Assessment of the durability and engineering properties of lesser-known hardwood timber species for use in marine and freshwater construction

A research report

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Cover photographs:
Shingle abrasion of greenheart pile. *TRADA Technology*
Cleaning test racks. *TRADA Technology*
Example of shipworm extracted from a Douglas fir bearer, *TRADA Technology*
Tropical hardwood groyne at Whistable, Kent. *TRADA Technology*

Contents

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Aitken & Howard Ltd
Marine & Constructional Timbers

Executive Summary

The Environment Agency (the Agency) builds and maintains coastal and freshwater structures throughout England and Wales, many of which incorporate timber. Historically, the Agency and much of the wider UK construction industry has favoured a narrow range of “tried and tested” tropical hardwood timbers for these purposes, with Greenheart and Ekki being the prominent timbers of choice. This approach puts pressure on supplies and strain on the environment. The Agency therefore commissioned research to identify alternative, lesser-used species (LUS) of tropical hardwood timber that would be suitable for use in marine and freshwater construction applications

An initial desk-based study by Biodiversity International Ltd was commissioned in 2007.The findings and recommendations of this study were a catalyst for the more comprehensive research project described in this report.

The current research project can be split into three stages:

Stage 1: To identify suitable candidate timbers (the “long-list”) based on a desk-based review of previous research, existing literature and database reference sources.

Stage 2: To assess the potential marine borer resistance and abrasion resistance of these candidate timbers using a range of novel, fast track laboratory screening tests, as well as a marine exposure trial.

Stage 3: To select five timbers from the “long-list” (on the basis of the findings of Stage 2 and a range of commercial considerations) and to determine their strength properties by testing structural sized specimens in accordance with the test method described in EN 408: 2003 *Timber structures – structural timber and glued laminated timber. Determination of some physical and mechanical properties.’*

This report describes the scope of work undertaken in each of the three stages, including information on the research methods used, together with the results and findings that were reported.

In all cases, the performance of the long-list candidate timbers were compared with the performance of Greenheart and Ekki (benchmark species) and also a number of reference species (Yellow Balau, Douglas Fir, Purpleheart, Karri, Oak and Bilinga). The reference timbers were included on the basis that they have been used in marine and freshwater construction applications in the UK, and their performance in these environments is relatively well known and understood.

The results of the laboratory screening trials undertaken in Stage 2 are detailed in the following table.

Results	Exposure to gribble	Exposure to abrasion
Timbers that performed significantly better than Ekki on the basis of laboratory screening trials	Niove Yellow Balau (R) Cupiuba Piquia Douglas Fir (R)	-
Timbers that performed significantly worse than Ekki on the basis of laboratory screening trials	Purpleheart (R) Mukulungu Eveuss Scots pine*	Greenheart (B) Okan Garapa Douglas Fir (R) Cloeziana Karri (R) Angelim Vermelho Piquia Purpleheart (R) Mora Dabema Basralocus Niove Cupiuba Opepe Massaranduba Bilinga (R)# Yellow Balau (R)
Timbers that performed significantly better than Greenheart on the basis of laboratory screening trials	Niove Yellow Balau (R) Cupiuba	Souge Oak (R) Eveuss Tali Ekki (B)
Timbers that performed significantly worse than Greenheart on the basis of laboratory screening trials	Massaranduba Oak (R) Tali Angelim Vermelho Purpleheart (R) Mukulungu Eveuss Scots pine*	Cupiuba Opepe Massaranduba Bilinga (R)# Yellow Balau (R)

* Used as a control to validate the vigour of the test organisms
(R) Reference species
(B) Benchmark species
Bilinga is another name for Opepe. Bilinga is kept separate throughout this document to reflect its procurement from a different source to Opepe.

The results of the marine exposure trial undertaken to establish the comparative resistance of the candidate timbers to attack by *Teredo* spp. (shipworm) at a site on the Algarve, where there is a known hazard associated with shipworm attack, are given in the following table. Data was obtained over an 18 month period (spring 2008 to autumn 2009).

Timbers resistant to attack by shipworm	Timbers moderately resistant to attack by shipworm		Timbers not resistant to shipworm attack
Timbers not exhibiting any colonisation by shipworm	Timbers exhibiting minor colonisation by shipworm	Timbers exhibiting moderate colonisation by shipworm	Timbers exhibiting extensive colonisation by shipworm
Angelim Vermelho Basralocus Bilinga (R) Yellow Balau (R) Greenheart (B) Ekki (B) Okan Tali	Cupiuba Eveuss Garapa Bilinga (R) Piquia Sapucaia Souge Timborana	Dabema Mukulungu	Cloeziana Karri (R) Mora Niove Oak (R) Scots pine (R) Purpleheart (R) Tatajuba

On the basis of the results of the laboratory screening tests and the marine exposure trial, as well as factors such as commercial availability within the timeframe of the research project and likely long-term security of supply into the civil engineering sector, five species of timber from the long-list of candidates timbers were selected for the strength testing programme (Stage 3). These five species were Angelim Vermelho, Cupiuba, Eveuss, Okan and Tali. The results of the structural testing programme are given in the following table.

Candidate timber	Botanical name	Strength Class
Angelim Vermelho	*Dinizia excelsa* Ducke	D60
Cupiuba	*Goupia glabra* Aubl	D50
Eveuss	*Klainidoxa gabonensis*.	D50
Okan	*Cylicodiscus. gabunensis* Harms	D40
Tali	*Erythrophleum micranthum*	D35
Ekki (B)	*Lophila alata*	D70
Greenheart (B)	*Chlorocardium rodiaei*	D70

(B) Benchmark species

If strength is not critical, a longer list of thirteen lesser-used species of timber which may be suitable for marine and freshwater construction applications has been identified. These are identified in the table below. It should be noted that these exhibit varying levels of resistance to abrasion and marine borers, as well as variable commercial availability, so their suitability for use will depend on site and project specific requirements.

Candidate timber	Botanical name
Basralocus	*Dicoryia guianensis*
Cloeziana	*Eucalyptus cloeziana*
Dabema	*Piptadeniastrum africanum*
Garapa	*Apuleia leiocarpa*
Massaranduba	*Manbarklak*
Mora	*Mora excelsa*
Mukulungu	*Autronella congoensis*
Niove	*Staudtia kamerunensis*
Piquia	*Caryocar* spp.
Sapucaia	*Lecythis paraensis*
Souge	*Parinari excelsa*
Tatajuba	*Bagassa* spp.
Timborana	*Enterolobium schomburgkii*

The key findings and conclusions of the research project are given below.

1. On the basis of the research undertaken, five lesser-used species of timber have been identified that are suitable for use in critical marine and/or freshwater construction applications, where a strength class for design purposes is required.

2. In addition to these five species, a longer list of suitable timbers has been identified for applications where strength class is not critical but where marine borer and/or abrasion resistance is required.

3. To promote the wider use of LUS, an approach to specifying timber based on key risk parameters (i.e. service requirements and service hazards) is advocated to ensure that these timbers are considered alongside more common “tried and tested” timbers such as Greenheart and Ekki. In other words, the functional performance of a timber and its ability to withstand the most dominant site-specific hazards, whether resistance to gribble, shipworm or abrasion, should drive the selection of timber species. However, it is recognised that other factors such as availability within project timeframes, cost, required section sizes may also influence the decision making process.

The following recommendations are made:

1. If, or when, funding and resources permit it is recommended that further research be undertaken into the long-list of candidate timbers identified during this research project (excluding the five timbers that have been strength tested as part of this research).

2. Whilst all reasonable tests on the five lesser-used species of timber have been undertaken as part of this research, to the point that the researchers believe these timbers can now be used with confidence in project applications where a strength class is required, it is recommended that a monitoring programme be established to assess and review the performance of these timbers over time, in live project applications.

3. The research programme has also established the marine borer and abrasion resistant of a wider range of lesser-used species and it is recommended that these species are introduced into schemes where strength class is not a critical consideration, and their performance monitored over time.

1 Introduction

1.1 The research project

The Environment Agency (Agency) builds and maintains coastal and freshwater structures throughout England and Wales, many of which use timber. Historically, the Agency and much of the wider UK and European construction industry has favoured a narrow range of "tried and tested" tropical hardwood timbers for these purposes, with Greenheart and Ekki being the prominent timbers of choice.

The chief disadvantage of relying upon a narrow inventory is that commercial exploitation of such a narrow species range can accelerate the depletion of, and inflate the price of, certain timbers extracted from tropical forests. Taking a holistic view of the timber trade, this makes profitable forestry and sustained yield management increasingly difficult to achieve.

Furthermore, the Agency has questioned whether Greenheart and Ekki are strictly necessary for many marine and freshwater construction applications, particularly if strength is not critical, and hence whether there is a tendency to over-specify the technical properties of timber for its intended end use.

The Agency recognises that, within the UK marine and freshwater engineering industry, there is a demand for strong, durable, cost-effective and environmentally acceptable construction materials. Timber is a renewable resource, and is an environmentally acceptable choice of material, particularly if recycled or obtained from well-managed forests. In commissioning the research, the Agency therefore aims to encourage the use of a wider range of legal and sustainable timber in construction.

The precursor to this research project was an Agency commissioned desk based study titled "*Study into alternatives to Greenheart and Ekki tropical hardwood timber*", undertaken by Biodiversity International Ltd in early 2007. Although the report of this study has not been published, the findings and recommendations acted as a catalyst for further research and in autumn 2007, the Agency commissioned the current, more comprehensive research project. The aim of this project was to identify lesser-used species (LUS) of timber that could be used for marine and freshwater construction applications in the UK, as alternatives to Greenheart and Ekki. The Agency hopes that the acceptance and use of a wider range of timber species, particularly those that have no current export end use, may help tilt the balance towards sustainable forest management in the longer term.

The research has been a collaborative project between the Agency, TRADA Technology (TRADA) and H R Wallingford Ltd (HRW). Significant funding has been contributed by the Agency and TRADA, with smaller contributions from British Waterways, The Crown Estate, CETMEF (Centre d'Etudes Techniques Maritimes Et Fluviales) and VolkerStevin Ltd. Timber samples were sourced from / provided as a contribution-in-kind by Ecochoice UK Ltd and Aitken & Howard Ltd, with Ecochoice UK Ltd also providing expert knowledge on LUS, their commercial availability and performance.

A Project Steering Group (PSG) oversaw the running of the project and provided valuable technical expertise and insight. The PSG members and their organisations are presented in Appendix I to this report.

This Technical Report details the scope of work undertaken, including information on the research methods used, together with the results and findings that were reported. The research project can be split into three stages, as detailed below.

- Stage 1: To identify suitable candidate timbers (the “long-list”) based on a desk-based review of previous research, existing literature and database reference sources. It was checked at this stage that all candidate timbers on the long list could be sourced with evidence of legality, sustainability and chain of custody, in accordance with the timber purchasing policies of the Environment Agency and UK Government (see Section 1.2 for further details).

- Stage 2: To assess the potential marine borer resistance and abrasion resistance of the candidate timbers on the long-list using a range of novel, fast track laboratory screening tests, as well as a marine exposure trial. The performance of the candidate species was compared against that of Greenheart and Ekki which were selected as benchmark species. In relation to marine borers, resistance to attack by the crustacean, *Limnoria* spp., hereafter referred to as gribble, and the mollusc, *Teredo* spp. hereafter referred to as shipworm, was assessed.

- Stage 3: To select five timbers (on the basis of the findings of Stage 2, as well as other commercial factors) and to determine their strength properties by testing structural sized specimens in accordance with the test method described in British Standard BS EN 408: 2003 *Timber structures – structural timber and glued laminated timber. Determination of some physical and mechanical properties’.*

In addition, informal workability and machinability tests were undertaken at workshops operated by the Environment Agency and British Waterways. Redundant samples from the structural testing programme were used to conduct the tests, the results of which are presented in Appendix VI.

Each stage is described in subsequent chapters of the report. Appropriate findings and conclusions are presented for each stage of the work undertaken, with an overall conclusions and recommendations section at the end, in Chapters 9 and 10

1.2 Responsible timber procurement

As of April 1st 2009, the UK Government’s timber procurement policy requires central government departments, their executive agencies and non-departmental public bodies to procure timber and wood derived products originating from either independently verifiable legal and sustainable or FLEGT-licensed (Forest Law Enforcement, Governance and Trade) or equivalent sources. Timber which only meets legality criteria will be accepted in special cases. As an alternative, contracting authorities can use recycled timber.

The policy requires evidence of chain of custody (movement of the timber through the various stages of the supply chain from the forest source to the end product) and that the source of the timber is legally and sustainably managed or FLEGT-licensed. This evidence can come in three forms.

1. **Category A evidence**: This is independent certification of the timber and timber products under a forest certification scheme recognised by the UK Government. These schemes currently include FSC (Forest Stewardship Council) and PEFC (Programme for the Endorsement of Forest Certification Schemes). The PEFC is an ‘umbrella scheme’ which endorses national schemes, including CSA (Canadian Standard Association), SFI (Sustainable Forestry Initiative) and MTCC

(Malaysian Timber Certification Council), all of which are recognised by the UK Government.

2. **Category B evidence**: This is alternative documentary evidence (other than Category A) that provides assurance that the source is legal and sustainable and chain of custody exists. Category B evidence can be combined with Category A evidence (for example a certified forest of origin combined with non-certified evidence of chain of custody).

3. **FLEGT-licensed, or equivalent**: Timber arriving in the UK from a country that has negotiated a bilateral Voluntary Partnership Agreement (VPA) with the European Community should be accompanied by appropriate licence documentation (effectively a FLEGT licence) which will be checked at the point of import. It is then necessary to have supply chain controls in place from the point of import to the point of delivery to contracting authorities. This could take the form of Category A evidence or Category B evidence. It should be noted, however, that currently there is no FLEGT-licensed timber available in the market.

The Environment Agency has a strict timber procurement policy which supports the UK Government approach. The Agency considers timber to be a “high-risk” commodity because of issues surrounding illegal forestry and unsustainable forest management practices in certain parts of the world. The Agency’s timber purchasing policy requires evidence of legality, sustainability and chain of custody for all purchases of timber. The Agency has recently been recognized as a leader in sustainable timber procurement after winning the ‘Best Process Improvement’ award at the Chartered Institute of Purchasing and Supply (CIPS) Awards 2008. Judges praised the Agency’s robust timber procurement policy, and for driving improvements in UK industry and worldwide forestry practices down through its supply chain.

Further information about the UK Government’s approach to timber procurement can be found at www.proforest.net/cpet. Information about the Agency’s policy can be found at www.environment-agency.gov.uk/aboutus/procurement

In relation to the long-list of candidate timbers assessed as part of this research project, all can be sourced with Category A evidence of legality, sustainability and chain of custody (FSC certification). It is beyond the scope of this research project to comment on FSC certification *per se.* However, further information about FSC and other forest certification schemes recognised by the UK Government can be found on the website maintained by the Central Point of Expertise on Timber Procurement (CPET), which is funded by the Department for Environment, Food and Rural Affairs (DEFRA).

2 Background

2.1 The case for timber and its required material properties

The marine environment is challenging for all construction materials but timber suffers remarkably little from the effects of the salt content of seawater compared to, for example, concrete and steel (Cragg 1996). In addition, the resilience and favourable strength to weight ratio of timber, and the relative ease of fabrication and repair, make it an attractive construction material for decision makers to design with, and specify.

Timber, particularly from tropical forests, has been used as a construction material for marine and freshwater engineering in the UK for centuries and has many applications ranging from coastal defences such as groynes and sheet piling systems to maritime structures including wharves, jetties, piers and navigation aids such as dolphins (Brazier 1995). However, the material cost of timber in a marine construction scheme is often dwarfed by the actual construction cost. Consequently, this sector of the construction industry is conservative and there is a reluctance to specify timber species without a proven track record, which partly explains why a relatively short list of timbers are typically used.

The desirable material properties of timber for use in marine and freshwater construction may be summarised as follows:

1. Durable in freshwater against fungal attack, and resistant to marine borers (i.e. gribble and shipworm) and fungal attack in the marine environment. If the timber is not classified as naturally durable against decay or resistant against attack by marine borers then, ideally, it must be permeable and capable of receiving preservative treatment.

2. The timber should be available in large sections of 300mm x 300mm or greater and often in lengths of more than 10 metres.

3. The timber must be able to withstand the scouring action of the waves and abrasion by beach material.

4. The timber must have good strength properties, and must be able to withstand impact and deflection under impact.

Historically, in the UK, the combination of the above factors has resulted in use of a fairly short list of tropical hardwoods, although Oak has been used in the past and is still often used today by organisations such as British Waterways. Designers have almost always chosen a dense, naturally durable timber with a proven track record such as Greenheart or Ekki, although a few other dense tropical hardwoods such as Balau, Opepe and Jarrah have also been used. The chief disadvantage of this conservatism is that commercial exploitation of such a narrow range of timbers can accelerate depletion and inflate the price of certain timbers extracted from tropical forests. Taking a holistic view of the timber trade, this makes profitable forestry and sustained yield management increasingly difficult to achieve (Williams *et al* 2004A).

It is the great variety of timbers available from tropical forests that makes them so valuable for industrial applications but at the same time presents an enormous challenge in their use (Plaster and Sawyer 1998). Marketing LUS and encouraging the specifier to use an unfamiliar timber has always tested the timber industry and this has been seen very clearly in the use of timber for marine construction. Suppliers into this conservative market place continue to introduce new timbers but typically face considerable end-user resistance to LUS as their technical properties are not fully appreciated.

Two of the principal obstacles to working with LUS are that either there is limited confidence in the pedigree of the technical information about the LUS, or little is known about their resistance to marine borer attack. It should be borne in mind that high natural durability in terrestrial conditions does not necessarily guarantee robust marine performance (Cragg 1996 and Williams *et al* 2004B).

2.2 The development of novel test methods to assess timber performance

Fast track laboratory screening trials to determine comparative marine borer resistance and abrasion resistance in a reliable cost effective manner have been devised and undertaken by TRADA, University of Portsmouth and the Forest Products Research Laboratory (Borges *et al* (2003) and Sawyer and Williams (2005)). Both trials concluded that it was possible to assess marine borer (gribble) and abrasion resistance under laboratory conditions, but that marine exposure trials were needed to determine resistance to shipworm. To date, a reliable fast track screening method to determine comparative resistance to shipworm attack has not been developed.

One of the drivers behind this previous research was that EN 275: 1992 *Wood preservatives. Determination of the protective effectiveness against marine borers* specifies a five year test period to assess timber for suitability in the marine environment. However, five years is too long a period for most screening tests to be economically viable. Furthermore, the tests described in EN 275 do not assess abrasion resistance. The rationale behind both fast track laboratory screening trials is '*if it fails in the lab then it is likely to fail in the sea*'. As a result, these trials can filter out poor performing timbers before progressing to longer, more expensive and time consuming marine exposure trials.

In relation to abrasion, it should be noted that Oliver and Woods (1959) undertook an investigation to determine the rates of wear by shingle abrasion of a number of timber species used as piles and planking in sea defence groynes. This study was undertaken over a six year period (1953-1959). However, many of the timbers assessed by Oliver and Woods are no longer commercially available and do not appear in the 'long list' of timber species identified in this research project. Other than the work of Oliver and Woods, a previous search of the literature by Sawyer and Williams (2005) found that there had been little other research on the resistance of marine timbers to the effects of marine abrasion.

2.3 An overview of marine borers

Timber that is exposed in the marine environment below the high tide mark is subject to attack by marine bacteria, fungi and wood boring animals. Of the three risks, marine bacteria and fungi have a comparatively minor role in the bio-deterioration of timber below the high tide mark. Marine boring animals, however, may cause severe damage to a timber structure over a comparatively short space of time.

With reference to the coastal waters around the UK and based upon previous TRADA research carried out in the 1960's, there are two main groups of marine borers - shipworm and gribble. Gribble are ubiquitous whereas shipworm tend to be limited to the south coast and isolated estuarine areas along the west coast of the UK.

Over the last twenty years stringent environmental legislation has led to a vast and continuing improvement in water quality which has enabled marine borer populations to flourish in harbour areas where pollution had previously excluded them (Eaton and Hale 1993). In addition, observed increases in water temperatures increase the vigour of these populations.

It is worth noting that the last coastline survey to determine the distribution and occurrence of marine borers in marine structures around the UK coastline was carried out by TRADA in the 1960's (Hall and Saunders 1967). Plaster and Sawyer (1998) identified a need to re-survey the coastline as environmental conditions have changed in the last 30-40 years. Given the improvements in water quality and temperature rises that have occurred, it is reasonable to surmise that the risks associated with marine borers are only going to increase in the future.

2.3.1 An overview of gribble (*Limnoria* spp.)

The wood boring crustaceans found around the UK coastline are members of the Limnoriidae more commonly known as gribble. In contrast to the static conditions that characterise wood boring molluscs (shipworm), adult gribble inhabit the surface of the timber and they are fully mobile (Eaton and Hale 1993). The most common recorded and most destructive species of gribble found around the UK are *Limnoria lignorum, L. quadripunctata* and *L. tripunctata.*

Attack by gribble tends to be superficial and results in the creation of an extensive network of galleries at or just below the wood surface. In softwoods, the animals favour the less dense earlywood which can rapidly lead to the timber forming wafer-like plates (Eaton and Hale 1993). Gribble are very small animals, just about visible to the human eye when timber is inspected *in situ*. The surveyor will find gribble by first locating timber that has been colonised by gribble and then by opening up the galleries. The galleries tend to be 1mm to 3mm in diameter with regularly spaced openings to allow respiration.

Gribble are generally 2mm to 4mm in length and are pale grey in appearance. In temperate waters, swarming of the animals tends to occur in the spring although additional swarming may occur in the autumn. Ecological factors such as sea temperature and salinity can affect the reproductive and feeding activity of gribble. The animals tend to concentrate at the intertidal zone. Photographs 1 and 2 illustrate the typical appearance of gribble.

Photograph 1: Scanned electronmicrograph of gribble. *Courtesy L Cookson. CSIRO*

Photograph 2: Electronmicrograph of gribble. *Courtesy S Cragg: University of Portsmouth*

Gribble tend to be sensitive to their environment. They can cause significant damage in harbours and estuarine environments, where there is less risk of abrasion.

