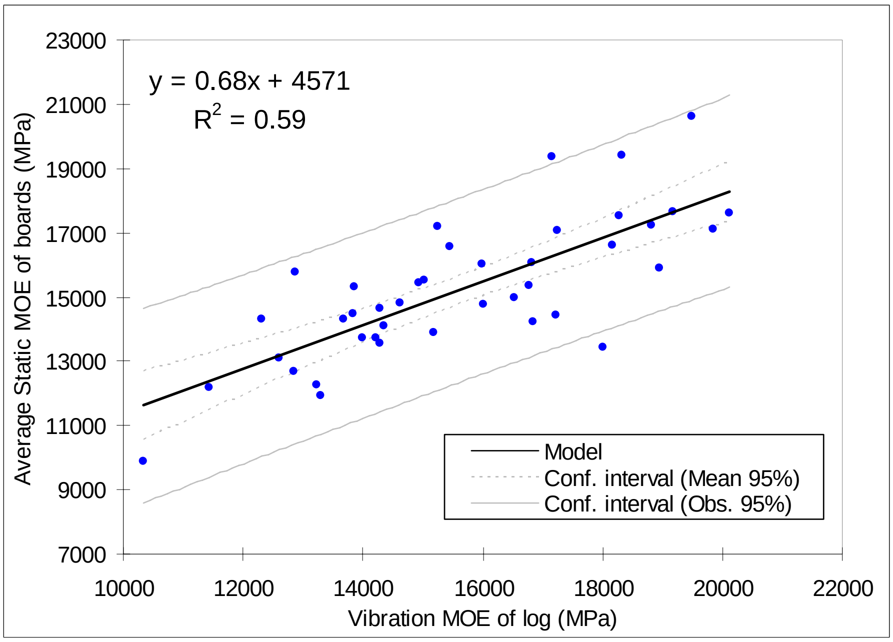


Figure 35. Simple linear regression of static MOE average obtained on a dry board sub-sample from each log by the vibration MOE calculated from the longitudinal vibration of the log (N=39).

While the prediction of static MOR is not as good as static MOE prediction as seen in Figure 36, either measure could potentially be useful to classify or grade logs in perhaps two or three classes. Sorting logs prior to processing could be a useful technique to optimise the grading process from plantation logs with highly variable mechanical properties. As this study only included a sub-sample of boards, further analysis of the potential correlation accounting for all the boards from the log should be very informative in a complementary study.

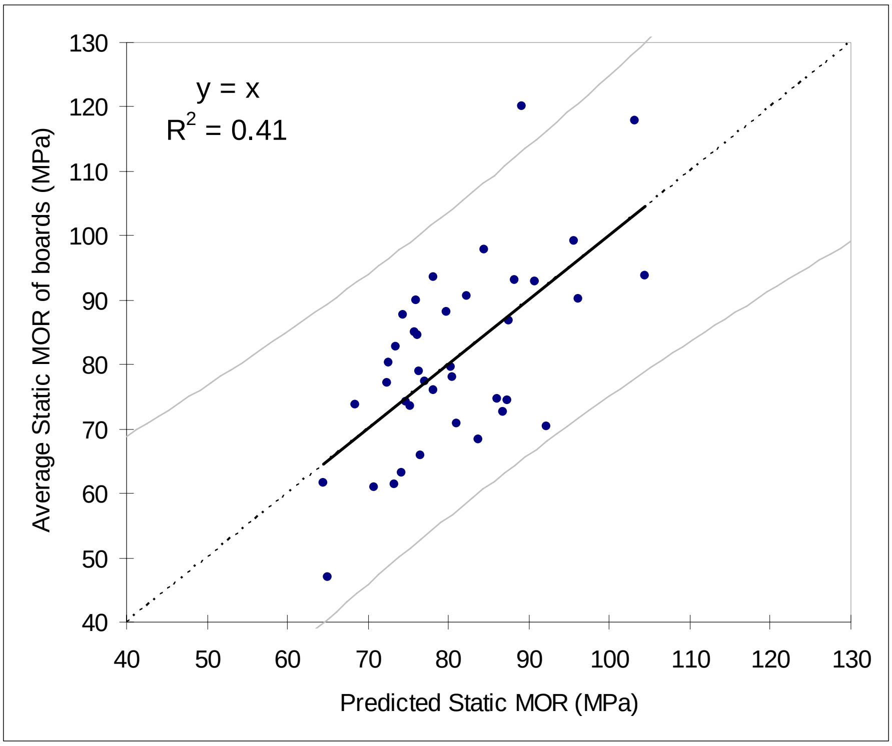


Figure 36. Multivariate linear regression of static MOR average obtained on a dry board sub-sample from each log by the vibration MOE and the first harmonic damping calculated from the longitudinal vibration of the log (N=39).

4.4.2 Green boards vibration versus green boards static bending

The correlation from data collected from green *E. cloeziana* boards for vibration MOE versus static bending MOE is displayed within Figure 37. The coefficient of determination is quite high and the standard error of estimate (957 MPa) is close to the laboratory standard error which indicates an accurate estimation of the reference measurement.

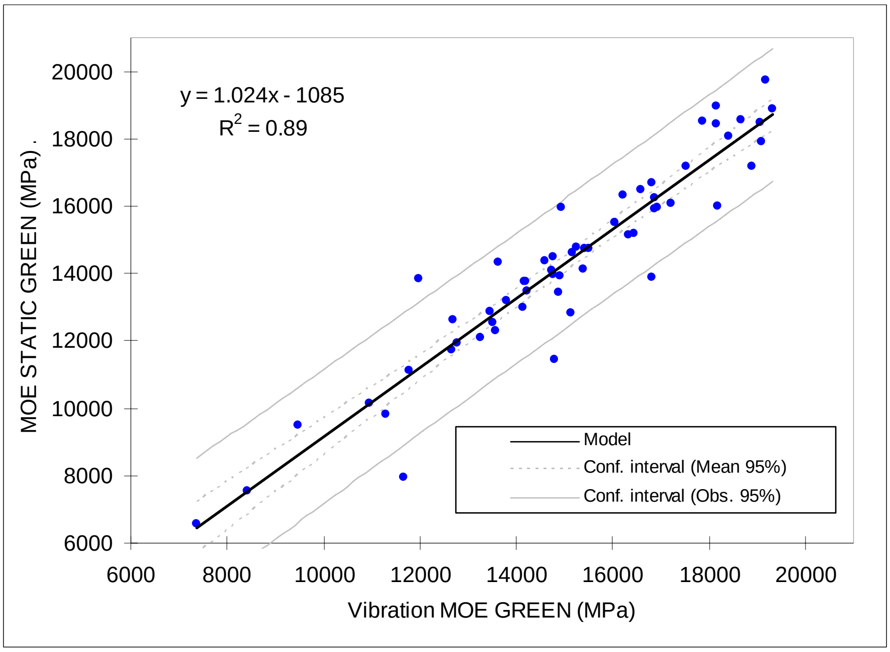


Figure 37. Static MOE by vibration MOE simple linear regression obtained on green boards (N=59).

For MOR, the best correlation is achieved with vibration MOE and first harmonic damping as explanatory variables (Figure 38). The coefficient of determination is high enough to potentially use this technique to grade the boards into 3 or 4 classes. Nevertheless, the number of boards is low and only two points out of 24 significantly improve the correlation. Despite the fact that previous results (Bailleres, 2007) prove that adding the damping parameter in multivariate analysis significantly improves the prediction of MOR, this result has to be considered cautiously. Further investigations will be required to develop a functional calibration.