However, where structures are exposed to the full force of the sea and where there is a high risk of mechanical abrasion, gribble find it difficult to establish large populations. This is because the abrasive nature of the environment destroys the galleries. In such instances, gribble tend to be restricted to the sheltered parts of structures, particularly where joints are formed as these act as a suitable refuge for the animals.

2.3.2 An overview of shipworm (*Teredo* spp)

Shipworm found around the UK coastline tend to be members of the Teredinidae. They have a soft worm like body with two shells or valves at the anterior end of the animal which enable it to bore into timber. The animal remains in the same tunnel throughout its life. Each tunnel is discrete and the animals avoid intruding into neighbouring tunnels as they grow and excavate into the timber. In warm waters some animals can grow in excess of one or two metres.

Even in timbers of limited volume, the shipworm will not emerge from the timber and will continue to bore alongside its neighbours until the timber is more or less destroyed and breaks apart (Eaton and Hale 1993). Usually, teredinids line their excavations with a secretion of calcium carbonate.

The posterior part of the animal maintains contact with the external seawater environment via a fine hole about 1mm to 2mm in diameter. This hole is the only external sign that shipworm have colonised a timber component which makes surveying for shipworm, using non-destructive techniques, extremely difficult *in situ.* Through this hole, two siphons protrude. The incurrent siphon draws in water to allow the animal to respire and to feed on micro-organisms. The excurrent siphon releases waste materials and reproductive gametes or larvae.

Growth rates can vary according to species and environmental conditions, particularly temperature. The animals usually line their tunnels with a calcareous secretion for protection. These linings absorb X-rays which enables the colonisation of timber by shipworm to be monitored using X-radiography. Photographs 3 and 4 illustrate an example of shipworm extracted from a Douglas fir bearer of the Barmouth viaduct and typical damage to a Douglas fir pile.

Photograph 3: Example of shipworm extracted from a Douglas fir bearer of the Barmouth viaduct within the intertidal zone of the estuary mouth of the River Mawddach, Gwynedd. Note the soft tubular body and the bulbous head comprising the bivalve shell. *TRADA Technology*

Photograph 4: Example of the typical damage that shipworm can cause to timber. This is a section of Douglas fir removed from a bridge located on the River Ystwyth, Gwynedd. *TRADA Technology*

3 Stage 1: Selection of the 'long list' of candidate timbers

3.1 Background information

The desk-based component of this research project (Stage 1) was undertaken between September and November 2007, under the direction of the Project Steering Group (PSG). The 'long list' was a term adopted by PSG to describe the candidate timbers identified and selected for Stage 2 on the basis of the findings of Stage 1.

Stage 1 involved a review of previous research, existing literature and reference databases that contain information on timber species and their properties, as follows:
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1. Data obtained on timbers assessed in earlier marine borer (gribble) resistance trials that were presented in the publication '*Manual on the use of timber in coastal and fluvial engineering' (*Crossman and Simm*, 2004)*. The trials were conducted by TRADA just prior to publication of the Manual. It should be borne in mind that these trials were primarily aimed at demonstrating the efficacy of the test methods and full variation of the timber samples to represent commercial timber supplies was not possible. The results are presented in Box 4.6 of the Manual and are replicated in Table 1, Section 3.2 of this report.

2. Information contained within the Biodiversity International Ltd report (2007-unpublished). Table G within the report, titled '*Nineteen species of certified and available timber thought suitable by the trade (based upon their experience and contact with others) as Greenheart or Ekki* replacements'. In drawing up this table, Biodiversity International Ltd had also undertaken a review of existing literature, research and database information.

3. UK publications for data on timbers, including TRADA's timber database and library. All references and sources of information are cited in Appendix II to this report. It should be noted that TRADA has not fully referenced the source of each material attribute for each timber.

4. International sources of information such as *Prospect*, United States Department of Agriculture Forest Products Laboratory timber species database and *Tropix 5* (French Agricultural Research Centre for International Development) database. Again, it should be noted that TRADA has not fully referenced the source of each material attribute for each timber.

Further information about data obtained from each source is given in Sections 3.2-3.4.

In addition to considering technical information, a number of commercial considerations were taken into account when drawing up the long list of candidate timber species. Of primary importance was the commercial availability of each LUS.

It was agreed by the PSG that to be considered for inclusion in the long list, it had to be possible to source the LUS in the UK i.e. there had to be an established supply chain. Furthermore, to work within the timetable constraints of the project, it had to be possible to source the LUS from one of the timber suppliers on the PSG, either Ecochoice Ltd (UK agent for Reef Hout BV) or Aitken & Howard Ltd. Whilst appreciating that this would limit the number of candidate species, it was necessary to ensure the successful completion of the project. For completeness, timbers not commercially available within the timeframe of the project but which exhibited good indicative performance based on a review of available data sources, are listed in Table 7, Section 3.6.

The second commercial consideration was price. Again, the PSG decided to exclude those LUS from the long list if they currently, or are likely in the future, to command a price premium. For example, if the LUS is known to be popular for carpentry or domestic applications.

3.2 Previous data obtained by TRADA

Table 1 summarises the performance of LUS previously tested by TRADA as part of their feasibility studies into developing fast track laboratory screening methods to determine resistance to gribble. It should be remembered that these findings are indicative as the trials were primarily aimed at demonstrating the efficacy of the test methods. The performance of LUS was compared against the performance of Greenheart which was used as a benchmark timber. Therefore, Table 1 identifies timbers with ‘good indicative performance’ i.e. those timbers that performed better than Greenheart, and timbers with ‘poor indicative performance’, i.e. those that performed worse than Greenheart. Timbers that performed poorly in comparison to Greenheart were subsequently excluded from the long list.

For cross-comparison purposes, Table 1 also identifies those timbers which were commercially available from the PSG timber suppliers within the timeframe of the project, and also those timbers that command a price premium, as discussed in Section 3.1.

Table 1: Timbers previously assessed by TRADA for their resistance to gribble.

No.	Trade name	Botanical name	Comments
1	Abiurana	*Pouteria guianensis*	Poor indicative performance therefore excluded from the long list.
2	Acaria quara	*Minquartia guianensis*	Good indicative performance. However, not commercially available from PSG timber suppliers during the timeframe of the project so excluded from the long list.
3	Afina	*Strombosia glaucescens*	Good indicative performance. However, not commercially available from PSG timber suppliers during the timeframe of the project so excluded from the long list.
4	Angelim vermelho	*Dinizia excelsa.*	Good indicative performance. Commercially available from the PSG timber suppliers.
5	Aweimfo samina	*Albizia ferruginea*	Good indicative performance. However, not commercially available from PSG timber suppliers during the timeframe of the project so excluded from the long list..
6	Ayan	*Distemonanthus benthamianus*	Good indicative performance. However, not commercially available from PSG timber suppliers during the timeframe of the project so excluded from the long list.

Table 1 continued

No.	Trade name	Botanical name	Comments
7	Balau	*Shorea spp.*	Commercially available. The properties of Balau are well understood and design values are available in BS5268:2:2002
8	Bompagya	*Mammea africana*	Good indicative performance. However, not commercially available from PSG timber suppliers during the timeframe of the project so excluded from the long list.
9	Brugeria	*Brugeria* spp.	Good indicative performance. However, not commercially available from PSG timber suppliers during the timeframe of the project so excluded from the long list.
10	Castan harana	*Lecythis prancei*	Poor indicative performance therefore excluded from the long list.
11	Cumaru	*Dipteryx* spp.	Good indicative performance but currently commanding a price premium and therefore excluded from the long list.
12	Cupiuba	*Goupia glabra*	Good indicative performance. Commercially available from the PSG timber suppliers.
13	Dabema (dahoma)	*Piptadeniastrum africanum*	Good indicative performance. Commercially available from the PSG timber suppliers.
14	Ekki	*Lophila alata*	Commercially available. The properties of Ekki are well understood and design values are available in BS 5268:2:2002
15	Essia	*Combretodendron africanum*	Poor indicative performance so excluded from the long list.
16	Favinha	*Chamaecrista duartei*	Poor indicative performance so excluded from the long list.
17	Favinha prunhela	*Enterolobium schomburgkii*	Good indicative performance. However, not commercially available from PSG timber suppliers during the timeframe of the project so excluded from the long list.
18	Greenheart	*Chlorocardium rodiaei*	Commercially available. The properties of Greenheart are well understood and design values are available in BS 5268:2:2002
19	Guariuba	*Claricia racemosa*	Good indicative performance. However, not commercially available from PSG timber suppliers during the timeframe of the project so excluded from the long list.
20	Heritieria	*Heritieria* spp.	Poor indicative performance so excluded from the long list.
21	Ipe	*Tabebuia guayacan*	Good indicative performance but currently commanding a price premium so excluded from the long list
22	Jarana	*Lecythis poiteaul*	Poor indicative performance so excluded from the long list.

Table 1 continued

No.	Trade name	Botanical name	Comments
23	Jatoba	*Hymenaea courbaril*	Good indicative performance but currently commanding a price premium so excluded from the long list.
24	Louro gamela	*Nectandra rubra*	Good indicative performance but currently commanding a price premium so excluded from the long list
25	Louro itauba	*Mezilaurus itauba*	Poor indicative performance so excluded from the long list.
26	Louro preto	*Ocotea fragrantissim*.	Poor indicative performance so excluded from the long list.
27	Oak	*Quercus spp*	Commercially available. The properties of oak are well understood and design values are available in BS5268:2:2002
28	Okan (denya)	*Cylicodiscus gabunensis*	Good indicative performance. Commercially available from the PSG timber suppliers.
29	Massaranduba	*Manilkara* bidenta	Good indicative performance. Commercially available from the PSG timber suppliers.
30	Muiracatiara	*Astronium le-cointei*	Good indicative performance. However, not commercially available from PSG timber suppliers during the timeframe of the project so excluded from the long list.
31	Pine	*Pinus sylvestris*	Poor indicative performance although used for validation of test results. Commercially available.
32	Piquia	*Caryocar villosum*	Good indicative performance. Commercially available from the PSG timber suppliers.
33	Piquia marfim	*Aspidosperma desmanthum*	Poor indicative performance so excluded from the long list.
34	Purpleheart	Peltogyne *spp.*	Good indicative performance. Commercially available.
35	Robinia	*Robinia pseudoacacia*	Good indicative performance during laboratory trials but poor performance when exposed to marine conditions. Not commercially available from the PSG timber suppliers so excluded from the long list.
36	Rhizophora	*Rhizophora stylosa*	Good indicative performance. However, not commercially available from the PSG timber suppliers so excluded from the long list.
37	Sapupira	*Bowdichia nitida*	Poor indicative performance so excluded from the long list
38	Tetekon	*Berlinia* spp.	Poor indicative performance so excluded from the long list.
39	Uchi torado	*Sacoglottis guianensis*	Good indicative performance. However, not commercially available from the PSG timber suppliers so excluded from the long list.

Table 1 continued

No.	Trade name	Botanical name	Comments
40	Wonton	*Morus mesozygia*	Good indicative performance. However, not commercially available from the PSG timber suppliers so excluded from the long list.
41	Xylocarpus	*Xylocarpus granatum*	Good indicative performance. However, not commercially available from the PSG timber suppliers so excluded from the long list.

Therefore, in summary, out of a total of forty-one timbers previously assessed by TRADA:

- the four mangrove timbers (Brugeria, Heriteria, Rhizophiora and Xylocarpus) were discounted as their commercial viability was unknown.

- a further thirteen (Abiurana, Castan harana, Essia, Favinha, Jarana, Louro itauba, Louro preto, Oak, Piquia marfim, Pinus sylvestris, Sapupira, Robinia and Tetekon) were discounted on the basis of their poor performance when compared to Greenheart. Note: whilst oak was discounted as a possible candidate timber it was still included in Stage 2 for comparative purposes as it is arguably the most important temperate hardwood used in the UK for structural purposes.

- Greenheart, Ekki, Balau and Purpleheart were included in the long list as reference timbers as they are well known commercially available species and their inclusion was helpful for comparative purposes.

From this initial starting point and considering the exclusion of the timbers detailed above, TRADA identified a total of twenty timbers with potentially good resistance to the marine borer, gribble. These timbers were:

1. Acaria quara,
2. Afina
3. Angelim vermelho
4. Awiemfo samina
5. Ayan
6. Bompagya
7. Cumaru
8. Cupiuba
9. Dabema
10. Favinha prunhela
11. Guariuba
12. Ipe
13. Jatoba
14. Louro gamela
15. Okan
16. Massaranduba
17. Muiracatiara
18. Piquia
19. Uchi torrado
20. Wonton

Of these twenty, four currently command a premium for high value end uses (Cumaru, Ipe, Jatoba and Louro gamela). Therefore, it is highly unlikely that these timbers would be supplied for marine construction so they were excluded from the long list.

Of the remaining sixteen timbers, only six were commercially available from the PSG timber suppliers within the timeframe of this project and these were therefore added to the long list. These timbers were:

1. Angelim vermelho
2. Cupiuba
3. Dabema
4. Okan
5. Massaranduba
6. Piquia

In relation to those LUS originating from West Africa (Afina, Awiemfo Samina, Ayan, Bompagya, and Wonton) that exhibited good indicative performance, but which were not available from the PSG timber suppliers, it is understood that the Timber Industry Development Division (TISS) in Ghana is keen to develop potential markets for these timbers so they may be the focus of a future marketing campaign. Currently, they are not commercially exported for use for marine and fresh water construction.

3.3 Candidate timber species identified by Biodiversity International Ltd

Table 2 lists the nineteen commercially available LUS identified in the Biodiversity International Ltd report as having the potential for use in marine and freshwater construction applications.

Table 2: Extracted from Table G of the Biodiversity International Ltd report (2007)

Trade name	Botanical name	Comments
Abiurana	*Pouteria guianensis*	TRADA screening trials indicated that this species performed poorly (see Table 1) so excluded from the long list.
Acaria quara	*Minquartia guianensis*	Not commercially available from the PSG timber suppliers during the timeframe of the project so excluded from the long list.
Angelim pedra	*Hymenolobium spp.*	Currently attracting a price premium and therefore not economically viable for marine and fresh water construction. Excluded from the long list.
Angelim vermelho	*Dinizia excelsa*	Commercially available from the PSG timber suppliers.
Aracanga	*Aspidosperma megalocarpum*	Not commercially available from the PSG timber suppliers during the timeframe of the project so excluded from the long list
Balau	*Shorea* spp.	Commercially available. The properties of Balau are well understood and design values are available in BS 5268:2:2002
Basralocus	*Dicoryia guianensis*	Commercially available from the PSG timber suppliers.
Castan harana	*Holopyxidium spp*	TRADA screening trials indicated that this species performed poorly (see Table 1) so excluded from the long list.
Cloeziana	*Eucalyptus cloeziana*	Commercially available from the PSG timber suppliers.
Cumaru	*Dipteryx* spp.	Currently attracting a price premium and therefore not economically viable for marine and fresh water construction so excluded from the long list.
Cupiuba	*Goupia glabra*	Commercially available from the PSG timber suppliers.

Table 2 continued

Trade name	Botanical name	Comments
Karri	*Eucalyptus diversicolor*	Commercially available. The properties of Karri are well understood and design values are available in BS 5268: 2:2002.
Massaranduba	*Manilkara* spp	Commercially available from the PSG timber suppliers.
Mata-Mata	*Eschweileria odora*	Not commercially available from the PSG timber suppliers during the timeframe of the project so excluded from the long list.
Piquia	*Caryocar* spp.	Commercially available from the PSG timber suppliers.
Purpleheart	*Peltogyne* spp	Commercially available. The properties of Purpleheart (with exception of permissible design stresses) are well documented.
Sapucaia	*Lecythis paraensis*	Commercially available from the PSG timber suppliers.
Tatajuba	*Bagassa* spp.	Commercially available from the PSG timber suppliers.
Timborana	*Enterolobium schomburgkii*	Commercially available from the PSG timber suppliers.

Therefore, in summary, of the nineteen timbers identified by Biodiversity International Ltd:

- two timbers (Abiurana and Castan Harana) were found to perform poorly in laboratory tests conducted by TRADA so were excluded from the long list
- two timbers (Angelim Pedra and Cumaru) are currently attracting a price premium and were therefore excluded from the long list
- Balau (Yellow Balau), Karri and Purpleheart are well documented timbers and were included as reference species in Stage 2
- three timbers (Acaria Quara, Aracanga and Mata-Mata) were not commercially available from the PSG timber suppliers during the timeframe of the project so were excluded from the long list.

Therefore, a total of nine out of nineteen timbers identified by Biodiversity International Ltd that were also commercially available from the PSG timber suppliers were included in the long list:

1. Angelim Vermelho
2. Basralocus
3. Cloeziana
4. Cupiuba
5. Massaranduba
6. Piquia
7. Sapucaia
8. Tatajuba
9. Timborana

3.4 Timber available from the PSG timber suppliers

Ecochoice Ltd, UK agents for Reef Hout BV, was one of two PSG timber suppliers who provided timber for both Stages 2 and 3 of the project. A list of commercially available timbers from Ecochoice Ltd is detailed in Table 3. It should be noted that many timbers detailed in this table are commercially available on the open market from other UK suppliers.

Table 3: Timbers available from Ecochoice Ltd

Trade name	Botanical name	Comments
Angelim Pedra	*Hymenolobium spp.*	Attracting a price premium. Not economically viable for marine and fresh water construction so excluded from the long list.
Angelim Vermelho	*Dinizia excelsa.*	Commercially available and previously assessed by TRADA
Basrolocus	*Dicoryia guianensis*	Commercially available
Bilinga (opepe)	*Nauclea diderrichii*	Commercially available
Cloeziana	*Eucalyptus cloeziana*	Commercially available but not previously tested by TRADA
Cumaru	*Dipteryx* spp.	Attracting a price premium. Not economically viable for marine and fresh water construction so excluded from the long list. Previously assessed by TRADA
Cupiuba	*Goupia glabra*	Commercially available and previously assessed by TRADA
Dabema	*Piptadeniastrum africanum*	Commercially available and previously assessed by TRADA
Ekki	*Lophila alata*	Commercially available. Benchmark species.
Eveuss	*Klainidoxa gabonensis*	Commercially available but not previously assessed by TRADA
Garapa	*Apuleia leiocarpa*	Commercially available but not previously assessed by TRADA
Greenheart	*Chlorocardium rodiaei*	Commercially available. Benchmark species.
Massaranduba	*Manilkara* spp	Commercially available and previously assessed by TRADA
Mukulungu	*Autronella congoensis*	Commercially available but not previously assessed by TRADA
Niove	*Staudtia kamerunensis*	Commercially available but not previously assessed by TRADA
Okan (denya)	*Cylicodiscus gabunensis*	Commercially available and previously assessed by TRADA

Table 3 continued

Trade name	Botanical name	Comments
Piquia	*Caryocar* spp.	Commercially available and previously assessed by TRADA
Sapucaia	*Lecythis paraensis*	Commercially available but not previously assessed by TRADA
Sougue	*Parinari excelsa*	Commercially available but not previously assessed by TRADA
Tali	*Erythrophleum ivorense*	Commercially available but not previously assessed by TRADA
Tatajuba	*Bagassa* spp.	Commercially available but not previously assessed by TRADA
Timborana	*Enterolobium schomburgkii*	Commercially available but not previously assessed by TRADA

In summary, of the timbers available from Ecochoice Ltd, seven had been previously assessed by TRADA and found to perform comparatively well in terms of their resistance to gribble (see Table 1).

Aitken & Howard Ltd was the other PSG timber supplier that provided material for Stage 2 of the project. The timbers supplied by them are detailed in Table 4 below.

Table 4: Timbers provided by Aitken & Howard Ltd.

Trade name	Botanical name	Comments
Balau	*Shorea* spp.	Commercially available. The properties of Balau are well documented and strength values are detailed in BS 5268:2:2002.
Douglas fir	*Pseudotsuga menziessii*	Commercially available. The properties of Douglas fir are well documented and strength values are detailed in BS 5268:2:2002
Ekki	*Lophila alata*	Commercially available. The properties of Ekki are well documented and strength values are detailed in BS 5268:2:2002. Benchmark species.
Greenheart	*Chlorocardium rodiaei*	Commercially available. The properties of Greenheart are well documented and strength values are detailed in BS 5268:2:2002. Benchmark species.
Mora	*Mora excelsa*	Commercially available
Opepe	*Nauclea diderrichii*	Commercially available. The properties of Opepe are well documented and strength values are detailed in BS 5268:2:2002.
Purpleheart	*Peltogyne* spp.	Commercially available although the strength properties of Purpleheart are not detailed in BS 5268:2:2002

By cross referencing the timbers in Tables 2 and 3, it can be seen that nine timbers listed in Table 3 as being commercially available within the timeframe of the project had also been identified by Biodiversity International Ltd as being suitable for marine construction. These were:

1. Angelim Vermelho
2. Cloeziana
3. Cumaru
4. Cupiuba
5. Piquia
6. Massaranduba
7. Sapucaia
8. Tatajuba
9. Timborana

With reference to Table 3, a further six timbers were commercially available that had not been identified by Biodiversity International Ltd, nor had they been previously assessed by TRADA. Identifying the reason for Biodiversity International Ltd's omission of these timbers was beyond the scope of this study. These timbers were:

1. Niove
2. Garapa
3. Mukulungi
4. Eveuss
5. Souge
6. Tali

The material properties of these six timbers were checked sing the PROSPECT and TROPIX 5 databases to confirm that their cited material properties indicated that they had good potential for marine and fresh water construction.

3.5 Selecting the 'long list' of timbers

The 'long list' of eighteen timbers presented in Table 5 was collated from the information provided in Tables 1 to 4, and was based on a range of factors including previous indicative marine borer (gribble) resistance, commercial availability within the timeframe of the project, published material properties and economic considerations.

Table 5: The 'long list of candidate timbers selected for Stage 2 of the research

Commercial name	Botanical name
Angelim Vermelho	*Dinizia excelsa*
Basralocus	*Dicoryia guianensis*
Cloeziana	*Eucalyptus cloeziana*
Cupiuba	*Goupia glabra*
Dabema	*Piptadeniastrum africanum*
Eveuss	*Klainidoxa gabonensis*
Garapa	*Apuleia leiocarpa*
Massaranduba	*Manbarklak*
Mora	*Mora excelsa*
Mukulungu	*Autronella congoensis*
Niove	*Staudtia kamerunensis*
Okan	*Cylicodiscus gabunensis*
Piquia	*Caryocar* spp.
Sapucaia	*Lecythis paraensis*

Table 5 continued

Commercial name	Botanical name
Souge	*Parinari excelsa*
Tali	*Erythrophleum ivorense*
Tatajuba	*Bagassa* spp.
Timborana	*Enterolobium schomburgkii*

KEY

(yellow)	Timbers previously assessed by TRADA (see Table 1, Section 3.2)
(green)	Timbers identified by Biodiversity International Ltd and also commercially available from the PSG timber suppliers within the timeframe of the project (see Table 2, Section 3.3)
(grey)	Timbers not previously assessed by TRADA, or identified by Biodiversity International Ltd, but which are commercially available and have good potential for marine construction based on a literature search.

It should be recognised that whilst the 'long list' detailed in Table 5 identifies a number of timbers with the potential for use in the marine environment, those timbers that are classified as being durable or very durable (i.e. resistant to attack by wood decaying fungi and wood destroying insects) may also be used for constructional purposes in the freshwater environment. The technical properties detailed in Appendix II to this report provide data on natural durability and other material properties.

Of the eighteen timbers identified in Table 5, it is known that Basralocus and Cloeziana are commercially available in lengths exceeding 10m. Other timbers identified in Table 5 may also be available in lengths exceeding 10m, but further enquiries with suppliers are needed to verify this. Timber available in lengths exceeding 10m is of interest for applications such as piling, where lengths in excess of 10m are often required.

3.6 Selecting benchmark and reference species

In order to benchmark the performance of LUS in the long list (Table 5), their performance needed to be compared with that of Greenheart and Ekki. In addition to these two tropical hardwoods, a number of additional hardwood species which are well known for their use in the marine and freshwater environments were selected as reference species (R). It should be noted that the selection of these particular reference species is not necessarily a reflection of their good performance, simply that they are known to be used in marine and freshwater construction applications. Douglas fir was included as it is a commercially important softwood and Scots pine sapwood was used to validate the tests and trials undertaken as part of Stage 3 of the research. The benchmark and reference timbers are presented in Table 6.

Table 6: Benchmark and reference species

Commercial name	Botanical name
Yellow Balau (R)	*Shorea* spp.
Ekki (B)	*Lophila alata*
Greenheart (B)	*Chlorocardium rodiaei*

Table 6 continued

Commercial name	Botanical name
Opepe (R)	*Nauclea diderrichii*
Purpleheart (R)	*Peltogyne* spp.
Douglas fir (R)	*Pseudotsuga menziesii*
Oak (R)	*Quercus* spp.
Karri (R)	*Eucalyptus diversicolor*
Scots pine sapwood (R)	*Pinus sylvestris*

3.7 Other candidate timbers (not selected for the long list)

It should be recognised that some LUS identified by TRADA and Biodiversity International Ltd as potentially suitable for use in marine and freshwater environments were not commercially available from project partners within the timeframe of the project. Those timbers not tested during this research project but considered as having the potential for marine and freshwater construction are detailed in Table 7.

A full appraisal of the reasons why these timbers are not being exported was beyond the scope of this study. The timbers detailed in Table 7 should be awarded priority for investigation as and when materials and funding become available.

Table 7: Timbers previously assessed by TRADA and/or identified by Biodiversity International Ltd that may have potential for marine and fresh water construction.

Commercial name	Botanical name	Comments
Acaria quara	*Minquartia guianensis*	Identified by Biodiversity as a possible timber for marine construction. Also previously assessed by TRADA. This timber performed well both under laboratory and marine conditions.
Aracanga	*Aspidosperma megalocarpum*	This timber has not been previously assessed by TRADA but was identified by Biodiversity as a possible timber for marine construction.
Afina	*Strombosia glaucescens*	Good indicative performance in previous TRADA trials.
Aweimfo samina	*Albizia ferruginea*	Good indicative performance in previous TRADA trials.
Ayan	*Distemonanthus benthamianus*	Good indicative performance in previous TRADA trials.
Bompagya	*Mammea africana*	Good indicative performance in previous TRADA trials.
Favinha prunhela	*Enterolobium schomburgkii*	Previously assessed by TRADA. Indicative laboratory results showed that this timber was comparable to Greenheart.

Table 7 continued

Commercial name	Botanical name	Comments
Mata-Mata	*Eschweileria odora*	Otherwise known as Manbarklak and not previously assessed by TRADA. This timber was identified by Biodiversity as a possible timber for marine construction.
Muiracatiara	*Astronium le-cointei*	Previously assessed by TRADA. Indicative results showed that this timber was comparable to Greenheart.
Uchi torado	*Sacoglottis guianensis*	Previously assessed by TRADA. This timber performed well both under laboratory and marine conditions.
Wonton	*Morus mesozygia*	Previously assessed by TRADA. This timber performed well under laboratory conditions.

3.8 The technical properties of the long list of timber species

The reference sources used to review the technical properties of the candidate timbers are detailed in Appendix II, along with a summary of the technical and 'trunk' properties of each candidate timber in the long list and the benchmark and reference timbers.

In relation to this summary, technically, the candidate timbers detailed in the 'long list' may meet the requirements for use in the marine and freshwater environments. However, important commercial specification requirements may also influence the choice of timber species. These being volumes, sizes, ease of procurement and price. Market forces and procurement factors such as rainy/dry seasons can influence availability. No attempt had been made by the PSG to rank the timbers by market availability as this may change. However, it must be stressed that all timbers identified on the 'long list' are commercially available although the time of ordering (rainy/dry season) can influence delivery times.

At the time of the scoping study, all proposed candidate timbers met the minimum timber purchasing requirements of the Environment Agency and UK Government (see Section 1.2 for further information).

4 Sample selection and validation of timbers on the long list

4.1 Origins of the candidate, benchmark and reference timbers

The regions of origin of the candidate, benchmark and reference timbers are presented in Tables 8 and 9 along with identification codes used to identify the timbers throughout the marine exposure trials.

Table 8: The long list of candidate timbers

Commercial name	Botanical name	Region of origin	Identification Code
Angelim Vermelho	*Dinizia excelsa.*	South America	AV
Basralocus	*Dicoryia guianensis*	South America	BA
Cloeziana	*Eucalyptus cloeziana*	South Africa	CL
Cupiuba	*Goupia glabra*	South America	CU
Dabema	*Piptadeniastrum africanum*	West Africa	DA
Evuess	*Klainidoxa gabonensis*	West Africa	EV
Garapa	*Apuleia leiocarpa*	South America	GA
Massaranduba	*Manilkara* spp	South America	MA
Mora	*Mora excelsa*	South America	MO
Mukulungu	*Autronella congoensis*	West Africa	MU
Niove	*Staudtia kamerunensis*	West Africa	NI
Okan (denya)	*Cylicodiscus gabunensis*	West Africa	OK
Piquia	*Caryocar* spp.	South America	PI
Sapucaia	*Lecythis paraensis*	South America	SA
Souge	*Parinari excelsa*	West Africa	SO
Tali	*Erythrophleum ivorense*	West Africa	TA
Tatajuba	*Bagassa* spp.	South America	TJ
Timborana	*Enterolobium schomburgkii*	South America	TI

Table 9: Benchmark and reference timbers

Commercial name	Botanical name	Region of origin	Identification code
Yellow Balau	*Shorea* spp.	S E Asia (Sabah)	BU
Douglas fir	*Pseudotsuga menziessii*	North America	DF
Bilinga	*Nauclea diderrichii*	West Africa	BI
Ekki	*Lophila alata*	West Africa	E
Greenheart	*Chlorocardium rodiaei*	Guyana	GH
Karri	*Eucalyptus diversicolor*	Australia	KA
Oak	*Quercus* spp.	Europe	AL
Opepe	*Nauclea diderrichii*	West Africa	OP
Purpleheart	*Peltogyne* spp.	South America	PU
European redwood	*Pinus sylvestris*	Western Europe	SP

4.2 Sample selection

For each candidate, benchmark and reference timber, the PSG timber suppliers provided ten sample boards from which all test material for each timber was obtained. These ten boards, also referred to as stock material, were selected at random by both suppliers. The suppliers made a reasonable attempt to ensure that the selected boards were widely dispersed within a timber parcel or parcels so that the natural variability of timber within commercial supplies was reproduced within our test specimen populations.

4.3 Validation of candidate timber species

One small sample was cut from one of the boards from each of the candidate, benchmark and reference timbers so that the genus could be confirmed. These small samples were assessed visually using a x10 hand lens to determine any features that could distinguish them prior to using microscopic techniques. Thin sections were then produced from the samples in order to determine the main anatomical features of the timber. These characteristics were then compared with published information and with those of reference timber samples held by TRADA.

On the basis of a visual and microscopic examination of the properties of each sample, it was possible to identify and confirm the genus of all candidate, benchmark and reference timber species, and check that this matched their reported commercial names. Whilst confirmation of genus was possible, it was not practicable to identify individual species as most commercial timbers comprise groups of species. Identification down to individual species usually requires inspection of botanical features such as leaves and flowering parts in the forest of origin, which was beyond the scope of this research project. Notwithstanding the above limitation of not being able to identify the candidate timbers down to species level, on the basis of an examination of the microscopic properties and consideration of the physical properties of the candidates, all candidates matched their reported commercial names.

5 Stage 2: Laboratory screening trial to determine resistance to attack by gribble

5.1 Introduction

The aim of this accelerated laboratory screening trial was to determine, in a short period of time, the potential suitability of the candidate timbers on the long list as alternatives to Greenheart and Ekki by establishing their comparative resistance to attack by gribble.

Control of gribble has proved particularly problematical, as they are capable of attacking preservative-treated wood (Cragg, 2003) and timbers that are otherwise naturally durable (Pitman *et al*., 1997). A variety of methods have been used to evaluate the resistance of novel preservatives and potentially durable timbers to gribble (Becker 1955; Cookson 1990, 1996; Cookson & Woods, 1995; Richards & Webb, 1975; Rutherford *et al*., 1979). Apart from the topical application tests of Rutherford *et al*., these experiments have used relatively long-term (up to one year) laboratory evaluation of the degradation of tests. Field test methods tend to involve an even more protracted observation period. For example, BS EN 275 requires a minimum of five years observation.

Faecal pellet production rate of gribble matches feeding or ingestion rate quite closely and it is much easier to measure than wood loss by ingestion. The approach used in this investigation takes advantage of this situation. The method described in this report has been developed from investigations of feeding biology of these organisms (Wykes *et al*., 1997) and evaluation of test conditions for this method (Praël *et al.*, 1999) and implemented in previous research undertaken by Borges *et al* (2003) and Williams *et al* (2004B). Their research demonstrated that determining gribble resistance in fast track laboratory trials was reliable.

5.2 Materials and methods

Specimens of *Limnoria quadripunctata Holthuis* were obtained from a laboratory population maintained in blocks of European redwood (*Pinus sylvestris*) kept in running seawater at temperatures comparable to the temperature at source of seawater in Langstone Harbour near Portsmouth, UK. The blocks were moved to a tank at 20ºC for one week. Twenty-four hours before the experiments took place, kitchen cloths were draped over the blocks to create anoxic conditions to induce the animals to leave their burrows. Animals were then transferred to experimental boxes with a fine sable brush or fine forceps.

The trial samples comprised sticks measuring 20mm x 4.5mm x 2mm that were prepared from the stock material. Heartwood was used in all cases except for the control timber (European redwood) for which sapwood was used. The vigour and health of the animals was assessed and confirmed by observing feeding rates on the sapwood blocks prior to the starting the trials. Confirmation of high feeding rates on additional sapwood blocks validated the data.

Each culture box contained 12 chambers as illustrated in Photograph 5. Therefore, 12 sticks per timber were selected. One stick from each of the 10 boards of stock material per timber was selected. A random number generator was used to select the additional two sticks from the sample populations so that all chambers were utilised. Prior to experimentation, the sticks were leached in seawater for one week, with a change of water after three days. Each stick was placed into 4ml of seawater in each chamber of a cell culture box containing 12 chambers measuring 20mm in diameter. The cell culture chambers were kept in the laboratory under ambient lighting conditions at 20±2ºC for 28 days.

Photograph 5: Culture boxes comprising 12 cells per test timber. *Courtesy S Cragg: University of Portsmouth*

One gribble was placed into each chamber. After the required period of time, animals and wood samples were carefully transferred to matching cell culture dishes with fresh seawater and the number of faecal pellets left in the original dishes were counted on digital macro images of the chambers viewed from above and illuminated from below. The rationale behind this laboratory test is that faecal pellet production rate matches feeding or ingestion rate quite closely.

Results were presented as average daily feeding rates and these were compared against results obtained for the two benchmark timbers, Greenheart and Ekki. A one-way analysis of variance (ANOVA) with Dunnet's post-hoc test was carried out to identify:

1. Timbers that performed significantly better than Ekki
2. Timbers that performed significantly better than Greenheart
3. Timbers that performed significantly worse than Ekki
4. Timbers that performed significantly worse than Greenheart

Faecal pellet counts were square-root transformed before analysis and residuals were examined to ensure that the requirements for normality of distribution and equality of variances were met with transformed data. The variation in pellet production rates between different candidate timbers on the long list was examined with a one way ANOVA and the timbers with rates that differed significantly from those of Greenheart and Ekki were identified using Dunnet's post hoc test.

5.3 Gribble resistance trial results

The data are presented in Table 10. Comparative feeding rates for candidate timbers on the long list and reference timbers are listed against the two benchmark species, Ekki and Greenheart. A negative figure in Table 10 indicates comparatively worse performance whereas a positive figure indicates comparatively better performance, expressed as a percentage reduction in daily faecal pellet production rate. For example, in can be seen in Table 10 that Niove exhibits 85.8% and 81.6 % reduction in daily faecal pellet production when compared to Ekki and Greenheart respectively, indicating comparatively better performance than both Greenheart and Ekki.

The sapwood of European redwood was used as a control to validate the experiment. The sapwood exhibited a 262% and 178.5% increase in daily faecal pellet production when compared to Greenheart and Ekki respectively, confirming the vigour of the test organisms and validating the laboratory trial.

Table 10: Comparison of gribble feeding rates on the different timber species

Timber	Feeding rate		
	mean pellets/day	**% reduction compared with Ekki**	**% reduction compared with Greenheart**
Niove	2.54	85.8	81.6
Yellow Balau (R)	3.68	79.5	73.3
Cupiuba	4.94	72.4	64.1
Piquia	7.66	57.3	44.4
Mora	11.10	38.1	19.5
Garapa	13.14	26.7	4.7
Opepe (R)	13.20	26.3	4.2
Tatajuba	13.54	24.4	1.7
Greenheart (B)	13.78	23.1	0.0
Timborana	14.21	20.7	-3.1
Dabema	14.67	18.1	-6.5
Sapucaia	15.49	13.6	-12.4
Ekki (B)	17.91	0.0	-30.0
Cloeziana	18.13	-1.2	-31.6
Okan	18.28	-2.0	-32.6
Souge	19.08	-6.5	-38.4
Bilinga	20.93	-16.9	-51.9
Karri (R)	21.26	-18.7	-54.3
Basralocus	22.35	-24.8	-62.2
Massaranduba	24.60	-37.3	-78.5
Oak (R)	25.00	-39.5	-81.4
Tali	26.54	-48.1	-92.5
Angelim Vermelho	27.02	-50.8	-96.0
Purpleheart (R)	31.14	-73.8	-125.9
Mukulungu	33.94	-89.4	-146.2
Eveuss	39.78	-122.1	-188.6
European redwood (C)	49.90	-178.5	-262.0

(R) Reference timber
(B) Benchmark timber
(C) Control timber

The variation in the test results is illustrated by the use of standard error bars in Figures 1 and 2. The data in Figures 1 and 2 present average pellet production rate per day over a 28 day period.

With reference to the results in Figure 1, the one way analysis of variance (ANOVA) identified three timbers (excluding Yellow Balau which is a reference timber) as performing significantly better than Ekki. In other words, these results are unlikely to have occurred by chance and are a result of the timber being more resistant to attack by gribble than Ekki. These species were Niove, Cupiuba and Piquia.

Further details pertaining to the data collated for this laboratory trial are presented in Appendix III of this report.

With reference to the results in Figure 2, the one way analysis of variance (ANOVA) identified two timbers (excluding Yellow Balau which is a reference timber) as performing significantly better than Greenheart and these were Niove and Cupiuba.

Key to Figures 1 and 2

(white)	Benchmark timber
(yellow)	No significant difference
(orange)	Candidate timber performed worse than Greenheart/ Ekki
(green)	Candidate timber performed better than Greenheart/ Ekki

Figure 1: Comparison of daily feeding rates (mean ± Standard Error) against Ekki.

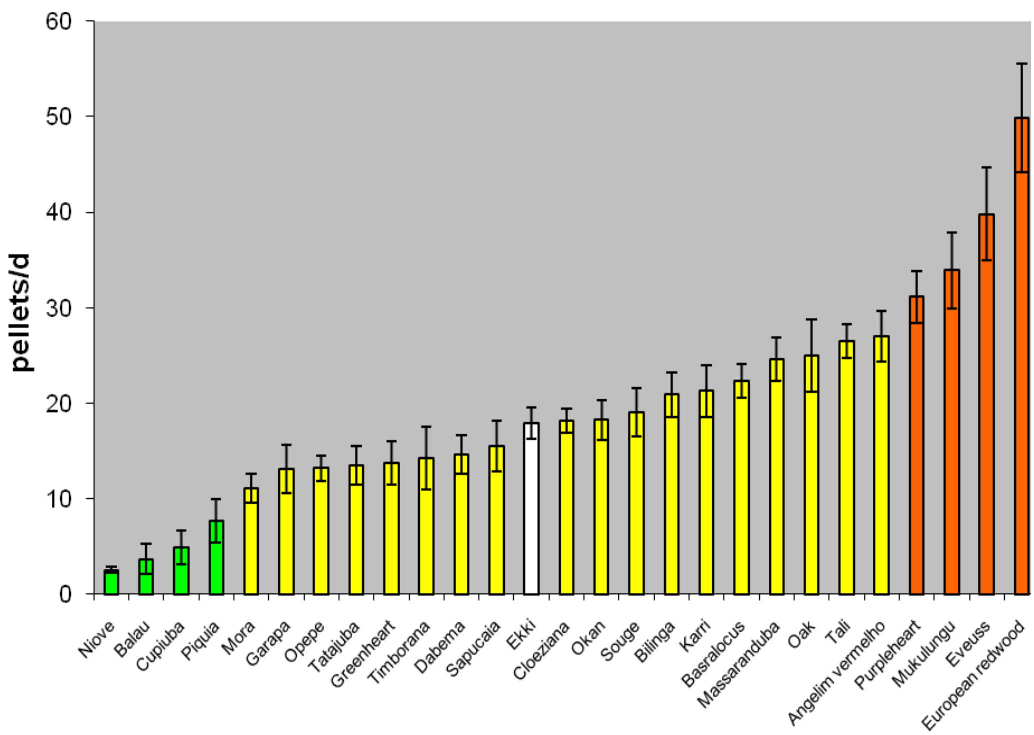
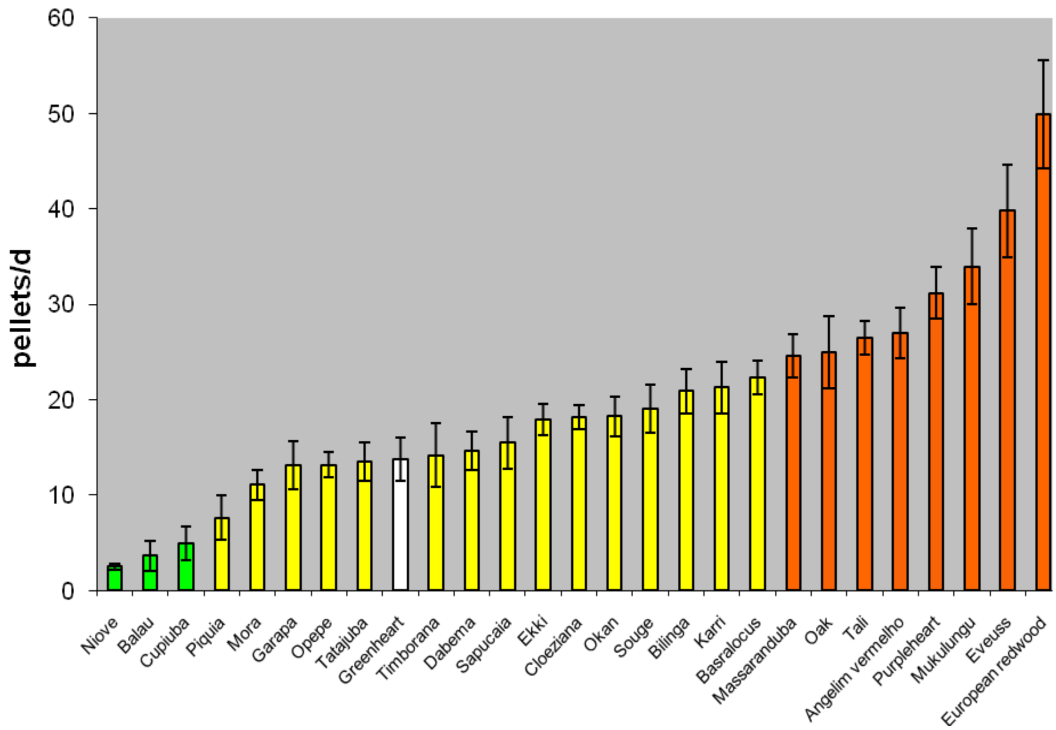
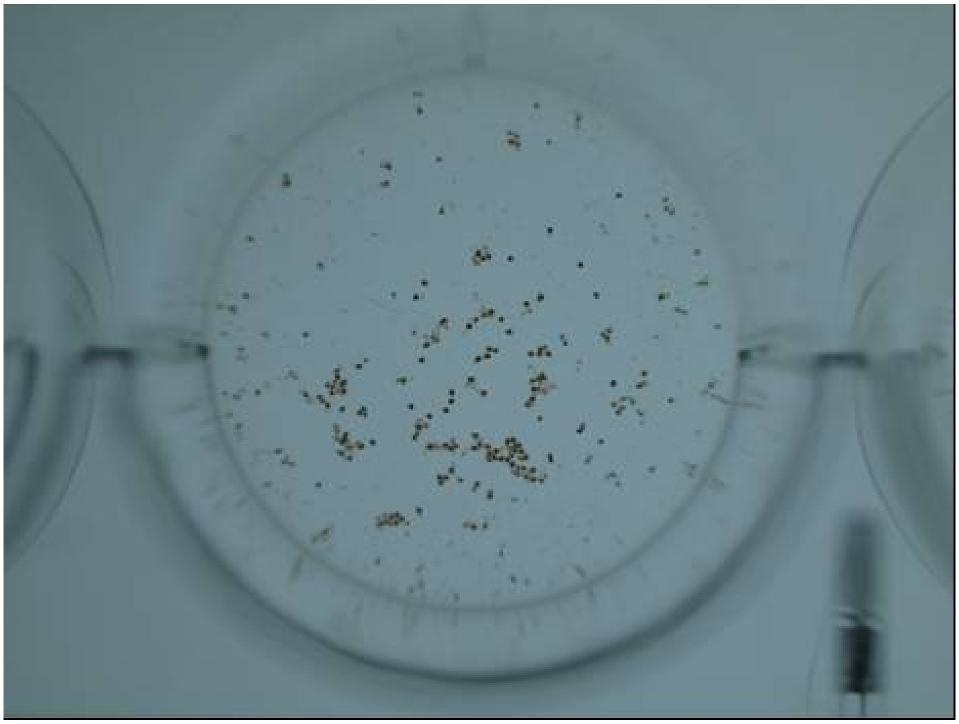


Figure 2: Comparison of daily feeding rates (mean ± Standard Error) against Greenheart.