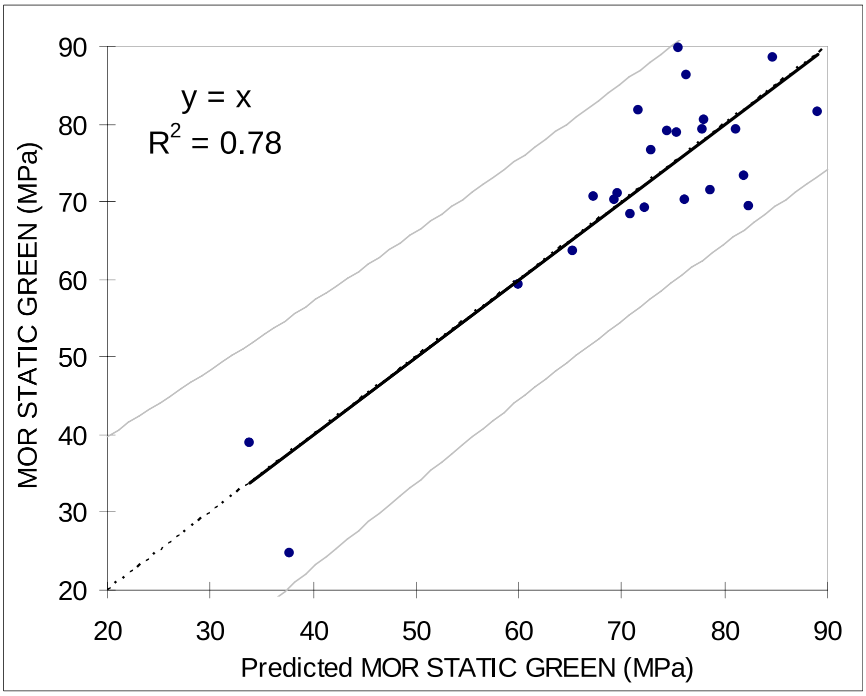


Figure 38. Multivariate linear regression of static MOR (MPa) on green board by vibration MOE and damping of the first harmonic on green boards (N=24).

4.4.3 Green boards vibration versus dry boards static bending

On *E. cloeziana* samples, the correlation between green board static MOE versus dry board vibration MOE is excellent as confirmed by Figure 39. A good correlation exists between dry board static MOR and vibration MOR measured on green boards (Figure 40). These correlations could be very useful for green board mechanical grading, potentially avoiding the cost of processing (e.g. seasoning and profiling) of boards that don't have desirable mechanical properties.

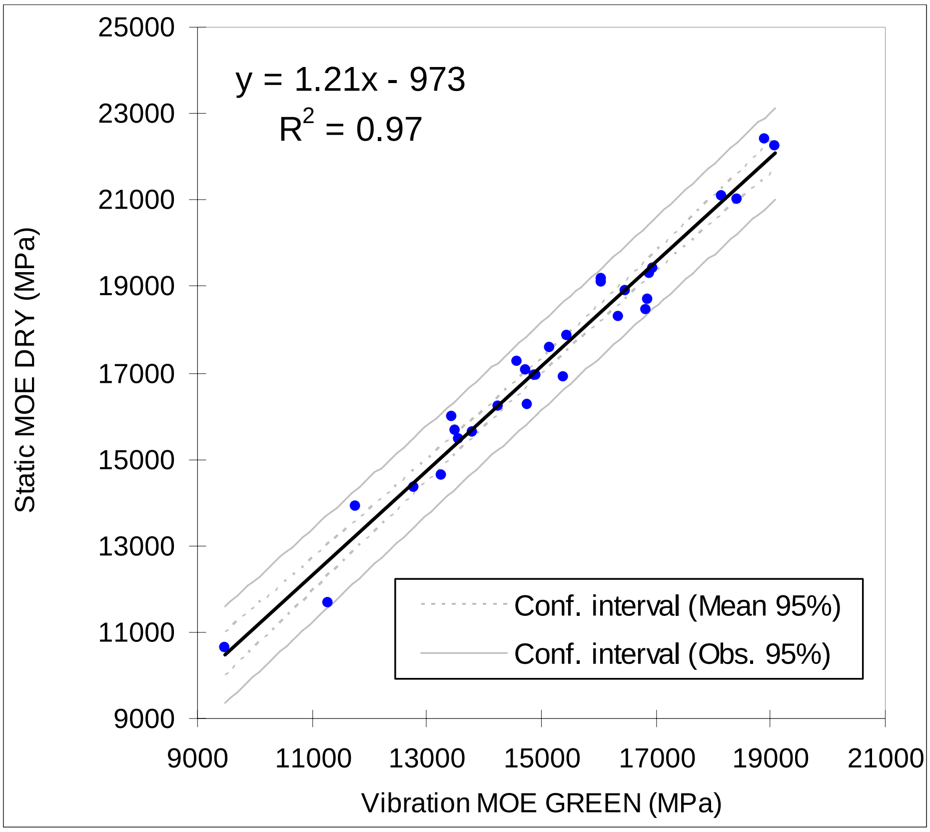


Figure 39. Simple linear regression for static dry board MOE versus vibration MOE from green board testing (N=30).