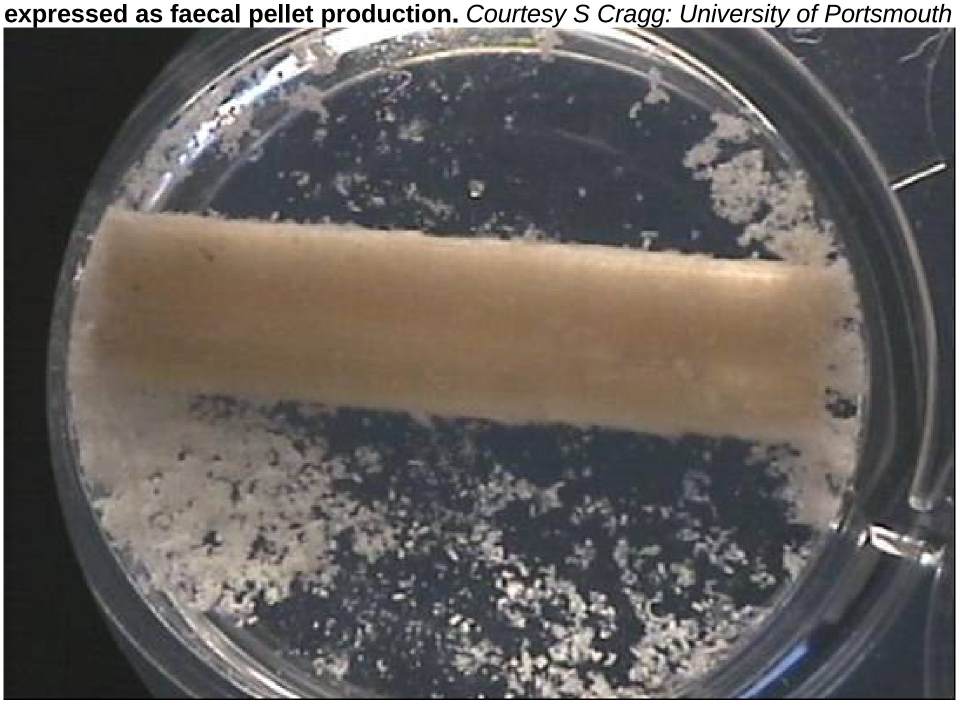


Photograph 6 illustrates typical faecal pellet production. Photograph 7 illustrates the large amount of faecal pellet production observed when the test organisms fed on the European redwood sapwood sticks. Photograph 8 illustrates the apparent lethal toxic effect of Ekki on gribble. In this picture, the test organism is dead and there is very little faecal pellet production visible.

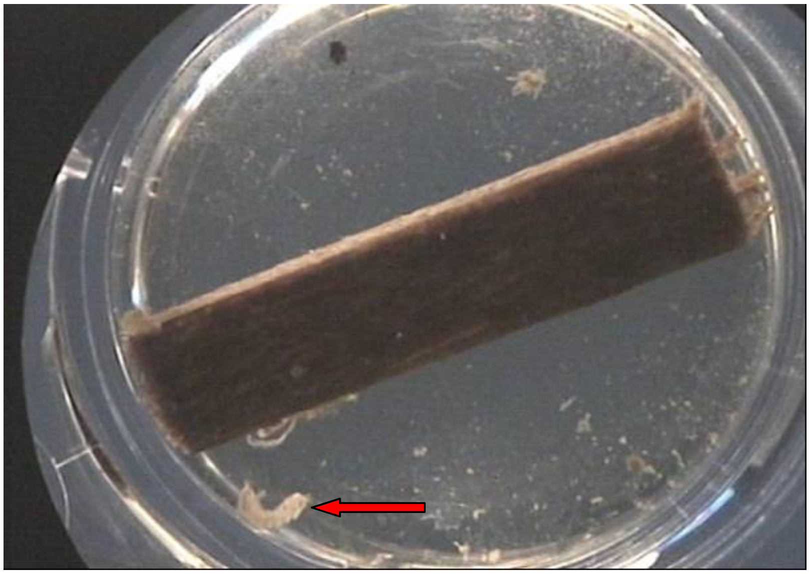
Photograph 6: Example of faecal pellet production. *Courtesy S Cragg: University of Portsmouth*



Photograph 7: European redwood sapwood and comparatively high feeding rate expressed as faecal pellet production. *Courtesy S Cragg: University of Portsmouth*



Photograph 8: Ekki with dead gribble (arrowed). *Courtesy S Cragg: University of Portsmouth*



5.4 Discussion

Comparison of the rate of pellet production on a candidate timber against that recorded on European redwood pine sapwood controls gives an indication of the suppression of the destruction rate by the candidate timbers, though this measure also integrates information regarding rates of feeding and organism survival. Comparison of the performance of the candidate timber, expressed as suppression of feeding rates, against the benchmark species Greenheart and Ekki provides an indication of their comparative resistance to gribble attack.

Though Greenheart is widely used for construction in British waters and generally performs well, it has been shown to be subject to attack by gribble (Pitman *et al.*, 1997). The reported durability of timber species against microbial decay may also play a part in assessing suitable candidate timbers as gribble has been shown to ingest wood colonised with wood-degrading fungi and bacteria (Daniel *et al.*, 1991). As stated previously, durability against attack by wood destroying fungi and insects is no indication of resistance to attack by marine borers. Furthermore resistance against attack by gribble may not indicate that the candidate is also resistant to attack by shipworm.

The accelerated laboratory screening trial provided a rapid assessment of the gribble resistance of the candidate timbers on the long list. Though more replication would be required to distinguish statistically between many of the candidates tested, only marked differences in gribble resistance against the benchmark timbers are of practical significance.

In addition to the LUS on the long list that were tested, the reference timbers (see Table 6) were also tested. The results for the reference timbers are included in Table 10 for information but it is beyond the scope of this research project to analyse in detail any comparisons between the LUS and the reference timbers. This project is focussed on identifying significant differences in performance the LUS on the long list and the benchmark species Ekki and Greenheart.

From a benchmarking point of view it can be seen that if significant differences in performance to Greenheart are chosen as a selection threshold then a comparatively high number of candidate species would be rejected at this stage. However, if significant differences in performance to Ekki are used as the selection threshold then only Purpleheart, Mukulungu and Eveuss would be considered for rejection at the screening stage. Given that Ekki is one of the favoured timbers used for marine and freshwater construction, it would be reasonable to use comparable performance to Ekki as our threshold for selection on the basis of these results alone.

5.5 Conclusions

1. The comparative high feeding rate observed on the European redwood sapwood samples confirmed the vigour and good health of the gribble colony used in this trial which validated the test results.

2. During the laboratory screening trial, Greenheart performed better than Ekki when challenged with gribble.

3. Niove Cupiuba and Piquia performed significantly better than Ekki, and Purpleheart, Mukulungu and Eveuss performed significantly worse than Ekki when challenged with gribble under laboratory conditions.

4. Niove and Cupiuba performed significantly better than Greenheart and Massaranduba, Oak, Tali, Angelim Vermelho, Purpleheart, Mukulungu and Evuess performed significantly worse than Greenheart when challenged with gribble under laboratory conditions.

5. These data suggest that there are a small number of candidate timbers on the long list that may not perform as well as Greenheart or Ekki in environments where gribble is prevalent. However, poor indicative performance against gribble may not rule out the use of these timbers where there is a low risk of gribble, for example in freshwater environments.

6. A lack of significant resistance to gribble, when compared to Greenheart and Ekki, does not necessarily mean a lack of resistance against shipworm. Conversely, good resistance to gribble does not necessarily mean that the candidate timbers will have good resistance to attack by shipworm.

7. The accelerated laboratory screening trial used in this research demonstrate that meaningful data can be generated in a comparatively short space of time at a fraction of the cost of full testing in accordance with BS EN 275. A further advantage of laboratory testing is that the samples do not suffer from marine fouling nor are they at risk of being lost through storm damage or vandalism. The latter problem is often the unpublicised reason for gaps in data or total abandonment of tests in the marine environment.

6 Stage 2: Laboratory screening trial to determine resistance to abrasion

6.1 Introduction

The aim of this accelerated laboratory screening trial was to determine, in a short period of time, the comparative resistance of the long list of candidate timbers to abrasion in the marine environment against the benchmark timbers Greenheart and Ekki.

The effects of abrasion in marine trials are difficult to study owing to the extreme variability of weather and site conditions. Existing laboratory methods also bear little resemblance to the effects of marine abrasion. For example, test methods such as the Janka hardness test which can provide an indication of abrasion resistance, is carried out using dry test material. The feasibility study undertaken by Sawyer and Williams (2005) forms the basis for the laboratory screening trial used in this instance.

6.2 Materials and Methods

Test blocks were prepared for testing by immersion in running sea water for four weeks to become saturated, as illustrated in Photograph 9. Moisture meter checks indicated that all blocks were above fibre saturation point (30%) but it was accepted that it was not possible to achieve full saturation, i.e. water logging of samples, within the timeframe of the project. Immediately prior to testing, the volume of the blocks was measured by displacement in an eureka can. Fresh water displaced by the blocks was weighed directly.

A total of six test samples per timber were prepared. Each test sample comprised two blocks taken from the same board of stock material. Each test block had dimensions 75mm wide by 80mm long, with the sample number carved into one face. The two blocks, from the same stock board, were then secured together with a single wood screw. In this way, the sample identification number was protected from abrasion throughout the trial as far as possible.

A total of 12 blocks (two taken from each of six stock boards) per candidate timber were assessed for their comparative abrasion resistance. The six stock boards per timber were selected randomly from a population of ten stock boards. This approach - rather than choosing one block from each of the ten stock boards and two others randomly selected from among the ten – was chosen since it was considered by TRADA to be a more pragmatic approach as it avoided introducing an additional variable within the trial. Each block was drilled centrally with a 8mm hole for securing to the test frames. Photograph 10 illustrates a typical test frame.

Photograph 9: Blocks immersed in sea water. *Courtesy Gervais Sawyer*

Photograph 10: Typical frame illustrating the arrangement of the test specimens. *Courtesy Gervais Sawyer*

The testing machine used was adapted from a Los Angeles aggregate fragmentation resistance apparatus. This comprised a heavy robust steel drum that can be sealed so as to be watertight. The speed of rotation had been determined from previous research (Sawyer and Williams 2005) and was 33 rpm. At this speed the shingle rolls smoothly around the drum, over and under the test frames and is not carried around the drum to later fall on the blocks. If this were to occur, the abrasion caused is more likely the result of impact damage rather than rubbing. A counter accurately counted the number of revolutions in order to stop the machine when necessary.

The test frames, six in number, were fabricated from medium carbon steel and constructed to ensure that the faces of the wood blocks were perpendicular to the moving shingle. They also allowed shingle to flow under and over the blocks. Five candidate timbers were tested during each test run, with a further frame containing the benchmark timbers of Ekki and Greenheart.

The testing regime used an initial charge of 25kg of 20mm flint shingle with 15 litres of seawater. The flint shingle was obtained from a local builders merchant who confirmed that a single source of shingle was used. This provided sufficient confidence that the timber was exposed to a consistent abrasive environment. Although literature reviews have failed to find evidence that seawater contributes to abrasion, it was felt that the test should simulate field conditions in this respect.

After 80,000 revolutions, the shingle was emptied and thoroughly flushed. Fresh shingle and seawater was loaded and the machine run for a further 80,000 revolutions. In this way, each test had a duration of 5 days. At the completion of testing, all blocks were thoroughly washed and cleaned and stored under water to prevent drying. Finally the volume loss of blocks was determined by the displacement method.

The arrangement of the samples on the test racks followed a latin square distribution so that each candidate timber was replicated at all the rack positions. Data showing the percentage loss in volume after the abrasion testing procedure were arcsine transformed and residuals were examined to ensure that the requirements for normality of distribution and equality of variances were met with transformed data. The variation in volume loss between different candidate timbers was examined with a GLM ANOVA, with candidate timber and position on rack as fixed factors. Dunnet's post hoc test was carried out to identify:

1. Timbers that performed significantly better than Ekki
2. Timbers that performed significantly better than Greenheart
3. Timbers that performed significantly worse than Ekki
4. Timbers that performed significantly worse than Greenheart

Oven dry density of the test samples was measured and expressed as specific gravity on the basis of oven dry weight/green volume determined geometrically (Koch 1985). The average specific gravity for each species is presented in Section 6.3.2 of this report.

The oven dry density for each timber was calculated and was taken as being equal to specific gravity x 1000 values. These data were compared against the average loss in volume of each timber and examined for evidence of correlation between density and loss in volume (abrasion resistance).

6.3 Abrasion trial results

6.3.1 Comparative abrasion resistance

The sapwood of European redwood was not included in the abrasion trials as a control as there was no requirement to validate the vigour of test organisms in this instance. However, Douglas fir was included as a reference timber because it is a commercially important softwood that is used for marine and freshwater construction. Furthermore, there is anecdotal evidence to suggest that Douglas fir performs better than some denser, harder tropical hardwoods as the less dense softwood structure can act as a shock absorber which more efficiently dissipates the energy expended on the timber surface under shingle impact.

Table 11 summarises the comparative abrasion rates presented as average loss of timber volume. The results are presented as percentage loss compared to Greenheart and Ekki, the benchmark timbers.

A negative figure in Table 11 indicates comparatively worse performance whereas a positive figure indicates comparatively better performance, expressed as a percentage reduction in volume caused by exposure to abrasion when compared to Greenheart and Ekki. For example, with reference to Table 11, Souge exhibited 41.7% less volume of timber lost when compared to Ekki, whereas Yellow Balau suffers 191.2% greater loss in volume than Ekki.

Table 11: Comparison of the different abrasion rates of the candidate timbers

Species	Abrasion		
	mean % volume loss	% reduction compared with Ekki	% reduction compared with Greenheart
Souge	5.3167	41.7	60.5
Oak (R)	7.3333	19.5	45.6
Eveuss	7.75	15.0	42.5
Tali	8.5	6.7	36.9
Ekki (B)	9.1125	0.0	32.4
Mukulungu	10.1333	-11.2	24.8
Timborana	11.3833	-24.9	15.5
Sapucaia	11.4333	-25.5	15.2
Tatajuba	11.7	-28.4	13.2
Greenheart (B)	13.475	-47.9	0.0
Okan	13.8	-51.4	-2.4
Garapa	13.85	-52.0	-2.8
Douglas Fir (R)	14.175	-55.6	-5.2
Cloeziana	14.7	-61.3	-9.1
Karri (R)	14.95	-64.1	-10.9
Angelim Vermelho	15.5667	-70.8	-15.5
Piquia	15.9167	-74.7	-18.1
Purpleheart (R)	17.05	-87.1	-26.5
Mora	17.3167	-90.0	-28.5
Dabema	17.9833	-97.3	-33.5
Basralocus	18.1833	-99.5	-34.9
Niove	18.2	-99.7	-35.1
Cupiuba	18.6167	-104.3	-38.2

Table 11 continued

Species	Abrasion		
	mean % volume loss	% reduction compared with Ekki	% reduction compared with Greenheart
Opepe (R)	19.0667	-109.2	-41.5
Massaranduba	19.5183	-114.2	-44.8
Bilinga	22.8333	-150.6	-69.4
Yellow Balau (R)	26.5333	-191.2	-96.9

(R) Reference timber
(B) Benchmark timber

The data in Figures 3 and 4 present average loss in volume of the candidate timbers. Comparison of abrasion data is presented as a measure of mean volume loss (±Standard Error) of the candidate timber species against the mean volume loss measured for Ekki and Greenheart.

With reference to Ekki, none of the candidate timbers indicated that they performed significantly better during this trial. However, 18 out of 26 candidate timbers (Greenheart included) performed significantly worse than Ekki when challenged with shingle, as can be seen in Figure 3.

With reference to Greenheart, Souge, Oak, Eveuss, Tali and Ekki indicated that they performed significantly better during this trial. Only Cupiuba, Opepe, Massaranduba, Bilinga and Yellow Balau performed significantly worse than Greenheart.

Further details pertaining to the data collated for this laboratory trial are presented in Appendix III of this report.

Key to Figures 3 and 4

	Benchmark timber
(yellow)	No significant difference
(orange)	Candidate timber performed worse than Greenheart/ Ekki
(green)	Candidate timber performed better than Greenheart/ Ekki

Figure 3: Average volume loss after 160,000 cycles for the candidate species compared to Ekki.

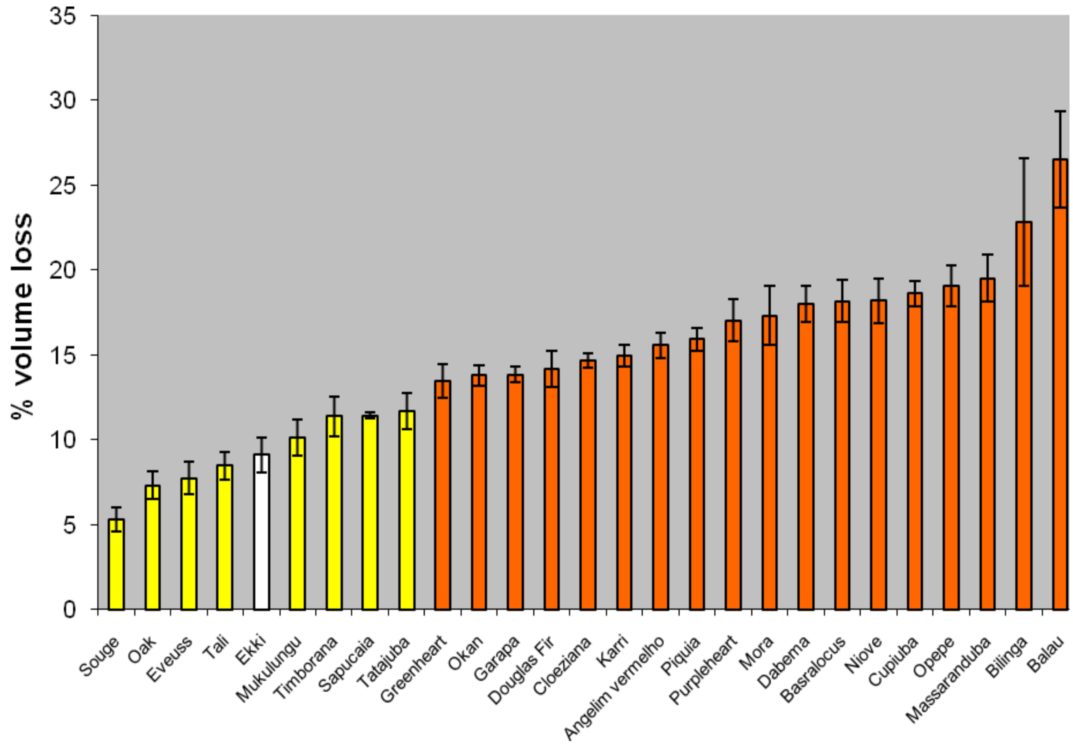
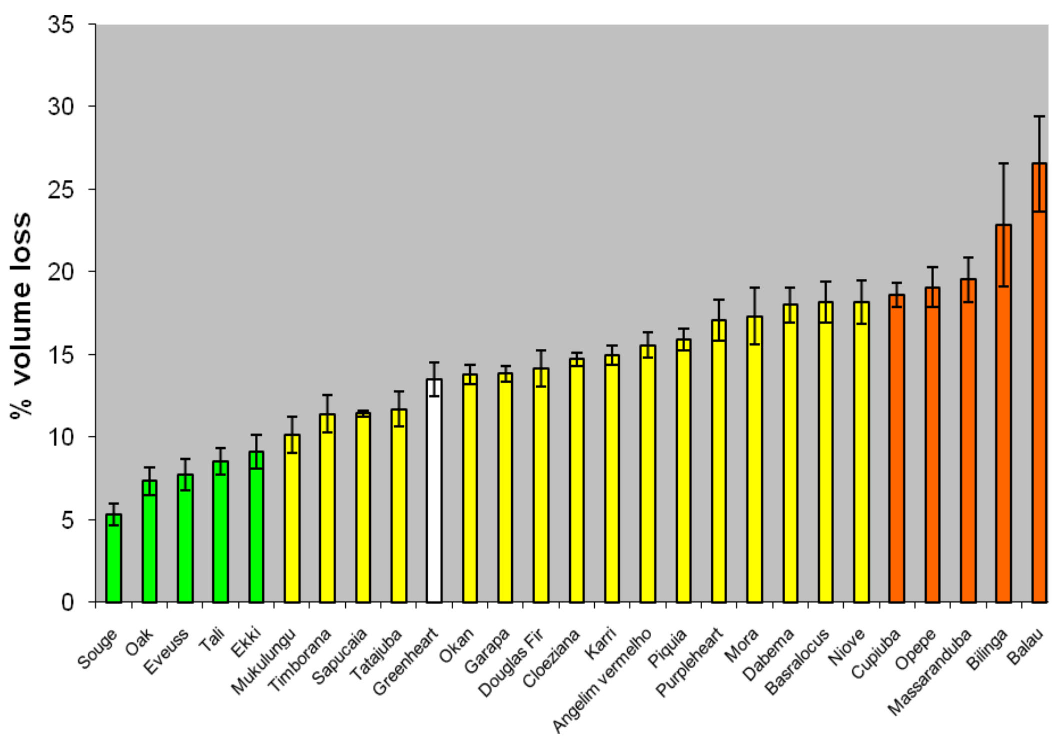


Figure 4: Average volume loss after 160,000 cycles for the candidate species compared to Greenheart.



Photographs 11 and 12 illustrate typical abrasion patterns after 160,000 cycles and Photograph 13 illustrates the effect of cold forging of the steel within the apparatus due to abrasion which is an indication of the severity of the test.

Photograph 11: Test run No. 1 after 160,000 cycles. The rack on the left (arrowed) supported six blocks of the benchmark timber, greenheart. *Courtesy Gervais Sawyer*

Photograph 12: Test rack supporting greenheart after 160,000 cycles. *Courtesy Gervais Sawyer*

Photograph 13: Cold forging of the steel caused by abrasion of the shingle. *Courtesy Gervais Sawyer*

6.3.2 Summary of average oven dry mass density and correlation versus abrasion resistance.

Table 12 summarises the average oven dry density values for each candidate timber and Figure 5 summarises the correlation between density and average percentage loss in volume for each timber (i.e. abrasion resistance).

Table 12: Average oven dry mass density of the candidate timbers

Candidate timber	Average density (kg/m3)	Standard Error
Angelim Vermelho	896.7	4.2
Yellow Balau (R)	681.7	37.7
Basralocus	613.3	10.2
Bilinga	603.3	14.1
Cloeziana	788.3	9.1
Cupiuba	740.0	6.3
Dabema	521.7	9.8
Douglas Fir (R)	491.3	8.1
Ekki (B)	892.7	4.2
Eveuss	798.3	9.5
Garapa	710.0	8.6
Greenheart (B)	850.0	7.9
Karri (R)	676.7	34.4
Massaranduba	865.0	16.5
Mora	775.0	7.6

Table 12 continued

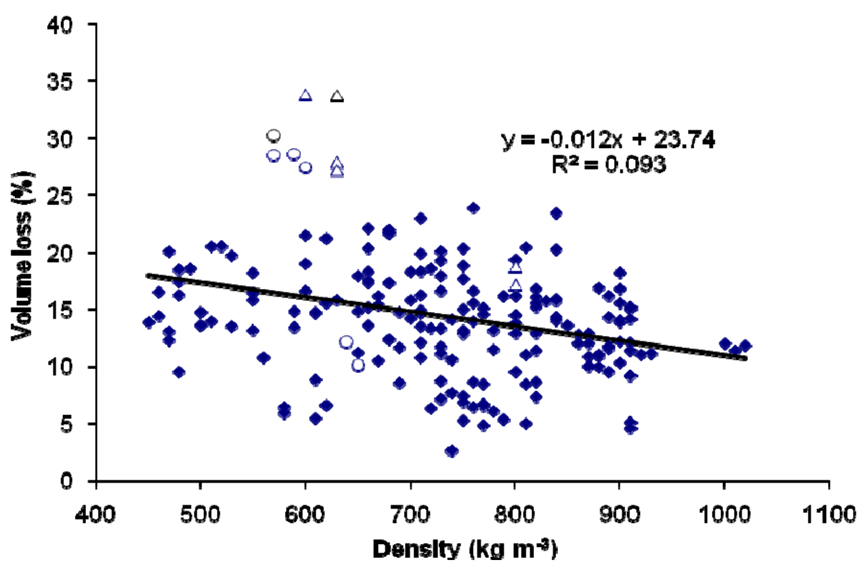
Candidate timber	Average density (kg/m3)	Standard Error
Mukulungu	746.7	5.6
Niove	711.7	4.0
Oak (R)	660.1	6.7
Okan	858.3	16.2
Opepe (R)	665.0	3.4
Piquia	645.0	6.7
Purpleheart (R)	696.7	8.4
Sapucaia	960.0	23.5
Souge	761.7	8.7
Tali	756.7	12.6
Tatajuba	718.3	4.0
Timborana	715.0	29.0

(R) Reference timber
(B) Benchmark timber

Overall the data in Figure 5 demonstrated a general trend that loss in timber volume (abrasion resistance) decreased as density increased. However, data analysis demonstrated that timber density by itself was a poor predictor (only 9% correlation) of abrasion resistance.

Other factors can contribute to abrasion resistance such as grain orientation, porosity and differences in the cell wall at the microscopic level. The triangles in Figure 5 represented one set of anomalies which indicated a wide variation within Yellow Balau. This could be partly explained by the large natural variation of Yellow Balau which is a commercial term for a group of over 300 species of *Dipterocarp*. The circles in Figure 5 represent Bilinga and were another set of anomalies. It is beyond the scope of this research to investigate the cause(s) for such variation within the Bilinga population.

Figure 5: Effect of oven dry density on volume loss



6.4 Discussion

During the comparative abrasion resistance trials it was observed that the rate of degradation of the shingle was quite rapid, producing fine mud that had lubricant properties. In the real world this mud would rapidly wash out to sea. The effect of lubricating mud could reduce the efficacy of the test. However, this was mitigated by removal of the mud and recharging the abrasion vessel with fresh shingle on a regular basis.

Previous experiments have suggested that the abrasion process may comprise simple rubbing of shingle over the surfaces and impact from stones thrown against the surfaces of the wood. This weakened wood may then abrade more easily. Earlier experiments (Sawyer and Williams 2005) noted how the impact was sufficient to cold forge the steel support frames. In the sea, both forms of abrasion may occur, particularly in storm conditions.

It is difficult to relate the number of cycles in the experiment to service conditions. Around British coasts, wave intervals of 10 to 15 seconds can be expected. Larger ocean waves may have longer intervals but dissipate more energy on breaking. Most movement of shingle occurs in the zone where the waves are breaking and disturbing the shingle. Shingle may be thrown up and then drawn back by the receding wave. Since the point at which a wave breaks varies with the height of the tide, it follows that any one piece of wood will only be affected by shingle abrasion for a short period each tide and then only when wave energy is sufficient to disturb the shingle. It should be noted that on sandy shores, sand can be disturbed quite easily and held in suspension producing abrasion conditions that may be significant. To date, research into comparative abrasion resistance has been carried out on a worst case scenario by challenging the timbers species with shingle.

The abrasion tests exposed the timbers to 160,000 revolutions. If we assume that timber *in situ* is exposed to 6 waves every minute, it follows that the structure will be exposed to 360 waves per hour. On the basis of these assumptions and in the absence of other information, the test of 160,000 cycles would therefore equate to about 450 tides. It is unlikely that all waves will have sufficient energy to subject the structure to abrasion with every wave cycle. Therefore, a second assumption has to be made that the waves will only generate abrasive conditions for 33 percent of the time. This would then equate to 1350 tides or about 675 days.

The abrasion tests described in this report have therefore condensed 675 days in service (almost two years) into a 5 day test period. However, it should be borne in mind that direct comparisons to exposure *in situ* are difficult to make and the assumptions detailed above could be viewed as theoretical. Notwithstanding this fact, the laboratory trial described in this report does provide a means to predict comparative performance of LUS of timber when exposed to shingle abrasion.

It is possible that different results could be obtained if the candidate timbers were exposed to sand abrasion. However shingle was chosen as it provided the test method with a 'worst case' scenario.

In relation to the reference timbers, results are presented in Table 11 for information only. It is beyond the scope of this research project to analyse in detail any comparisons between the LUS and the reference timbers. This project is focussed on identifying significant differences in performance between the LUS on the long list and the benchmark species Ekki and Greenheart.

6.5 Conclusions

1. Generally, abrasion resistance increased with density. However, there was little correlation (only 9%) when the average density of a particular candidate timber was compared to the average loss in volume (abrasion resistance) of that timber. The data in Figure 5 demonstrates that assessing density by itself is not an accurate predictor of abrasion resistance

2. From a benchmarking point of view, it can be seen that if a significant difference in performance compared to Greenheart is chosen as a selection threshold then five candidate timbers performed significantly better than Greenheart. These were Ekki, Tali, Eveuss, Oak and Souge. However, if Ekki is chosen as a selection threshold, all candidate species would be rejected at this stage as none performed significantly better than Ekki. Therefore, it was decided to use comparable performance to Greenheart as the threshold for selection, if abrasion resistance was the key material attribute required.

7. Stage 2: Marine exposure trial to determine resistance to shipworm

7.1 Introduction

The principal objective of the marine exposure trial was to determine the resistance of the candidate timbers to attack by shipworm in a known hazardous environment and to benchmark their performance against Greenheart and Ekki. Currently there is no reliable laboratory method of assessing resistance to shipworm hence the requirement for a marine exposure trial. In addition to determining comparative resistance to attack by shipworm, this marine exposure trial also provided the opportunity to collate secondary data on the comparative resistance to attack by gribble as previous research by Williams *et al* (2004B and 2004C) recorded the presence of gribble at the marine trial site.

The test site for the marine exposure trial was located in Olhăo harbour on the Ria Formosa lagoon, Portugal. The tidal regime at this location is semi-diurnal with a range of 1.35 m on neap tides to 3m on spring tides. Although the lagoon is on an Atlantic coast, the climatic conditions are essentially Mediterranean with hot dry summers and warm wet winters. The average temperatures and salinities of the lagoon water at Olhão (Newton, 1995) range between 12°C and 28°C and 33-36.5 psu, respectively. Brown *et al* (2003) reported a higher range of 30-40 psu for average salinities. However, most studies on the Ria Formosa confirm that the lagoon is brackish in the winter and hyper-saline in the summer (Newton and Mudge, 2003). Previous research by Williams *et al* (2004C) reported the presence of aggressive shipworm (teredinid) and gribble (limnoriid) attack on timbers vulnerable to attack by these marine borers.

7.2 Materials and Methods

Six samples of each candidate, benchmark and reference timber were cut to dimensions of 20mm x 75mm x 200mm and were prepared for immersion. Each timber was assigned an identification code, as detailed in Tables 8 and 9, which was routed into the face of the samples. European redwood sapwood was used for control purposes and to demonstrate the validity of the test results.

EN 275 requires that samples are arranged vertically. The test method in this trial is an improvement on EN 275 as the racks were immersed horizontally which ensured that all samples were exposed to the same tidal marine conditions, with the samples orientated vertically. The test racks were weighted before lowering into the harbour. The racks were inspected at low tide to ensure that they were fully immersed and suspended approximately 0.5m from the sea bed. Photograph 14 illustrates a typical test rack.

Photograph 14: Typical test rack. The timber code has been engraved into the surface of the samples. Also, the stock board number has been engraved into the timber surface. All test racks and the position of the timbers were logged to allow traceability of each sample during the trials. *TRADA Technology*

Photograph 15 illustrates the general appearance of the Ria Formosa lagoon and the arrows indicate where the racks were immersed.

Photograph 15: View of the test site at high tide (arrowed). *TRADA Technology*

The marine exposure trial lasted for 18 months, from March 2008 to September 2009. During this period, three assessment visits were made by TRADA to monitor the performance of the candidate timbers. However, regular maintenance and inspection of the racks by field staff took place on a monthly basis. This was to ensure that racks were not lost due to collision with vessels and chains supporting the racks were not damaged. During each assessment visit, the racks and samples were cleaned of all marine fouling.

At each assessment visit, the timber samples on the racks were examined for signs of gribble and shipworm attack and assessed using the visual assessment categories detailed in Table 13. The racks were then wrapped in polyethylene bags to prevent stress to shipworm populations in the timber samples caused by drying out of the timber during transportation between the test site and a local X-ray clinic. Photograph 16 illustrates typical cleaning of the racks and Photograph 17 illustrates the typical marine fouling that had to be removed prior to carrying out X-ray photography. Repair and maintenance of the racks was also carried out as part of the cleaning process prior to re-immersion.

Photograph 16: Cleaning test racks. *TRADA Technology*

Photograph 17: Typical fouling. Note that removal of the barnacles leaves behind a calcareous deposit (arrowed) that has to be removed prior to assessment for attack by gribble and assessment using X ray photography. *TRADA Technology*

Table 13: Visual assessment categories (continuous, non-linear scale) used to estimate marine borer attack

Numerical assessment category	Amount of surface attack caused by gribble (limnoriids) as % board area	Amount of attack caused by shipworm (teredinids) as % board volume
0	No attack	No attack.
1	Minor attack. Single or a few galleries covering not more than 10% of surface area of the specimen.	Minor attack. Single or a few scattered tunnels not covering more than 10% of the specimen areas as it appears on X-ray film.
2	Moderate attack. More than 10% of the total surface area of the specimen covered with galleries. Cross section dimensions practically unchanged.	Moderate attack. Tunnels not covering more than 25% of the specimen area as it appears on X-ray film.
3	Severe attack. Surface of the specimen fully covered with galleries. Cross sectional dimensions substantially reduced.	Severe attack. Tunnels covering between 25% - 50% of the area of the specimen as it appears on X-ray film.
4	Failure. More than half of the original volume of the specimen lost or specimen broken from rack or can be broken by hand.	Failure. Tunnels covering more than 50% of the area of the specimen as it appears on X-ray film.

For each candidate timber, the visual assessment ratings for each test sample were added and the result divided by the number of test samples to yield a notional average rating. In some cases, particularly towards the end of the trial, test samples were lost due to disintegration caused by marine borer attack or mechanical damage. These occurrences are reflected in the notional averages summarised in Table 14 and Figures 6 and 7. Further details pertaining to the data collated for the marine exposure trial are presented in Appendix IV of this report.

7.3 Marine trial results

The data collated over the 18 month assessment period are summarised in Table 14 and illustrated in Figures 6 and 7. Those data represented by '✖' indicate that no samples remained for assessment at the time of inspection due to disintegration of the samples caused by attack by marine borers.

Table 14: Summary of attack by gribble (*Limnoria* spp.) and shipworm (*Teredo* spp.)

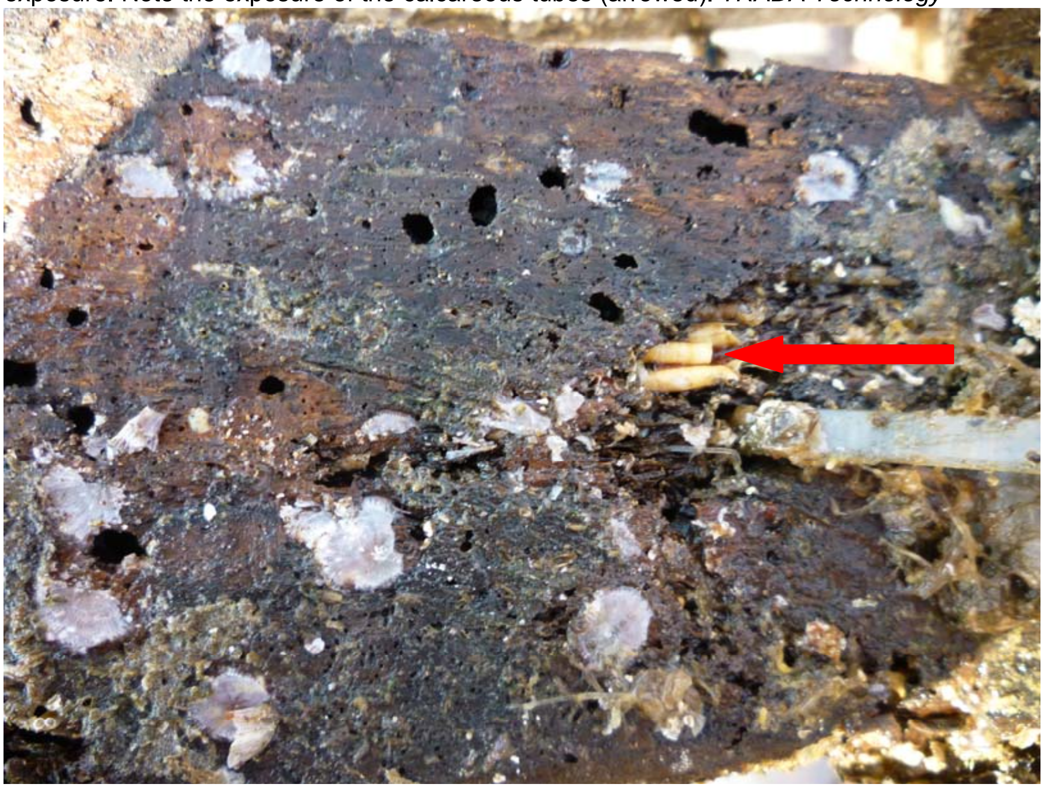
Timber	**Average mean visual assessment rating**					
	Gribble			**Shipworm**		
	Exposure time (months)					
	6	**12**	**18**	**6**	**12**	**18**
Angelim Vermelho	0	0	0	0	0.16	0
Basralocus	0	0	0.25	0.33	0	0
Bilinga	0	0	0	0.33	0	0
Yellow Balau (R)	0	0	0	0	0	0
Cloeziana	0	0	0.33	0	1	2.16
Cupiuba	0	0	0	0	0.16	0.33
Dabema	0	0	0.5	0.33	0.83	1.67
Douglas fir (R)	1.84	4	✖	4	4	✖
Ekki (B)	0	0	0	0	0	0
Eveuss	0	0	0	0	0	0.5
Garapa	0	0	0	0.16	0	0.2
Greenheart (B)	0	0	0.16	0	0	0
Karri (R)	*0.5*	*1.83*	✖	*3.66*	*4*	✖
Massaranduba	0	0	0	0.16	0.16	1
Mora	0	0	0.67	1	4	4
Mukulungu	0	0	0.5	0	0.33	1.83
Niove	0	0	0.2	0	1.33	3.8
Oak(R)	*0*	*2.16*	✖	*3.66*	*4*	✖
Okan	0	0	0	0	0	0
Opepe (R)	0	0	0	0	0.16	0.33
European redwood (C)	*1.33*	✖	✖	*4*	✖	✖
Piquia	0	0	0	0.16	0.5	0.67
Purpleheart (R)	0	0	1.5	2.83	4	4
Sapucaia	0	0	0	0.16	0	0.2
Souge	0	0	0	0.16	0	0.6
Tali	0	0	0.25	0.16	0	0
Timborana	0	0	0	0	0.16	0.2
Tatajuba	0	0	0.83	0	0.5	2.67

(R) Reference timber
(B) Benchmark timber
(C) Control timber

It can be seen from the data in Table 14 that Douglas fir, Karri, Oak and European redwood disintegrated due to attack by marine borers during the marine exposure trail.

Photograph 18 illustrates typical sever attack by shipworm. With severe attack of this nature, it is arguable whether X-ray photography is necessary. However, maintaining the position of the sample on the test rack combined with the observation that the sample has been heavily colonised and assigned a visual assessment rating of 4, can help with referencing and identifying other samples that do not exhibit sever attack by shipworm. X-ray photography is used as a means to accurately assess shipworm attack in samples that are still robust and resistant to probing with a knife and being struck by a hammer and chisel.

Photograph 18: Severe shipworm attack in a sample of Purpleheart after 18 months marine exposure. Note the exposure of the calcareous tubes (arrowed). *TRADA Technology*



The data in Figures 6 and 7 illustrate the comparative performance of the candidate timbers exposed in the marine trial over the 18 month period. However, the data do not differentiate between those candidates that resisted attack by marine borers and represented by a mean visual assessment rating of '0' and those candidates that had disintegrated as a consequence of aggressive attack by marine borers and identified by ✖' in Table 14. These can be differentiated by referring to the tabulated data in Table 14.