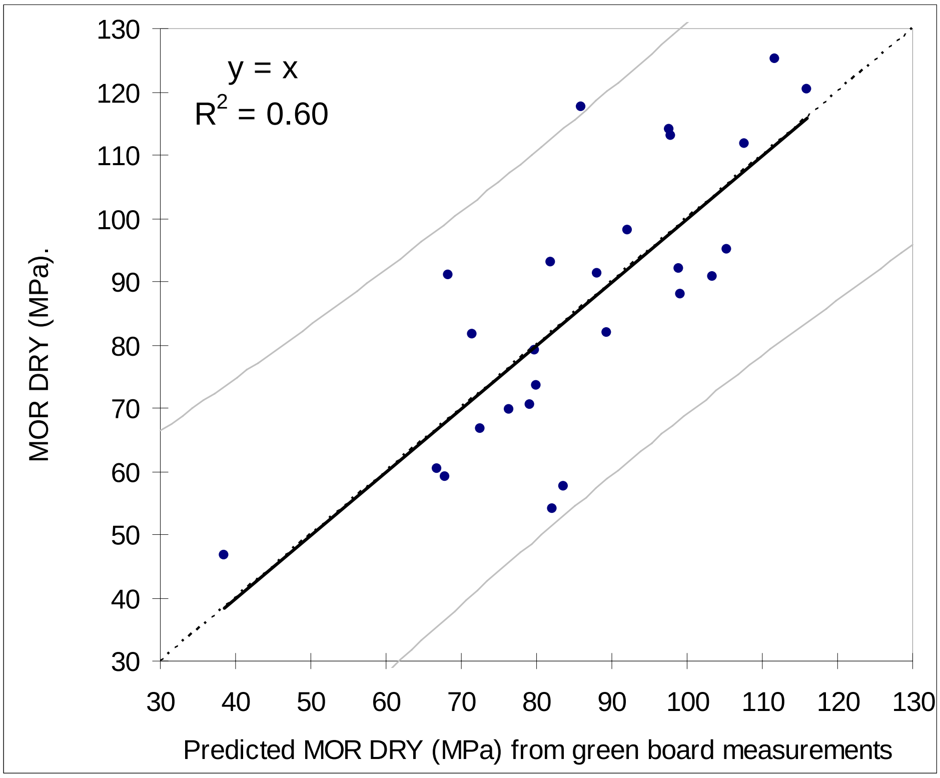


Figure 40. Multivariate linear regression for static MOR (MPa) from green boards by vibration MOE (MPa) and damping of the first harmonic (N=26).

4.4.4 Dry boards vibration versus dry boards static bending

Prediction of static MOE

Figure 41 and Figure 42 display the correlations for both species between static MOE and natural transversal vibration which provides a measured MOE in flexion and natural longitudinal vibration which provides a measured MOE in traction-compression.

Whatever the vibration mode used, longitudinal or transverse, the correlations between static bending and vibration MOE were always high. The transverse vibration displays better correlation than longitudinal vibration as expected given the test configuration.

Several outliers did influence the quality of the regressions; however additional analysis on the reference method protocol with regard to the defect location and its nature should result in improvements to the correlation. Nevertheless, the level of these correlations is quite satisfactory for providing an excellent and simple grading technique. The use of multivariate regression technique using the parameters extracted from the digital signal didn't improve the level of correlation significantly.

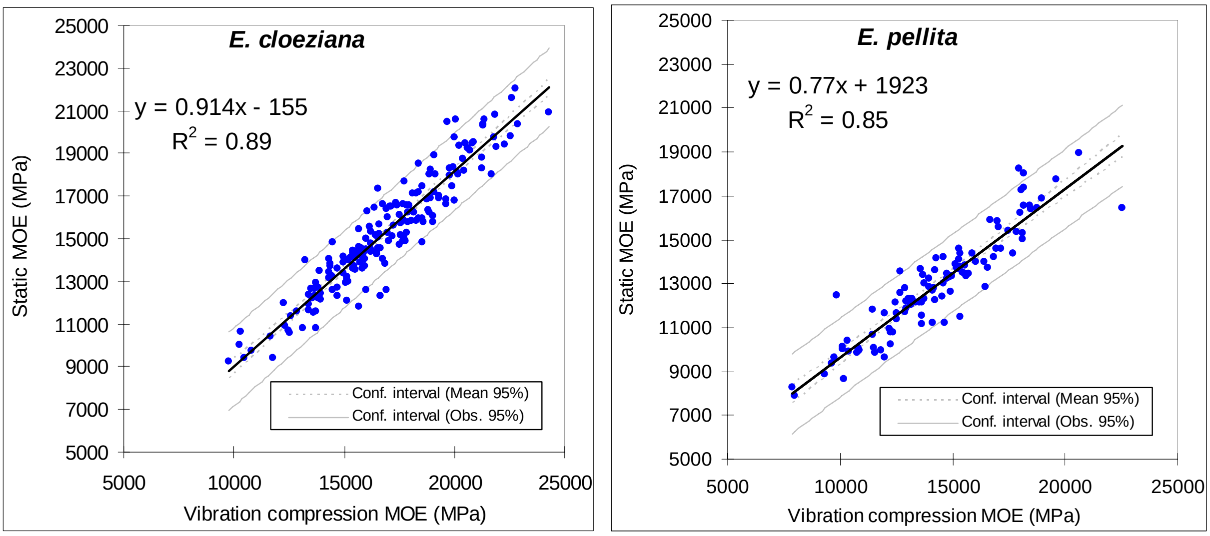


Figure 41. Simple linear regression for static MOE by longitudinal vibration MOE (compression-traction mode) on dry board (N=187 for *E. cloeziana* and N=112 for *E. pellita*).

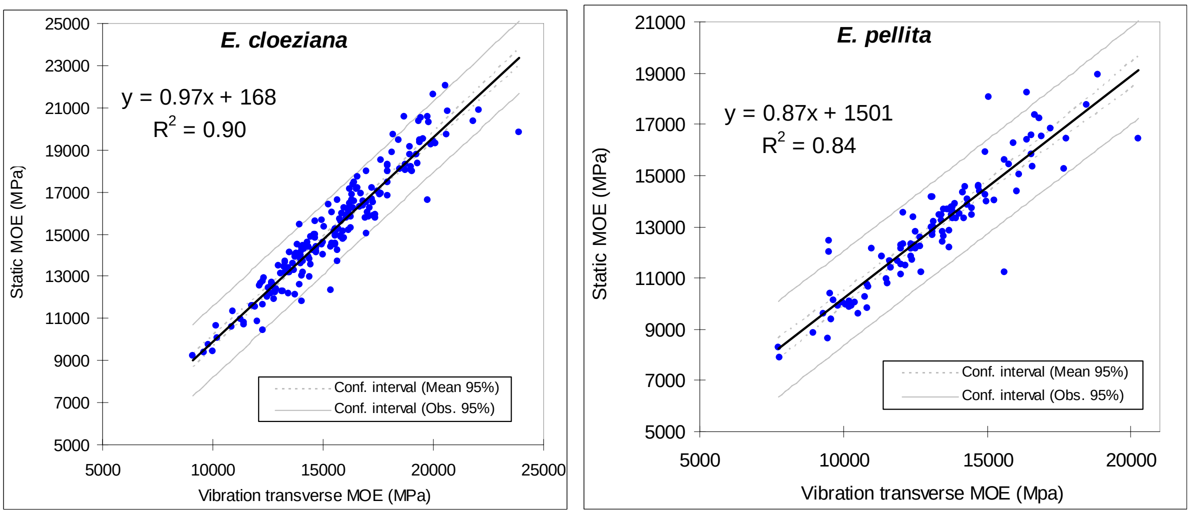


Figure 42. Simple linear regression for static MOE by transverse vibration MOE (flexion mode) on dry board (N=187 for *E. cloeziana* and N=112 for *E. pellita*).

While the correlations are obviously very high they will never be perfect. This is due to stress being homogeneously distributed on the whole section in traction-compression mode contrary to bending mode where the stress is in a form of a gradient with the maximum on the curved faces of the bent beam. On the other hand, the static bending is performed on a portion of the beam corresponding to the inner two bending points whereas vibration occurs in the whole board. Regarding this stress field difference, the position of a local defect obviously affects the bending properties. The closer the defect is to the face, the lower the bending property. The longitudinal vibration MOE is less affected by the position of the defect related to bending neutral axis. There is no prediction gain using a transverse vibration measurement, especially as it is practically slower and more difficult to use.

Vibration MOEs were always significantly greater than static bending MOE because the dynamic measurement (vibration) provides theoretically higher MOE measurements due to the visco-elastic nature of wood.

Prediction of MOR

The use of linear multivariate regression based on 25 parameters extracted from the digital signal improves the level of correlation significantly (around 0.1 to 0.2 on the coefficient of determination). The optimum correlation for MOR prediction is performed with MOE and damping extracted from the first harmonic (Figure 43 and Figure 44). This improvement is due to the impact of the defect on the vibration characteristics. Advanced multivariate regression such as partial least squares (PLS) regression applied on the vibration parameters should improve the prediction of MOR. Further investigations using chemometrics[6] tools could be performed in complementary studies.

As already discussed in paragraph 4.2.3 and displayed in Figure 29, the correlation between static MOE and MOR is influenced by some outliers, displaying very low MOR comparatively to MOE, very likely due to brittle heart. The equivalent correlations obtained from the vibration analysis are consistent (or even better in the case of *E. pellita)* to those observed between static MOR and MOE from the static test (Figure 29). The non elastic parameter extracted from the digital vibration signal seems to be responsive to defect such as brittle heart.