KEY

(blue)	Six months exposure
(red)	Twelve months
(green)	Eighteen months exposure

Figure 6: The comparative performance of the candidate timbers against attack by gribble expressed as a mean visual assessment rating

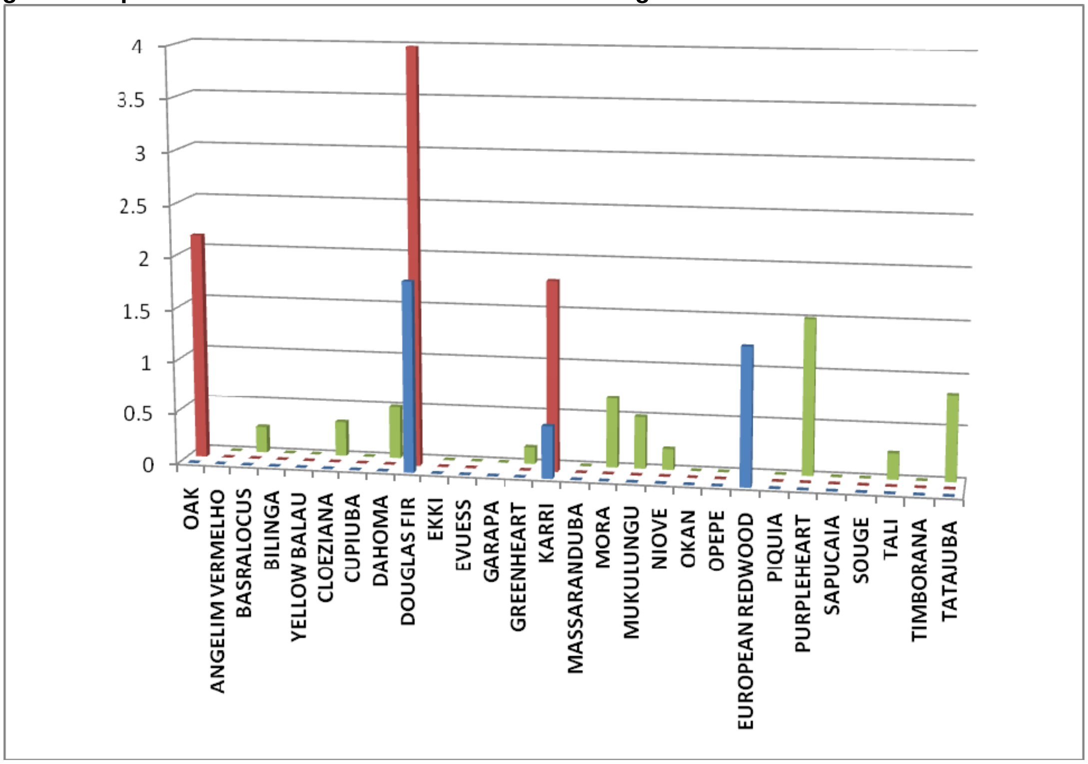
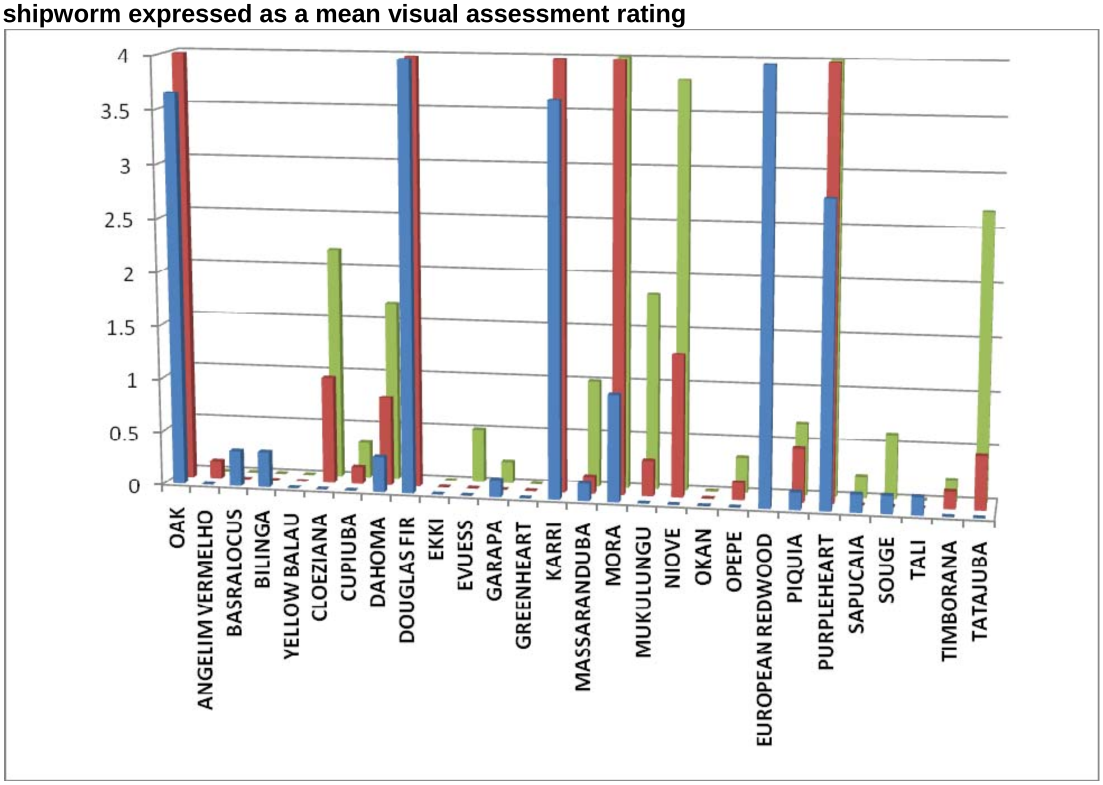
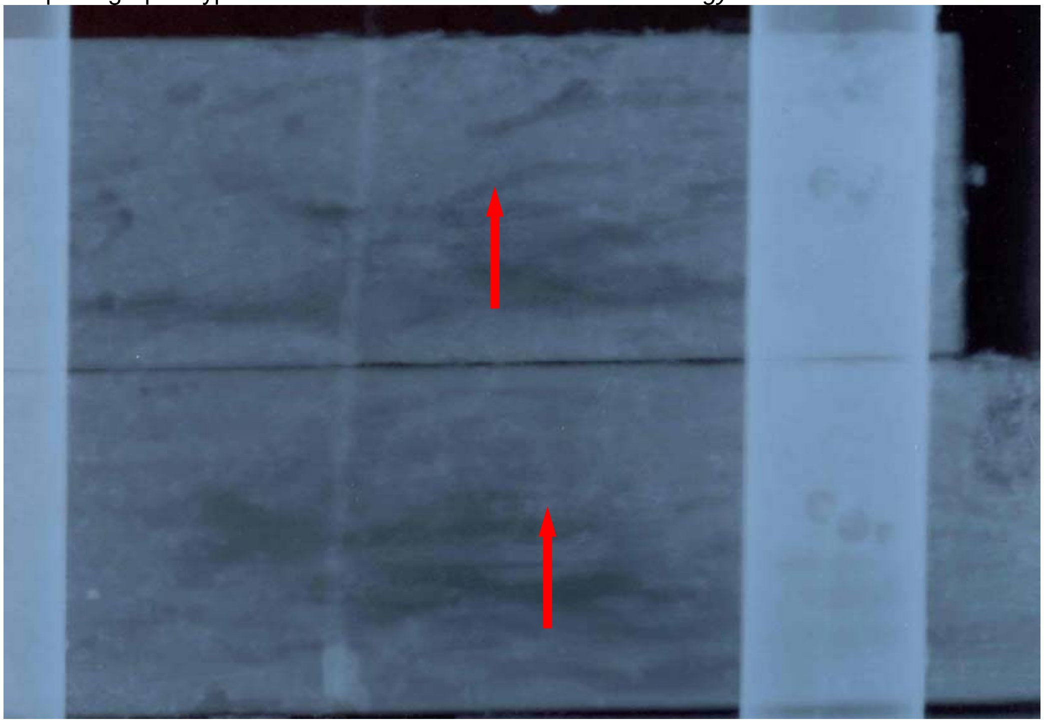


Figure 7: The comparative performance of the candidate timbers against attack by shipworm expressed as a mean visual assessment rating

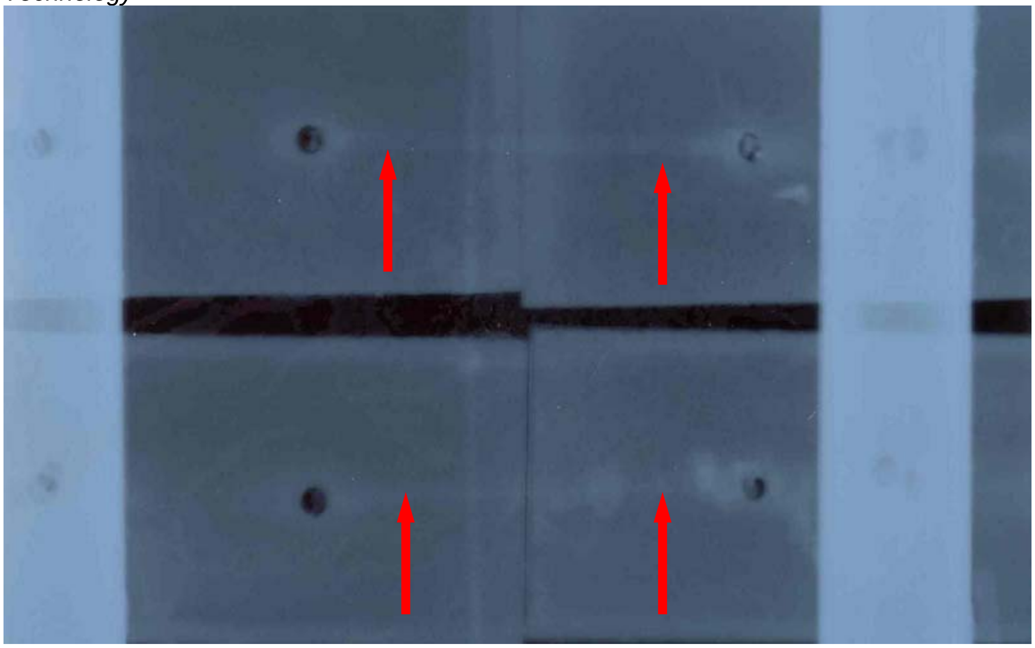


Photographs 19 and 20 illustrate the typical results obtained by X-ray photography of the timber samples.

Photograph 19: Example of severe shipworm attack in European redwood control samples. Note the extensive tunnelling by shipworm that shows up under X-ray photography as paler parts of the photograph. Typical tunnels are arrowed. *TRADA Technology*



Photograph 20: Examples of Okan and Opepe mounted on Rack 1. Both samples were free from shipworm attack after eighteen months exposure. The feint lines (arrowed) are plastic ties used to secure the samples to the test racks and should not be confused with shipworm tunnels. *TRADA Technology*



7.4 Discussion

Visual assessment scales with too many categories are difficult to apply with a consistent degree of accuracy. Those visual assessment scales with few linear categories may not be sensitive enough to differentiate between, what would be in this case, a classification equating to resistant timber and a moderately resistant timber.

The visual assessment categories described in Table 13 are skewed towards the lower end of the assessment scale. With reference to marine borer attack, it is important to separate those samples with less than 10% colonisation and those with 10% to 25% colonisation. It is this band where the interpretation of results may provide the basis for differentiating candidate timbers which may be classified as being resistant to attack by marine borer and those that are classified as moderately resistant.

In the context of this research, a candidate timber that is classified as being resistant to attack by marine borers (in this instance the principal attack was by shipworm) required a mean visual assessment rating of 1.0 or less. A candidate timber that is classified as being moderately resistant to attack by marine borers (in this instance the principal attack was by shipworm), required a mean visual assessment rating of between 1.0 and 2.0.

A mean visual assessment rating in excess of 2.0 indicated severe attack. There is little point in defining differences above this threshold level as timbers with a rating above this level may have no practical resistance to attack by shipworm. The ability to assess shipworm resistance in screening trials is important as it is difficult to accurately assess shipworm attack of timber in service using non-destructive methods.

Experience from previous trials (Williams *et al* 2004B) has shown that assessing field trial data using *in situ* visual assessment schemes can be subjective and can be influenced by assessor experience and interpretation of the X-radiography data. As can be seen in Table 14, there are cases where initial colonisation of shipworm has resulted in a very low average assessment rating of, for example, 0.16 (Tali) or 0.33 (Basralocus and Bilinga), but this low average assessment rating has decreased further (rather than increased) at a later stage in the trial. These small anomalies are likely to be due to subjectivity on the part of the assessor, most probably caused by misinterpretation of shipworm activity in its early stages of colonisation.

The effective use of X-radiography as a method of assessment relies upon thorough cleaning of the timber samples as the remnants of calcareous material (e.g. of barnacles as illustrated in Photograph 17), can lead to misinterpretation with the early stages of colonisation by shipworm. As the trials progress, the juvenile shipworm grow and extend their tunnels. As they grow they become more distinctive when assessed using X-radiography. As a consequence, small variations in the mean visual assessment ratings of candidate timber during the early stages of the trial may be discounted.

Previous marine trials carried out at this site by Williams *et al* (2004B and 2004C) have indicated that aggressive gribble populations were present. In this particular marine exposure trial, the gribble attack was limited to a small range of the candidate timbers, in particular Douglas fir, Karri and Oak, which was an unexpected result. Unpublished work by Portsmouth University has indicated that gribble are able to actively choose which timber to colonise, although the precise method used by gribble to select a particular timber is still unknown. However, it is likely that based upon this current unpublished work that gribble selected which timbers to colonise in this trial. Overall, however, more aggressive attack by gribble was expected during this marine exposure trial so the results should be treated with caution. When the individual visual assessment ratings for the candidate timbers are examined in Appendix IV it can be seen that the visual assessment ratings for Mukulungu and Dabema, in addition to Cloeziana and Tatajuba varied considerably which would suggest that there may be variation in resistance to shipworm in these timbers. Identifying the precise cause for this variation is beyond the scope of this research

7.5 Conclusions

1. The marine exposure trial to determine the comparative resistance of the candidate timbers to attack by shipworm was successful, as evidenced by the fact that European redwood samples had disintegrated before the assessment at 12 months indicating aggressive attack by shipworm. Furthermore, all samples of Oak, Karri and Douglas fir disintegrated after 12-18 months exposure due to attack by marine borers which further indicated the aggressive nature of the marine trial site.

2. Analysis of the gribble data obtained from the marine exposure trial apparently contradicted data derived from the laboratory screening trial described in Chapter 5. This is discussed in more detail on Chapter 9. More aggressive attack by gribble was expected during this marine exposure trial so the results from the marine trial should be treated with caution.

3. In summary, after 18 months exposure in a hazardous marine environment, the following candidate timbers performed comparably to Ekki and Greenheart, in that no shipworm attack was detected: Angelim Vermelho, Basralocus, Okan and Tali.

4. Those timbers exhibiting minor attack by shipworm were Cupiuba, Eveuss, Garapa, Massaranduba, Piquia, Sapucaia, Souge and Timborana. However, after 18 months exposure, the mean visual assessment ratings of these timbers was still less than 1.0 which indicated that these candidate timbers may be considered as resistant to attack by shipworm, despite performing slightly worse than Greenheart and Ekki.

5. Only Dabema and Mukulungu were considered as being moderately resistant to attack by shipworm.

6. In this particular trial, those timber species that yielded a mean visual assessment rating in excess of 2.0 were considered to have little resistance to attack by shipworm. The candidate timbers that fall into this category are Cloeziana, Mora, Niove and Tatajuba.

7. When the individual visual assessment ratings for the candidate timbers are examined it can be seen that the visual assessment ratings for Mukulungu, Dabema, Cloeziana and Tatajuba varied considerably which would suggest that there may be variation in resistance to shipworm in these timbers. Identifying the precise cause for this variation is beyond the scope of this research.

8. Stage 3: Determination of the strength properties of five species of timber in accordance with BS EN 408

8.1 Introduction

Reliable information regarding the strength and stiffness of lesser-used species (LUS) is one of the major obstacles to their use in marine and freshwater construction applications. The allocation of a species/grade combination to a strength class allows engineers to use the mechanical properties of the strength class in structural design. The objective of the mechanical testing programme was to allocate each of the five candidate timbers selected from the long list to a strength class. The possible strength classes are those contained in BS EN 338: 2003 *'Structural timber. Strength classes'.*

In selecting the five timbers from the long list, a number of criteria were taken into account. These included the comparative performance of the timbers in the marine borer and abrasion resistance trials, as well as commercial factors such as available cross section sizes, continuity of supply, standing volumes in forest concessions and whether the timbers could be sourced with FSC/PEFC certification. The final selection of the five timbers was drawn from a short list of ten and based upon consensus within the PSG.

The commercial names of the five species selected are Cupiuba, (*Goupia glabra* Aubl.), Angelim Vermelho, (*Dinizia excelsa* Ducke.) Eveuss (*Klainidoxa gabonensis*), Tali (*Erythrophleum micranthum*) and Okan (*Cylicodiscus*. *gabunensis* Harms). The timbers were supplied by Ecochoice Ltd, UK agents for Reef Hout BV. It should be noted that these five timber species are also commercially available on the open market from other UK suppliers. In general, these species have high densities and were expected to achieve high strength classes

The number and choice of tests was determined by the requirements of BS EN 384: 2004 '*Structural timber. Determination of characteristic values of mechanical properties and density*'. The programme of tests was designed to determine the bending strength, stiffness, density and moisture content of graded timber of the five species. Testing was conducted in accordance with BS EN 408: 2003 '*Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties*'.

Test data has been used to derive characteristic values for bending strength, modulus of elasticity and density in accordance with BS EN 384:2004.

Historically, any values available for design for very heavy and exceptionally heavy tropical hardwoods were derived from a mixture of structural-sized tests and tests on small defect-free (clear) test specimens. For instance, Test Record E/TR/20 from the Timber Development Association (TDA, the forerunner to TRADA) dated February 1961 documents a test programme of 100 structural sized tests on Greenheart specimens 11'×2"×6" (3350mm × 50mm × 150mm). However, correspondence in the early 1980s on the assignment of tropical hardwoods to the original BS5268 strength classes and the boundaries of those classes shows that small clear data was still considered. There was also a desire to avoid down-grading species when there no evidence of poor performance in the field.

The approach of BS EN 384 is to require structural sized testing of graded timber. The method for deriving the characteristic strength values used in design places great importance on the lowest values in the test, so that a relatively small number of results can determine the strength class. Although this approach is rigorous and logical, it appears to be more conservative than that originally taken in assigning tropical hardwoods to strength classes.

8.2 Materials and Methods

8.2.1 Test material

The test material was visually graded in Holland by TRADA graders following British Standard BS 5756: 2007 *'Specification for the visual strength grading of hardwood'*. The material arrived at TRADA as packs in a covered lorry. Cupiuba and Angelim Vermelho were delivered on 23rd January 2009. The remaining species were delivered on 14th April 2009. Around 160 pieces were delivered of each species, including about ten pieces of each species that had failed the grading.

The specimens were conditioned before testing, as described below. Testing was conducted at TRADA Technology's laboratories, near High Wycombe. Testing was started on 26th March and completed on 27th of August.

After testing, the failed specimens were collected by the Environment Agency for further workability and machinability tests at their workshops, and at workshops run by British Waterways. The results of these tests are summarised in Appendix VI.

8.2.2 Conditioning of test samples

The conditioning requirement is that, prior to testing, specimens must be conditioned at (20 ± 2) °C and (65 ± 5) % relative humidity. When the mass of the specimens changes by less than 0.1% within at least 24 hours it is considered that the timbers have become conditioned and that the moisture content is at equilibrium with the ambient conditions.

Twenty beams per species were selected at random on arrival and their weights and moisture contents were recorded. Three moisture content readings were taken for each specimen; one at each end and one from the middle.

The moisture content was measured with an electrical moisture meter manufactured by Brookhuis. The meter has built-in adjustment factors for a wide range of species, although not all of the species in this test programme. For species where no factor was available, the factor for a similar species was chosen by density. A resistance meter is a non-destructive measurement method that is less accurate than the oven dry method used on the failed specimens. The moisture content readings provided an indication of the amount of conditioning required.

Cupiuba and Angelim Vermelho were stacked and stickered in the conditioning rooms on arrival in January 2009. The remaining specimens were stacked and stickered in enclosed storage, which promoted drying, until space became available in fully conditioned rooms. They were moved to the conditioning rooms as space became available - Okan on 20th April, Tali on 19th June and Eveuss on 26th June.

The mass of five specimens of each species was monitored while in the conditioning room. The monitoring demonstrated that the specimens had reduced in weight considerably by the time of test, but were not sufficiently stable to fulfil the equilibrium requirement. Nevertheless the decision was taken to proceed with testing, since it was clear from the rate of change of the weight that equilibrium would not be reached within the time available for the test programme. By comparison with reported equilibrium moisture contents for species of similar density (Dick, 1972), the expected moisture content at equilibrium was between 12% and 15%.

As a point of comparison, the TDA report on Greenheart recorded an air-drying time of two years, leading to specimens with moisture contents between 16% and 20% at time of test.

In use, the moisture content of the timber will be above fibre saturation point where it is under water or in the intertidal zone. Parts of the structure that are regularly wetted, either from spray or precipitation, will typically be at a moisture content of at least 20%.

8.2.3 Dimensions of test samples

Each beam was nominally 50mm wide *b* and 150mm depth *h* and at least 3000mm long. BS EN408 specifies that the cross-section of each test piece must be measured to an accuracy of 1% immediately prior to testing. In line with best practice, the average of a minimum of three separate measurements at different positions along the length of each piece was recorded.

8.2.4 Determination of moisture content

BS EN 408: 2003 states that moisture content should be determined in accordance with British Standard BS EN 13183: 2002: Part 1 '*Moisture content of a piece of sawn timber - Part 1: Determination by oven dry method*'. For moisture content determination, a full cross sectional piece, free of knots and resin pockets is to be cut from the test specimen. BS EN 408 also states that for strength tests, the moisture content piece must be cut as close as possible to the fracture point.

Moisture content at test ω_{test} was calculated as a proportion of the oven-dry mass:

$$\omega_{test} = \frac{m_1 - m_0}{m_0}$$

Where;
m_1 is the mass of the test slice before drying
m_0 is the mass of the test slice after drying at (103 ± 2) °C until equilibrium

The result is presented to the nearest 0.1 percentage point moisture content (BS EN 13183-1).

8.2.5 Density of test samples

Density is a measure of the amount of wood cell wall material present in a set volume of timber and is one of the most important physical characteristics of timber. Density is not only a measure of the mass of a specified volume of timber, but also an indicator of many of the strength and stiffness properties of clear timber.

BS EN 408 requires that the density of the whole cross-section of the test piece is determined on a section cut from the test specimen. Normally the same piece of the test specimens is used both for determination of moisture content and determination of density.

Density ρ is defined as;

$$\rho = \frac{m}{v}$$

Where;

m is the mass of the specimen at time of test
v is the volume of the specimen at time of test

The apparent density of timber varies with moisture content so the density value was adjusted to present it at 12% moisture content, as required by EN384. This adjustment is an approximation that takes account not only of the loss of mass due to the change in moisture content, but also the change in volume due to shrinkage.

There are two steps to the adjustment:

1. If the moisture content was above fibre saturation point (taken as 30% moisture content) the density was adjusted in proportion,

$$\rho_{fsp} = \rho_{test} \frac{100\% + \omega_{fsp}}{100\% + \omega_{test}}$$

Where:
ρ_{fsp} is the density at fibre saturation point (30% moisture content)
ρ_{test} is the density at test
ω_{fsp} is the 30% moisture content at fibre saturation point.
ω_{test} is the moisture content at test.