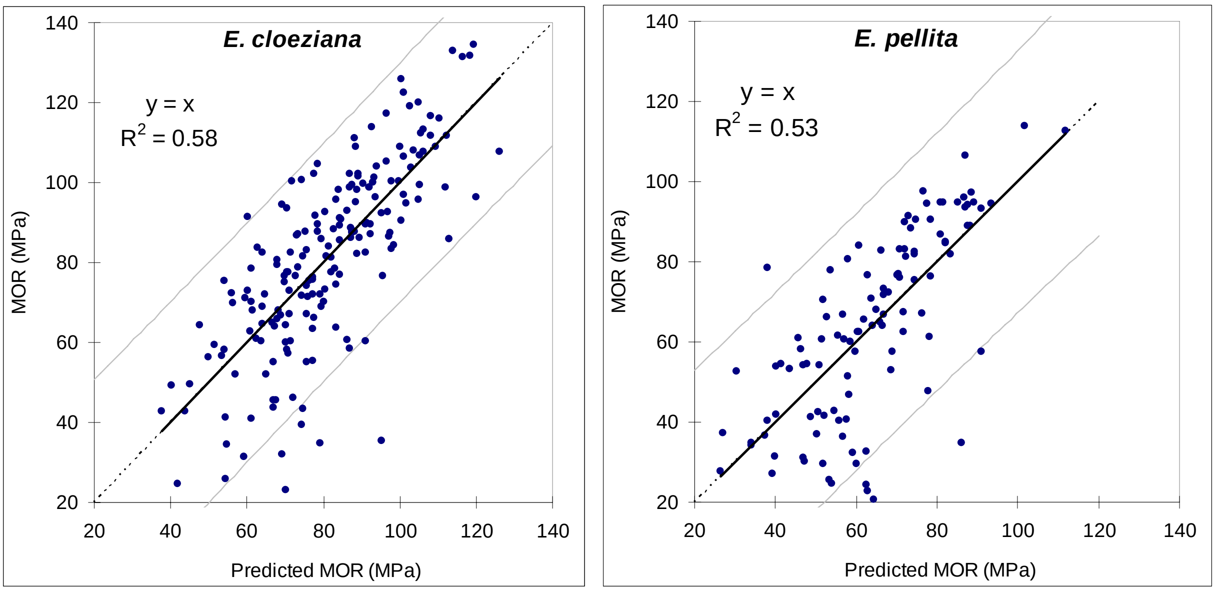


Figure 43. Multivariate linear regression for MOR versus predicted MOR from longitudinal vibration MOE (compression-traction mode) and damping of the first harmonic on dry board (N=187 for *E. cloeziana* and N=112 for *E. pellita*).

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[6] Chemometrics is the science of relating measurements made on a chemical system or process to the state of the system via application of mathematical or statistical methods.