2. If the moisture content was below fibre saturation point but above 12% (no specimens were below 12%) and for specimens adjusted in the first step, the density was adjusted according to EN384,

$$\rho_{12\%} = \rho_{test} \left(1 - 0.005(\omega_{test} - 12\%)\right)$$

Where:
$\rho_{12\%}$ is the density at 12% moisture content
ρ_{test} is the density at test, or at fibre saturation point from the first step
ω_{test} is the moisture content at test or at fibre saturation point for specimens adjusted in the first step

The density at 12% moisture content is expressed in kg/m³ to the nearest integer.

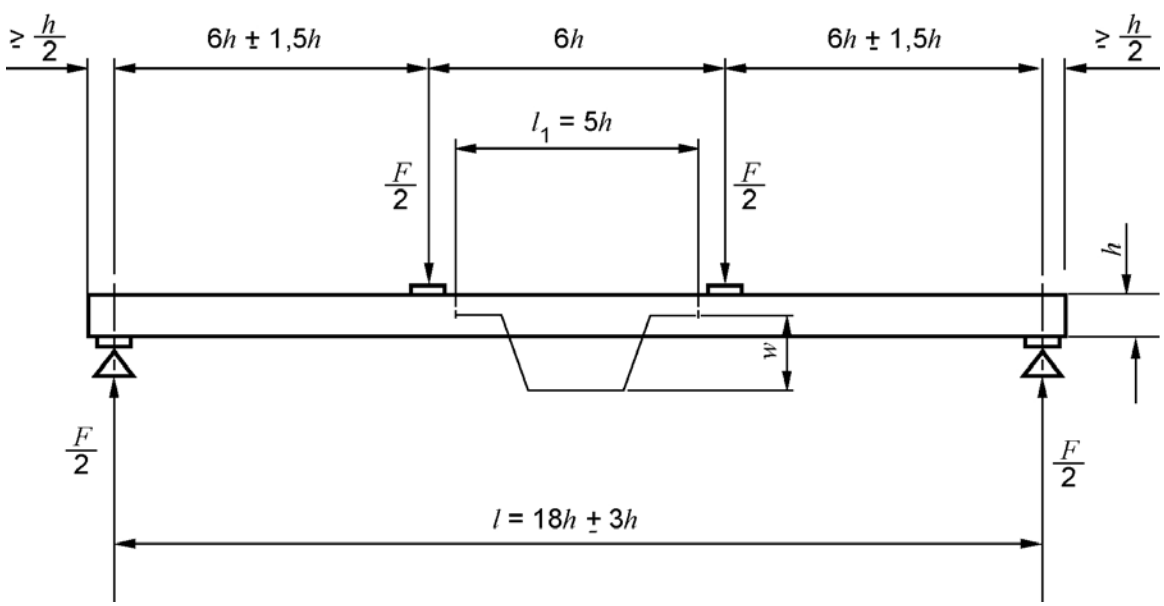
8.2.6 Test Method for determination of local modulus of elasticity

As required for BS EN 384, the modulus of elasticity (MoE) was measured over the central portion of each beam.

The loading equipment used is capable of measuring the load to an accuracy of better than 1% of the load applied to the test piece and is calibrated annually by a UKAS accredited third party.

Figure 8 shows the test arrangement in detail. This is a reproduction of Figure 1 of BS EN 408:2003.

Figure 8: Test arrangement for measuring local modulus of elasticity in bending



The specimens were symmetrically loaded in bending on simple supports at two points over a span of 18 times the depth. The permitted variation in the overall target span of ± 3*h*, where *h* is the depth of the specimen, was not used. The standard does not provide tolerances for the target lengths, although a tolerance of ± 2mm is reasonable.

Measures were taken to avoid local indentation and damage to the specimen surface at the supports and loading points. To prevent buckling, lateral restraints may be provided as necessary. The end supports used incorporated lateral restraints that allow the beam to deflect without significant frictional resistance.

The load was applied at a constant rate. The resulting rate of movement of the loading head was not greater than 0.003*h* mm/s. The maximum load applied did not exceed $0.4F_{max}$ to avoid damage to the test piece.

The deformation was taken as the average of measurements on both faces at the neutral axis, measured at the centre of a central gauge length of 5*h*.

The load and deflection were recorded on a data acquisition system that is part of the calibrated test machine. The dimensions were also recorded in this system, so that it could calculate the stiffness immediately at the end of the test. Separate checks were made on a sample of results to ensure that the calculations were correct.

The detailed TRADA Test Protocol is included in Appendix V to this report.

8.2.7 Calculation of local modulus of elasticity in bending

The initial estimated fracture load $F_{max,est}$ was obtained from literature and experience. Using data obtained from the local modulus of elasticity test, the load/deformation graph was plotted on the computer screen after the test.

The software selected points at $0.1F_{max,est}$ and $0.3F_{max,est}$ and these were displayed for checking on the screen to ensure that they were in the linear portion of the load-deflection curve.

The local modulus of elasticity was calculated from the following expression:

$$E_m = \frac{a l_1^2 (F_2 - F_1)}{16 I (w_2 - w_1)}$$

Where:
a is the distance between a loading position and the nearest support in a bending test, in millimetres;

l_1 is the central gauge length, in millimetres;
I is the second moment of area, in millimetres to the fourth power. For a rectangular cross section $I = bh^3/12$
$(F_2 - F_1)$ is an increment of load in Newtons on the between the selected points
$(w_2 - w_1)$ is the increment of deformation in millimetres corresponding to $(F_2 - F_1)$

The local modulus of elasticity is presented to the nearest integer in N/mm².

8.2.8 Determination of bending strength

The test set up is the same as for the set up for modulus of elasticity determination, but no deflection transducers are used.

The loading equipment used is capable of measuring the load to an accuracy of better than 1% of the load applied to the test piece and is calibrated annually by a UKAS accredited third party.

Load was applied at a constant loading-head movement so adjusted that maximum load is reached within (300 $\pm$ 120)s. The mode of fracture and the growth characteristics at the fracture section of each test piece were recorded.

The detailed TRADA Test Protocols are included in Appendix V.

8.2.9 Calculation of bending strength

The bending strength f_m is given by the equation

$$f_m = a\frac{F_{max}}{2W}$$

Where:
a is distance between a loading position and the nearest support in the test, in millimetres;
F_{max} is the maximum load, in newtons;

W is the section modulus, in millimetres to the third power. For a rectangular cross section $W = bh^2/6$

The bending strength is presented to the nearest integer in N/mm^2

8.2.10 Adjustment of values according to moisture content

It is well documented that most properties of timber vary with variation in moisture content below fibre saturation point.

Following BS EN 384, Strength Class values are derived from timber at about 12% moisture content, which is taken as a reference moisture content. However, to have been certain that the timbers in this project were dried to 12% moisture content would have delayed completion by several months.

Adjustments to results are desirable where the moisture content at test differs significantly from 12%. Two types of adjustment are considered here, an adjustment for shrinkage and an adjustment for the presence of moisture.

8.2.11 Adjustment for shrinkage

An adjustment for shrinkage provides greater consistency between specimen results for stiffness and strength, since variation in the values of depth and breadth have a disproportionate effect on the final values.

Below fibre saturation point, changes in moisture content lead to changes in the cross-sectional dimensions. Within HMSO publications, shrinkage is defined as the percentage dimensional change from green to 12% moisture content and is listed in the tangential and radial directions for a range of species.

The Handbook of Hardwoods (Dick, 1972) lists shrinkages for a number of high density tropical hardwoods including Ekki, Greenheart, Okan and Purpleheart. Given a difference of 18% between an assumed fibre saturation point of 30% (Skaar, 1988) and the 12% reference moisture content, a conservative shrinkage value of 3.6% provides 0.2% shrinkage per 1% moisture content change.

This correction factor was applied to the stiffness and strength values to provide a value consistent with the dimensions of the cross section at 12% moisture content. The correction factor was a function of the moisture content at test for each specimen.

8.2.12 Adjustment for presence of moisture

Moisture within the cell walls of timber reduces its strength and stiffness. The variation is most commonly documented for defect free timber, and the relationship is usually described by an inverse logarithmic function, so that higher moisture contents cause lower strength and stiffness. Some strength properties are affected more than others.

For structural sized timber, the dependency of strength on moisture content is often less important than the incidence of defects, so the strength of timber with a high incidence of defects is only weakly dependent on moisture content.

There are three possible approaches that can be considered.

1. Derive the Strength Class from the test data, as though testing had occurred at 12% moisture content. This is a conservative approach, since the test values will be below those obtained from drier material, and Service Class 3 (SC3, exterior use) applications will reduce them further.

2. Calculate an adjustment factor that will raise the test data for an assumed moisture content of 12%. This factor will be based on the correlation between the strength and moisture content of individual tests, provided the specimens were below fibre saturation point at test. It is best calculated with as large a database as possible. It may be possible to combine data from different species, if they do not show a statistical difference.

3. Calculate the design properties for the Strength Classes for SC3 exposure. Assign the timber to a Strength Class based on these modified design properties, since SC3 exposure should produce a moisture content in the timber close to that at test. However, designers may use the timber at other exposures and the data must be capable of supporting this.

Examination of the graphs (in Appendix V) of strength against moisture content show that there is no measureable correlation between the two for any of the species. This implies that anatomical features, such as the presence of knots or sloping grain are governing the behaviour of the timbers. This effect is probably increased by the choice of a relatively small section size, since defects are of finite size, and occupy a greater part of small sections than large sections.

Examination of the graphs (in Appendix V) of stiffness against moisture content also show little evidence of a correlation between the two for any of the species.

Given the lack of correlation, approach 2 cannot be justified, and an enhanced performance for Service Classes 1 and 2 cannot be justified for strength. Therefore it is proposed that the conservative approach 1 is adopted. Engineers may feel justified in neglecting the adjustment for Service Class 3, bearing in mind that for marine applications, the moisture content in use will be close to that at test.

8.3 Strength test results

Full results are tabulated in Appendix V. The summary table below shows the characteristic values determined in accordance with BS EN 384.

The results were calculated from specimens that had passed the grading. Specimens that failed the grading are shown in the graphs in the appendices with a different colour and marker, but were not included in the calculations.

Specimens that failed outside their central portion were excluded from the strength calculations, since the stress at failure cannot be determined, but were not excluded from the stiffness calculations.

Note that equivalent values determined in accordance with BS EN 384 on reference species such as Greenheart and Ekki are not readily available.

Table 15: Summary of Test Results

Species	*n*	$f_{m.k}$ (N/mm²)	$E_{m.mean}$ (N/mm²)	$E_{m.05}$ (N/mm²)	$\rho_{mean.12\%}$ (kg/m³)	ρ_{k12} (kg/m³)
Angelim Vermelho	147	60.4	22084	18551	1082	1012
Cupiuba	129	53.1	21414	17987	822	729
Eveuss	150	51.0	20998	17638	1019	981
Okan	135	47.3	19318	16227	998	898
Tali	132	40.5	17200	14448	815	672

$f_{m.k}$	Characteristic fifth percentile bending strength established by ranking
n	Number of valid strength tests
$E_{m.mean}$	Characteristic mean bending modulus of elasticity
$E_{m.05}$	Characteristic fifth percentile bending modulus of elasticity $0.84(E_{m.mean})$
$\rho_{mean.12\%}$	Characteristic mean density corrected to 12% moisture content
$\rho_{k.12\%}$	Characteristic fifth percentile density corrected to 12% moisture content established from an assumed normal distribution

Following BS EN384, the fifth percentile of a strength property *f* is obtained by ranking the data for each species, so:

$$f_{05} = f_r$$

where f_{05} is the fifth percentile and f_r is the relevant value from the ranked data. The data is ranked by arranging it in ascending order according to its value. The subscript r shows which data point is used. For the lower fifth percentile

$$r = n\frac{5}{100}$$

where *n* is the number of results in the sample. For example, in a sample of 160 tests f_{05} is the eighth value. Linear interpolation was used where r was not an integer.

BS EN 384 provides an adjustment factor for section depth. However, since the specimens tested were nominally at the reference depth of 150mm, this factor was not applied.

Following BS EN 384, the mean modulus of elasticity from test $\overline{E}_{m.test}$ was modified to obtain a pure modulus of bending as follows:

$$E_{m.mean} = 1.3(\overline{E}_{m.test}) - 2690$$

The modified value is taken as characteristic mean bending modulus of elasticity $E_{m.mean}$

BS EN 384 gives a specific relationship for hardwoods for the lower fifth percentile of the modulus of elasticity $E_{m.05}$

$$E_{m.05} = 0.84(E_{m.mean})$$

The density is measured using mass and volume at time of test. The density is adjusted to a nominal 12%. The lower fifth percentile for each sample is taken from a normal distribution

$$\rho_{05} = \bar{\rho} - 1.65SD$$

where $\bar{\rho}$ is the mean density from the sample and SD is the standard deviation.

BS EN 384 provides a method of averaging fifth percentiles or means from data sets of different sizes to obtain characteristic values. Since there was only one sample per species, this step is redundant, and the characteristic values are the fifth percentiles or mean values as calculated above, i.e. $f_{m,k} = f_{m,05}$.

BS EN 384 requires a reduction in the characteristic bending strength dependent on size and number of samples. Given that the samples tested were made of material from as wide a range of deliveries as possible at the time, and that the total number of valid tests per species was between 129 and 147, this adjustment was not applied.

Examination of the tables in Appendix V shows that there were a number of tests for each species where “No Data” is recorded. Apart from experimental error, these results arise in two ways:

1. the specimen broke prematurely during the stiffness test, in which case both stiffness and strength results are missing,

2. the specimen broke outside the central portion, so the failure stress cannot be determined, in which case only the strength results are missing.

Examination of the figures shows that in general the grading was successful in excluding low strength specimens. Since the grading was carried out in conditions no better than are normally found in industry, this demonstrates both the importance and effectiveness of proper grading.

8.4 Allocation of Strength Classes

Strength classes are sets of material properties that can be assigned to specific combinations of timber species and strength grades. The use of strength classes is intended to simplify the specification of timber, since it groups species in pre-defined categories. However, it takes no account of the durability or appearance of a species, and may penalise a species compared to using species-specific values.

Characteristic values are taken from bending strength, bending stiffness and density. The allocation to a strength class is governed by the lowest strength class applicable to one of these properties. The threshold values are shown in Table 16.

Table 16: Threshold values for hardwood strength classes from BS EN 338

Class	$f_{m,k}$ (N/mm²)	$E_{m,mean}$ (N/mm²)	$E_{m,05}$ (N/mm²)	ρ_{mean} (kg/m³)	$\rho_{k,05}$ (kg/m³)	Example species
D30	30	10000	8000	640	530	Oak
D35	35	10000	8700	670	560	Beech
D40	40	11000	9400	700	590	Iroko, Teak
D50	50	14000	11800	780	650	Merbau, Opepe
D60	60	17000	14300	840	700	Kapur, Kempas
D70	70	20000	16800	1080	900	Greenheart, Ekki

The threshold values were compared with the characteristic values from the test programme (Table 17). BS EN 338 states that a timber population may be assigned to a strength class if its characteristic values of bending strength and density equal or exceed the values for that strength class and its characteristic mean modulus of elasticity in bending equals or exceeds 95% of the value for that strength class

The example species are taken from EN 1912: 2004 '*Structural timber — Strength classes — Assignment of visual grades and species*'. The strength classes of Oak and Beech are for German grades, otherwise the grade is HS from BS5756.

The threshold values from the proposed strength classes are shown below with the test values.

Table 17: Proposed allocation to EN 338 hardwood strength classes, with characteristic values for comparison

Class	$f_{m,k}$ (N/mm²)	$E_{m,mean}$ (N/mm²)	$E_{m,05}$ (N/mm²)	ρ_{mean} (kg/m³)	$\rho_{k,05}$ (kg/m³)
Angelim Vermelho	60.4	22084	18551	1082	1012
D60	60	17000	14300	840	700
Cupiuba	53.1	21414	17987	822	729
D50	50	14000	11800	780	650
Eveuss	51.0	20998	17638	1019	981
D50	50	14000	11800	780	650
Okan	47.3	19318	16227	998	898
D40	40	11000	9400	700	590
Tali	40.5	17200	14448	815	672
D35	35	10000	8700	670	560

Both Tali and Angelim are close to a strength class boundary. The proposal is to demote Tali, as is shown in the table. This is because a number of specimens failed prematurely during the bending test, so were included with the strength data. Had they been included they would have pulled the value of $f_{m,k}$ down.

Strength is the governing property for each species. All the species are much stiffer than predicted by their strength class. This may give engineers confidence to use the Strength Class values without reduction for Service Class 3 (SC3), since the structures are less likely to suffer from excessive flexure.

8.5 Conclusions to the Mechanical Test Programme

1. The proposed strength class allocations shown below are conservative for use in any Service Class.

Table 18: Proposed allocation to EN 338 hardwood strength classes

Species	Class
Angelim Vermelho	D60
Cupiuba	D50
Eveuss	D50
Okan	D40
Tali	D35

1. The characteristic strength values for the five lesser-used species detailed in Table 17 were derived from timber tested at a moisture content close to that likely to be found in service for SC3, i.e. greater than 20%). This is likely to be the case for most marine and fresh water structures. During the test programme no correction was made for the higher timber moisture content and on this basis structural engineers need not apply the strength reduction for SC3 in their designs when specifying Angelim Vermelho, Cupiuba, Eveuss, Okan and Tali. However, this must not be taken as advice that the strength values may be increased if the expected Service Class is SC1 or SC2.

2. Where structural performance is critical, the five lesser-used species identified in Table 18 may be considered as alternatives to Greenheart and Ekki, provided their resistance to marine borer attack and abrasion, where relevant, and their strength properties meet project requirements. These timbers have been allocated to strength classes, as detailed in Table 18 on the basis of test results for bending strength, bending stiffness and density. The strength classes provide values that may be used in design for all the necessary mechanical properties.

3. Careful grading by graders trained in tropical hardwood grading is an essential part of ensuring that expected strength is achieved.

9 Discussion

This chapter summarises a number of discussion points contained within previous sections of the report to present an overall picture of the research project undertaken, in terms of its scope, the results obtained and the direction of future work.

Overall, and in relation to Stage 1 of this research programme, it should be borne in mind that not all timbers previously identified by TRADA and Biodiversity International Ltd as having potential for marine construction were included in the long list as they were not all commercially available within the timeframe of the project. Furthermore, the project had to be set up, managed and delivered within the confines of the available budget. However, for completeness, a number of lesser-used species of timber considered as having potential for use in marine and freshwater construction applications, but which were not included in this research project, have been identified in Table 7 in Section 3.6.

The initial screening programme (Stage 2) set out to identify both the marine borer resistance (resistance to attack by both gribble and shipworm) and abrasion resistance of the ‘long list’ of candidate timbers. Each trial described in Chapters 5, 6 and 7 may be viewed as a stand-alone investigation. However, when data from each trial is viewed as a whole, there appear to be a number of contradictions in the results. This is to be expected, to a certain extent, when undertaking timber research due to the variation of a natural material. For example, when data from the gribble screening trial (Chapter 5) and abrasion resistance trial (Chapter 6) are compared it can be seen that Eveuss and Tali performed significantly worse than Greenheart when challenged with gribble. However, when challenged with shingle, these timbers performed significantly better than Greenheart in terms of their comparative abrasion resistance.

It is beyond the scope of this report to cross reference and analyse resistance to abrasion with resistance to marine borer attack for all candidate timbers. What these data indicate is that good resistance to marine borer attack may not necessarily mean that the candidate timber also has good resistance to abrasion. Furthermore, good resistance to gribble attack may not mean that the candidate timber is also resistant to attack by shipworm.

The data also indicated contradictions between the results for the laboratory trial to determine resistance to gribble and the results of data obtained from the marine exposure trial. When the laboratory performance of Eveuss is compared with its performance in the marine exposure trial, it can be seen that in the laboratory, Eveuss performed significantly worse than Greenheart and Ekki. However, during the marine exposure trial, Eveuss was not attacked by gribble. More aggressive attack by gribble was expected during the marine exposure trial so apparent resistance to gribble, as suggested by the marine exposure trail data in this instance, should be treated with caution. This follows for all timbers that appeared to perform better in the marine exposure trial to attack by gribble than they did during the laboratory trial.

The data suggest that it may be possible to specify timber on the basis of an understanding of the most significant hazard that a timber has to counter and withstand in service. For example, if the primary hazard is one of abrasion, then marine borer resistance, particularly gribble resistance, may not be as critical as abrasion resistance. This is because the abrasive nature of the environment may prevent the establishment of large colonies of gribble.

However, the relationship between abrasion resistance and gribble resistance is complex. Gribble is ubiquitous around the UK coastline, although the animal favours sheltered, warmer coastal environments. It follows that the risk of gribble infestation is lower on exposed areas of the coastline where there is a high risk of abrasion in the intertidal zone on the beach. It should be borne in mind that where the timber is permanently submerged then the risk associated with attack by gribble increases so the requirement for resistance to gribble may not be fully discounted from design considerations but may take second place to abrasion resistance as a required material attribute.

Similarly, coastal environments characterised by a high risk of abrasion are also hostile environments for the shipworm. The abrasive nature of the environment can prevent the shipworm from establishing a burrow in the timber. However, where timber is permanently submerged the risk associated with attack by shipworm increases. Therefore, the requirement for resistance to shipworm may not be fully discounted from design considerations but may take second place to abrasion resistance as a required material attribute.

Records show that shipworm tends to be limited to the south and south west coast of the UK. However, it should be recognised that a coastal survey has not been carried out since the 1960's and information on the current distribution of shipworm is scant. Current records regarding the distribution of shipworm may, therefore, be considered to be obsolete.

To date, there is no known reliable laboratory screening trial that can assess the resistance of a timber species to shipworm. This is partly due to the difficulties in maintaining viable shipworm larvae. However, if reproducing shipworm populations can be maintained *in vitro* it may be feasible to develop a fast track test that focuses on assessing larvae that successfully colonise the candidate timbers. Such a trial could be run concurrently with gribble resistance and abrasion resistance trials with the result that timber screening can be much faster and more cost effective.