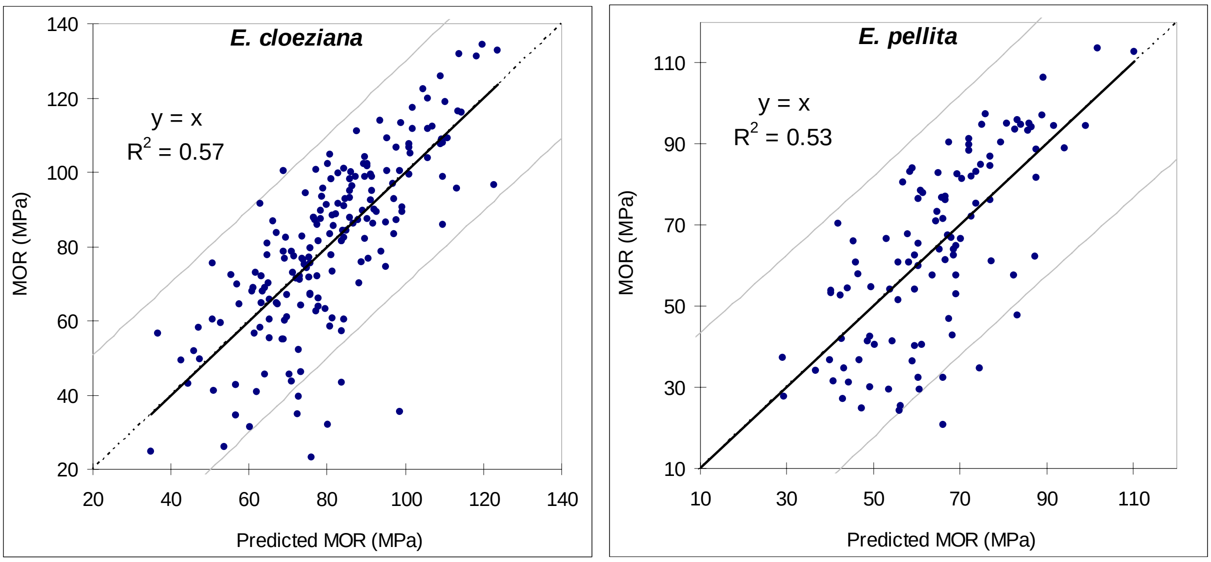

Figure 44. Multivariate linear regression for MOR versus predicted MOR from transverse vibration MOE (flexion mode) and damping of the first harmonic on dry board (N=187 for *E. cloeziana* and N=112 for *E. pellita*).

4.5 Comparison with Australian planted softwood

It is interesting to compare the results obtained within this study against technical data from Australian plantation-grown softwood species, as these species are widely used for structural purposes.

Results obtained from this study show that the basic density varies from 450 to 650 kg/m^3 (590 kg/m^3 on average) for *E. pellita* and from 650 to 750 kg/m^3 (715 kg/m^3 on average) for *E. cloeziana*. MOE on full size specimen varies from 9000 MPa to 17000 (13000 MPa on average) for *E. pellita* and from 10000 MPa to 20000 (15200 MPa on average) for *E. cloeziana*. MOR on full size sections vary from 20 MPa to 100 MPa (63 MPa on average) for *E. pellita* and from 30 MPa to 120 MPa (81 MPa on average) for *E. cloeziana*.

Average mechanical properties (density, MOE, MOR) measured for the *Eucalyptus* species tested in this study (see 4.1.3, 4.1.7 and 4.2.3) are above the average values of Australian-grown exotic softwood species commonly reported in the literature for full size sections (Harding *et al.* 2000 and McKinley *et al.* 2003).

For small clear wood specimen, some values from recent publications are displayed in tables 19 and 20. For density, *E. cloeziana* is consistently above the reported softwood values whereas *E. pellita* is closer to the higher density pines (basic density is lower by approximately 10% compared to density at 12% moisture content).

Table 19. Average air dry density of Australian-grown exotic softwoods (source: Hopewell, 2006, except *Harding 2007).

Species	Latin name	Occurrence in Australia	Density at 12% MC (kg/m^3)
slash pine	*Pinus elliottii*	Qld	625
Caribbean pine	*Pinus caribaea* var. *hondurensis*	Qld	545-575
hybrid pine	*Pinus elliotii* x *Pinus caribaea*	Qld	495*
radiata pine	*Pinus radiata*	Qld, NSW, Vic, ACT, Tas, SA	545
maritime pine	*Pinus pinaster*	WA	560-600

Table 20. Clear wood properties of Australian-grown exotic softwoods (source Bootle, 2005)

	Clear wood properties		
Species	***Pinus radiata***	***Pinus elliotti***	***Pinus caribaea***
Density at 12% MC (kg/m^3)	500	530	480
Basic density (kg/m^3)	400	450	410
Modulus of rupture (MPa) dry	81	85	67
Modulus of elasticity (MPa) dry	10000[1]	9700	5400
Max. crushing strength (MPa) dry	42	41	35
Hardness (Janka) (kN) dry	3.3	3.5	na

Some differences can be noted between the diverse sources of information referenced and probably denotes the variation effect that juvenile wood has on such properties. , whereby the reference material reported in Bootle's publication was likely to be younger than the material reported in Hopewell's publication.

The gradient of air dry densities induced by the juvenile wood phase ranges from 350 kg/m^3 to 600 kg/m^3 for Australian-grown exotic softwoods (Larson *et al.* 2001, Harding *et al.* 2000 and McKinley *et al.* 2003). This variation is greater than the one observed for the *Eucalyptus* species in this study. In addition, the lower density wood situated around the pith in softwoods, is associated with a higher incidence of knots compared to *Eucalyptus* species. This knotty core has a tendency to increase the difference on full size specimen mechanical properties between inner juvenile wood and mature wood which displays a lower proportion of knots.

5 Conclusions

The wood quality attributes measured for 19 year-old *Eucalyptus cloeziana* and 15 year-old *Eucalyptus pellita* plantation are consistent with natural grown timber properties and results of previous studies on younger material of the same species. The average properties measured in this study are positioned between natural grown and younger material. Compared to mature natural grown timber of the same species, *E. cloeziana* displays equivalent properties performance overall, whereas, unexpectedly, *E. pellita* shows relatively poor wood quality similar to that observed in young 8 year-old trees. Nevertheless the overall wood quality as measured by physical and mechanical properties of the *E. pellita* studied is superior to Australian-grown exotic softwoods when considering structural products. While the plantations were damaged during the cyclone event, there was nothing observed during the study to suggest any negative impact on wood quality or mechanical properties of the selected trees.

Heartwood proportion in both species is lower than natural forest grown material where it is expected to be around 90% of the stem surface. An average of 76% for *E. cloeziana* and 67% for *E. pellita* was measured. The comparatively younger age of *E. pellita* studied may explain the lower result in comparison to *E. cloeziana*. Heartwood proportion would be likely to reach its maximum at a tree age of approximately 30 years.

Extractive content is comparable for both species and varies greatly between trees. The within tree variation demonstrates a 40% increase from inner to outer heartwood. The lower extractive content around the pith could explain the early decay observed in some trees, particularly in *E. pellita*. Given the implications of this characteristic for high quality products, it should be included in genetic improvement schemes.

Within tree variation in wood properties was higher than between tree variation. This is the general trend for all planted fast grown species but is not the case for wood from mature native forest trees. Within tree property variation is predominately due to the juvenile phase which creates wood property gradients from pith to bark. This reflects the ontogenetic process of wood properties of fast growing trees. The latter induces a volumetric expansion of juvenile wood where many properties vary up to a mature state which occurs at a cambial age of approximately 25- to 30-years-old. The gradient of these variations also depends on genetic by environment interaction effects. In this study, the basic density and related properties which are linked to cell wall ultrastructure, mainly all the mechanical properties, demonstrate a broad variation that increases from the inner to outer heartwood. For *E. pellita*, the low mechanical properties observed are explained by a longer juvenile phase compared to *E. cloeziana* which seems to reach a mature state relatively quickly.

It is important to note that the observed gradients are not greater than those observed in many plantation softwoods processed in Australia. These gradients lead to a wide heterogeneity of the sawn products which necessitates a grading process for technical and commercial reasons.

Appearance grading leads to a low grade recovery essentially due to knots. *Eucalyptus pellita* has the worst recovery with more than half of the boards rejected. A docking process improves the appearance grade recovery appreciably but the benefit of such method needs to be assessed economically.

For structural purposes, this material displayed good mechanical properties with MOE and MOR being around 20 to 40% higher than structural slash pine (*Pinus elliottii*). The variation in mechanical properties is quite large because of the large proportion of juvenile wood along with a significant volume influenced by the knotty core. This central part of the log seems to induce a brittle rupture characterised by an average level of MOE but a low MOR value. This tends to downgrade a larger proportion of boards when compared to previous studies on similar material. This phenomenon should be further analysed with regard to genetic and environmental factors. This heterogeneity will need to be carefully considered when planning processing and product strategies to ensure the maximum value is gained.

The current visual grading system does not provide a reliable grading method for this material since the visual grading rules were defined on mature wood from native forests. The development of a mechanical grading system needs to be explored. Vibration analysis techniques, mainly the resonance method, provided a reliable, practical and simple means of structural grading. Longitudinal vibration measurement could be the simplest way for industry to obtain a consistent and accurate sorting process. The economic benefits will be substantial with reduced cost-adding to low grade and out-of-grade material, by early detection of this wood and diversion to more appropriate product streams. It could provide:

- More accurate grading of structural wood by analysis of the prediction capability of the multivariate equations.
- Guidelines to assist the processing industry in their specification and investment decisions to source and implement improved grading systems.
- Reduction in the proportion of dried, milled product falling out-of-grade due to strength and/or stiffness limitations, resulting in improved confidence in graded products.
- Greater resource optimisation reduced costs and increased profits for the hardwood sector.

A rough assessment of the genetic impact on wood properties was performed on two provenances of *E. cloeziana*. No significant difference was found between MOR and MOE for small clear and full sized samples, distortion, hardness or nail and screw withdrawal. Heartwood proportion, extractive content, basic density and unit shrinkage display significant differences between the two provenances studied. This difference could help breeders to refine the selection process based on wood quality as well as growth and stem geometry characteristics.

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