The screening trials described in this report do not individually offer a precise method of assessing suitability but when taken together, and applied in a tiered approach, they are a valuable precursor to undertaking trial installations, structural testing or use in critical components.

The reference timbers detailed in Table 6 were included in the research programme simply because they are commercially available and have been used for marine and freshwater construction, albeit on a much smaller scale than Greenheart and Ekki. Of the reference timbers included, there are records of Karri, Purpleheart and Yellow Balau being used for selective groyne planking (groynes 31 to 35) at Bournemouth (Perscomm. Harlow 2003), for example. These groynes were assessed by TRADA and HR Wallingford back in 2003 but it would be helpful to resurvey them to determine their ongoing performance. Interestingly, this research project has found that Yellow Balau performs comparatively well in terms of marine borer resistance, but Karri and Purpleheart perform poorly when compared to Greenheart and Ekki. As well as assessing the ongoing performance of groynes 31 to 35 with respect to marine borer resistance, an assessment of comparative abrasion resistance could also be considered.

This research programme has not established the piling and driveability characteristics of any of the candidate timbers, in particular the five timbers selected for structural testing. Whilst the piling/driveability characteristics of some candidate timbers may be established by experience gained within the UK and overseas, the driveability characteristics of other timbers can only be determined through pilot studies. There are obvious limitations with pilot studies as only limited numbers of candidate species can be assessed and the costs of such pilot studies may limit the scope of the trials.

Marketing lesser-used timbers has always tested the timber industry and there has often been considerable end-user resistance to working with lesser-used species of timber as their technical properties are not fully appreciated. The data and conclusions contained within this report should begin to erode this conservatism and encourage the use of a wider range of lesser-used species of timber in marine and freshwater applications. In the longer term, this will help make profitable forestry and sustained yield management easier to achieve.

10 Conclusions and Recommendations

10.1 Conclusions

1. Currently, there is little practical guidance regarding the use of lesser-used species of timber in marine and freshwater construction applications. With increasing pressure on engineers to provide environmental benefits within schemes whilst ensuring that works are also technically and economically sound, there is considerable scope for the increased use of timber. Timber is a renewable resource and is an environmentally acceptable choice of construction material, provided it can be sourced with evidence of legality, sustainability and chain of custody. Established and lesser-used species of timber exhibit a range of properties, making them fit for purpose for a variety of construction applications. The findings presented in this report will help designers, engineers and specifiers to use a wider range of hardwood timber species with confidence.

2. Two of the principal obstacles in using lesser-used species of timber are that either little is known about their resistance to marine borer attack, or there is limited confidence in the pedigree of existing technical information about their performance. This research project has sought to address both of these obstacles by establishing the comparative marine borer and abrasion resistance of eighteen lesser-used species of timber when benchmarked against the performance of Greenheart and Ekki using proven laboratory and field screening techniques.

3. Where structural performance is critical, this research has determined the strength classes for five LUS: Angelim Vermelho, Cupiuba, Eveuss, Okan and Tali. These five timbers may be used as alternatives to Greenheart and Ekki for marine and freshwater structural applications, provided their resistance to marine borer attack and abrasion, where relevant, and their strength properties meet project requirements.

4. With reference to the structural test programme, strength was the governing property for each species. Examination of the graphs in Appendix V of strength against moisture content show that there was no measureable correlation between the two for any of the species. This implies that anatomical features, such as the presence of knots or sloping grain, have governed the behaviour of the timbers. This effect was probably increased by the choice of a relatively small section size, since defects are of finite size and occupy a greater part of small sections than large sections. Examination of the graphs in Appendix V of stiffness against moisture content also showed little evidence of a correlation between the two for any of the species. Therefore engineers may feel justified in neglecting the adjustment for Service Class 3 for the strength classes detailed for Angelim Vermelho, Cupiuba, Evuess, Okan and Tali in Table 15, bearing in mind that for marine applications, the moisture content in use will be close to that at test (i.e. 20%).

5. All the species were much stiffer than predicted by their strength class. This may also give engineers confidence to use the strength class values detailed in Table 15 without reduction for Service Class 3, since the structures are less likely to suffer from excessive flexure.

6. If strength is not critical, a longer list of thirteen lesser-used species of timber which may be suitable for marine and freshwater construction applications has been identified. These timbers exhibit varying degrees of resistance to marine

borers and abrasion, so their suitability will need to be assessed on a site and project specific basis.

7. The data in this report should provide the basis for the incremental development of confidence in specifying and using the researched lesser-used species of timber in the marine and freshwater construction industry, in the UK and elsewhere.

8. Ultimately, the specification and use of lesser-used timbers from the 'long list' will require a holistic approach where in addition to considering marine borer resistance, abrasion resistance and strength data, other factors such as price, section sizes, shrinkage, movement in service, workability and machinability characteristics, and delivery times may influence choice.

10.2 Recommendations

1. To promote the wider use of lesser-used species of timber, it is recommended that an approach to specifying timber based on key risk parameters is adopted by engineers to ensure that these timbers are considered alongside more common "tried and tested" timbers such as Greenheart and Ekki. In other words, the functional performance of a timber and its ability to withstand the most dominant site-specific hazards, whether resistance to gribble, shipworm or abrasion, should drive the selection of timber species. However, it is recognised that other factors such as availability within project timeframes, cost, required section sizes may also influence the decision making process.

2. If, or when, funding and resources permit, it is recommended that further research be undertaken into the long-list of candidate timbers identified during this research project (excluding the five timbers that have been strength tested as part of this research).

3. Looking forward, it is recommended that a monitoring programme be established to assess and review the performance of Angelim Vermelho, Cupiuba, Eveuss, Okan and Tali in future live project applications. Whilst all reasonable tests on these five lesser-used species of timber have been undertaken as part of this research, to the point that the researchers believe these timbers can now be used with confidence in project applications, it would be prudent to monitor a number of projects to assess the performance of these timbers over their service life so that reliable asset management data can be collated.

4. If, or when, funding permits, the option of devising a laboratory test to determine the energy absorption characteristics of candidate timbers should be investigated. It was beyond the scope of this research project to determine the piling and driveability characteristics of any of the candidate timbers, but these factors are important in determining operational suitability. The test would need to determine the energy absorption characteristics of the candidate timbers compared to Greenheart and Ekki, with a particular focus on Greenheart. This is because Greenheart has excellent piling characteristics on account of the bole being cylindrical and available in long lengths as opposed to tapered boles which are a common feature of some of the larger tropical trees such as Ekki and Purpleheart. Laboratory test data could feed into the establishment of full size piling trials.

5. If, or when, funding permits, an up-to-date comprehensive UK coastline survey to establish the risk posed by marine borers should be undertaken. The last such survey was undertaken by Hall and Saunders in the 1960's. Since the 1960's a cleaner marine environment and reported increases in sea temperature can only favour an increase in the incidence of marine borers. In the absence of updated survey information, local knowledge and experience should be considered to help determine the risk posed by marine borers. Where known to be reliable, local knowledge and experience should be used in conjunction with the outputs from this research and development programme when choosing timber lesser-used timbers from the 'long list'.

6. The Environment Agency should keep records of where and when timbers identified on the long list are used for schemes. This will facilitate easier and more effective monitoring in service of all timbers identified on the long list as and when funding becomes available.

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APPENDIX I

List of members of the Project Steering Group

Melanie Meaden	Sustainable Procurement Advisor	Environment Agency
Paul Sedgwick	Commercial Manager	Environment Agency
Richard Copas	Senior Environment Assessment Officer	Environment Agency
Will Martin	Procurement Strategy Manager	Environment Agency
Jonathon Simm	Technical Director	H R Wallingford Ltd
Bridget Woods-Ballard	Principal Engineer	H R Wallingford Ltd
Dr. John Williams	Senior Technical Consultant	TRADA Technology
Sébastien Dupray	Project Manager	CETMEF
Prof. Mike Cowling	Chief Scientist	The Crown Estate
Christopher Rainger	Principal Civil Engineer	British Waterways
Mike Bekin	Director	Ecochoice Ltd
Paul Kemp	Director	Aitken and Howard Ltd
Tony Camilleri	Managing Director	J T Mackley & Co Ltd
Dave Riley	Operations Director	VolkerStevin Ltd

APPENDIX II

Literature sources used during the scoping study and the technical properties of the 'long list', reference and benchmark timbers

Literature sources used during the scoping study

A technical appraisal of the material and ‘trunk’ properties of the timber species detailed in Tables 5 & 6 is presented in Appendix III. The ‘long list’ species (Table 5 are considered to have potential as alternatives to greenheart and ekki). This list is by no means exhaustive and the rationale behind the selection of the ‘long list’ has already been presented in Chapter 3.

At the time of production of this scoping study, all proposed timber species are understood to meet the minimum (CPET Category B) timber purchasing requirements of the Environment Agency.

Technically, the ‘long list’ of timbers detailed in Table 5 are good candidate species that may meet the requirements for use in the marine and freshwater environments. As well as material properties of the timber, important commercial specification requirements may influence the choice of timber species. These being volumes, sizes, ease of procurement and price. Market forces and procurement factors such rainy/dry seasons can influence availability. No attempt has been made to rank the timber species by market availability as this may change. However, it must be stressed that all timber species detailed in Table 5 are commercially available in large volumes although the time of ordering (rainy/dry season) can influence delivery times.

Individual sources of information cited in this appendix are identified by their numerical reference in Appendix III (see below). It is beyond the scope of this exercise to cite all references but the review has focussed on PROSPECT as our primary source of data with CIRAD’s TROPIX 5.0 database as our secondary source. Tertiary sources were selected from TRADA’s reference library. The purpose of this exercise is to review the technical properties of the ‘long list’ of species to confirm their potential suitability for marine and fresh water construction. With reference to the PROSPECT database, technical characteristics have been determined by reviewing the source of information. Generally, the technical property with the most ‘authoritative’ sources has been presented.

In some cases (PROSPECT database) natural durability and marine borer ratings are based upon data obtained from unspecified conditions. Given the vagaries of such sources, it follows that the current benchmarking tests of commercial supplies of timber of the selected species in this study will provide comparative marine borer resistance.

Published data on strength is generally based upon ‘ultimate strength values’ which are derived from kiln dried, small clear, defect free sections of the candidate species. It is important to stress that these values are not design values. All strength and density values are for air ‘dry’ timber (12% moisture content) which allows for comparison between species. Data on strength values for ‘green’; timber from the primary and secondary data sources is incomplete and has therefore been omitted from this scoping study. Shrinkage values are for shrinkage from the green to dry state as, typically, these timbers will be used in large section sizes that prevents complete drying prior to use. Where available, movement in service characteristics are also given. Whilst marine and fresh water construction will require immersion of the timber, some sections and components will be out of contact with water and can be expected to move in service.

The cited electronic databases form the basis of our literature search.

Primary data source

(1) PROSPECT Oxford Forestry Institute

Secondary data source

(2) TROPIX 5 database: CIRAD Forestry Department

Tertiary reference texts

(3) Bolza, E. Keating W. G. (1972) African timbers – the properties, uses and characteristics of 700 species. *Division of Building Research, Commonwealth Scientific and Industrial Research Organisation*

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(7) HMSO (1997) The Handbook of Hardwoods. *Building Research Establishment*

(8) Mainieri, C. and Chimelo, J.P. (1989) Fichas de caracteristicas das Madeiras Brasileiras.*Instituto de Pesquisas Tecnologicas Divisão de Madieras. São Paulo.*

(9) Mettem, C.J. and Richens, A.D. (1991) Hardwoods in construction. *Timber Research and Development Association*

(10) Oliver, A.C. (1974) Timber for marine and fresh water construction. *Timber Research and Development Association.*

Note: with reference to Marine borer resistance (EA trials) Where performance is significantly worse than greenheart or ekki < greenheart and < ekki have been used.
Note: with reference to the data for teredinids, only those species that yielded a mean visual assessment rating greater than 2 were deemed to be not resistant to teredinids.
Note: with reference to the data for teredinids, those species which yielded a mean visual assessment rating of 0.0 to 1.0 were classified as resistant
Note: with reference to the data for teredinids, those species which yielded a mean visual assessment rating between 1.0 and 2.0 were considered moderately resistant

Timber Species		Performance characteristics								Marine borer resistance (EA trials)	
Common name	***Botanical name***	**Natural durability**	***Marine borer resistance***	**Density (Kgm3)**	**Strength**		**Shrinkage on drying**		**movement in service**		
							Tangential (%)	**Radial(%)**		**Gribble**	**Teredinids**
Angelim vermelho	*Dinizia excelsa*	(1) very durable	*(1) no data*	(1) 1080 -1200	(1) high to very high		(1) fairly large	(1) fairly large	(1) no data	< greenheart	resistant
					MoR (N/mm2)	**MoE(N/mm2)**					
		(2) durable	*(2) resistant*	(2) 1070	(2) 160	26,280	(2) 8.5	(2) 5.1	(2) medium to large		
Basralocus	*Dicoryia guianensis*	(1) very durable	*(1) resistant*	(1) 720 -840	(1) medium to high		(1) large	(1) medium to fairly large	(1) medium	resistant	resistant
					MoR (N/mm2)	**MoE(N/mm2)**					
		(2) durable	*(2) resistant*	(2) 790	(2) 121	(2) 18,350	(2) 8.2	(2) 5.1	(2) medium		
Biliga (opepe)	*Nauclea diderrichii*	(1) very durable	*(1) resistant*	(1) 720 - 840	(1) medium to high		(1) medium	(1) medium	(1) small	resistant	resistant
					MoR (N/mm2)	**MoE(N/mm2)**					
		(2) durable	*(2) resistant*	(2) 760	(2) 95	(2) 14,660	(2) 7.5	(2) 4.5	(2) small to medium		
Cloeziana	*Eucalyptus cloeziana*									resistant	not resistant
Cupiuba	*Goupia glabra*	(1) durable	*(1) susceptible*	(1) 840 - 960	(1) medium to high		(1) medium	(1) medium	(1) large	resistant	resistant
					MoR (N/mm2)	**MoE(N/mm2)**					
		(2) moderately durable	*(2) no data*	(2) 840	(2) 110	(2) 18,190	(2) 8.8	(2) 5.1	(2) large		
Dabema	*Piptadeniastrum africanum*	(1) durable	*(1) susceptible*	(1) 600 - 840	(1) low to medium		(1) fairly large	(1) medium	(1) medium	resistant	moderately resistant
					MoR (N/mm2)	**MoE(N/mm2)**					
		(2) moderately durable	*(2) no data*	(2) 700	(2) 98	(2) 15,190	(2) 8.5	(2) 3.8	(2) medium		

Timber Species Common name	 *Botanical name*	Natural durability	*Marine borer resistance*	Density (Kgm3)	Performance characteristics Strength		Shrinkage on drying Tangential (%)	 Radial(%)	movement in service		
Evuess (kruma)	*Klainidoxa gabonensis*	(1) very durable (2) very durable	*(1) no data* *(2) no data*	(1) 1080 -1200 (2) 1060	(1) high **MoR (N/mm2)** (2) 168	(1) very high **MoE(N/mm2)** (2) 25,620	(1) large (2) 9.5	(1) large (2) 7.5	(1) no data (2) large	< greenheart < ekki	resistant
Garapa	*Apuleia leiocarpa*	(1) durable (2) moderatley durable	*(1) no data* *(2) resistant*	(1) 840 - 960 (2) 790	(1) high **MoR (N/mm2)** 116	(1) high **MoE(N/mm2)** 15,880	(1) fairly large (2) 7.5	(1) medium (2) 4.2	(1) no data (2) medium	resistant	Not resistant
Massaranduba	*Manilkara bidentata*	(1) very durable (2) very durable	*(1) susceptible* *(2) resistant*	(1) 960 - 1080 (2) 1100	(1) fairly high **MoR (N/mm2)** (2) 170	(1) high **MoE(N/mm2)** (2) 24,410	(1) fairly large (2) 9.4	(1) large (2) 7.1	(1) medium (2) large	< greenheart	resistant
Mora	*Mora excelsa*	(1) durable (2) durable	*(1) susceptible* *(2) no data*	(1) 960 -1080 (2) 1030	(1) low to high **MoR (N/mm2)** (2) 141	(1) high **MoE(N/mm2)** (2) 18.940	(1) large (2) 10.0	(1) large (2) 6.5	(1) large (2) medium to large	resistant	not resistant
Mukulungu	*Autronella congoensis*	(1) durable (2) durable	*(1) resistant* *(2) resistant*	(1) 840 - 1080 (2) 940	(1) high **MoR (N/mm2)** (2) 119	(2) very high **MoE(N/mm2)** (2) 17.060	(large) (2) 8.4	(1) large (2) 7.4	(1) large (2) large	< greenheart < ekki	moderately resistant
Niove	*Staudtia kamerunensis*	(1) durable (2) very durable	*(1) no data* *(2) no data*	(1) 840-1080 (2) 880	(1) medium to very high	(1) no data	(1) no data (2) 6.0	(1) no data (2) 4.6	(1) small (2) small	resistant	not resistant
Okan	*Cyclodiscus gabunensis*	(1) very durable (2) durable	*(1) resistant* *(2) no data*	(1) 960 -1080 (2) 910	(1) high **MoR (N/mm2)** (2) 134	(1) high **MoE(N/mm2)** (2) 22260	(1) small (2) 7.9	(1) medium (2) 5.8	(1) no data (2) medium to large	resistant	resistant

Timber Species					Performance characteristics						
Common name	***Botanical name***	**Natural durability**	***Marine borer resistance***	**Density (Kgm3)**	**Strength**		**Shrinkage on drying Tangential (%)**	**Radial(%)**	**movement in service**		
Piquia	*Caryocar spp.*	(1) durable (2) durable	*(1) moderately resistant* *(2) no data*	(1) 840 - 1080 (2) 800	(1) medium to fairly high **MoR (N/mm2)** 109	(1) medium **MoE(N/mm2)** 17,640	(1) large (2) 9.6	(1) large (2) 5.2	(1) Large (2) large	resistant	resistant
Sapucaia	*Lecythis paraensis*	(1) no data (2) no data	*(1) resistant* *(2) no data*	(1) no data (2) no data	(1) high **MoR (N/mm2)** (2) no data	(1) high **MoE(N/mm2)** (2) no data	(1) medium (2) no data	(1) fairly large (2) no data	(1) no data (2) no data	resistant	resistant
Souge	*Parinari excelsa*	(1) not durable	*(2) resistant*		(1) medium **MoR (N/mm2)**	(1) medium **MoE(N/mm2)**	(1) medium **to large**	(1)medium **to large**	(1) large	resistant	resistant
Tali	*Erythrophleum ivorense*	(1) very durable (2) very durable	*(1) resistant* *(2) no data*	(1) 840 -1080 (2) 910	(1) high **MoR (N/mm2)** 128	(1) high **MoE(N/mm2)** 19,490	(1) Small (2) 8.4	(1) Small (2) 5.1	(1) small (2) small to medium	<greenheart	resistant
Tatajuba	*Bagassa spp.*	(1) durable (2) very durable	*(1) moderately resistant* *(2) no data*	(1) 720 - 840 (2) 800	(1) high **MoR (N/mm2)** 109	(1) high **MoE(N/mm2)** 21,490	(1) fairly large (2) 5.2	(1) medium (2) 3.7	(1) no data (2) small	resistant	not resistant
Timborana	*Enterolobium schomburgkii*	(1) durable (2) moderately durable	*(1) no data* *(2) no data*	(1) 960 - 1080 (2) 800	(1) high **MoR (N/mm2)** (2) 122	(1) very high **MoE(N/mm2)** 19,120	(1) Fairly large (2) 6.9	(1) small (2) 4.6	(2) medium	resistant	resistant

Timber Species						
Common name	***Botanical name***	**length of bole (m)**	**Bole diameter (cm)**	**shape of bole**	**Grain**	**Other comments**
Angelim vermelho	*Dinizia excelsa*	20 - 40	50 - 200	Cylindrical	Interlocked grain	
Basralocus	*Dicoryia guianensis*	20 - 30	50 - 200	Buttressed	Straight or interlocked grain	High silica content
Bilinga (opepe)	*Nauclea diderrichii*	20 - 30	50 - 200	Cylindrical not buttressed	Interlocked grain	Skin irritant
Cloeziana	*Eucalyptus cloeziana*					**no data**
Cupiuba	*Goupia glabra*	10m -30m	50 - 150	Buttressed	Straight grained	
Dabema (dahoma)	*Piptadeniastrum africanum*	10m - 20m	50 - 200	Buttressed	Interlocked grain	Respiratory effects
Evuess (kruma)	*Klainidoxa gabonensis*	30 - 40	50 - 200	Buttressed	Straight or interlocked grain	
Garapa	*Apuleia leiocarpa*	10m - 20m	100 - 150	no data	Straight grained	Skin irritant
Massaranduba	*Manilkara bidentata*	10m - 30m	50 - 150	Buttressed	Straight or interlocked grain	Skin irritant
Mora	*Mora excelsa*	10m - 30m	50 - 150	Buttressed	Straight or interlocked grain	
Mukulungu	*Autranella congolensis*	20m - 40m	100 -200	Cylindrical or buttressed	Straight or interlocked grain	Respiratory effects
Okan	*Cyclodiscus gabunensis*	20m - 40m	50 - 400	Straight, cyclindrical or buttressed	Interlocked grain	Respiratory effects
Niove	*Staudtia kamerunensis*	10m - 30m	50 - 100	Not buttressed	Straight grained	

Piquia	*Caryocar spp.*	20m -30m	50 - 150	Cylindrical or buttressed	Straight or interlocked grain	
Sapucaia	*Lecythis paraensis*	<10m	150 - 200	no data	Straight grained	
Souge	*Parinari excelsa*	10m - 30m	50 - 200	Buttressed	Interlocked grain	High silica content
Tali	*Erythrophleum ivorense*	<20m	50 - 200	Buttressed	Interlocked grain	Respiratory effects
Tatajuba	*Bagassa spp.*	10m - 30m	50 - 100	Cylindrical not buttressed	Interlocked grain	
Timborana	*Enterolobium schomburgkii*	20m - 30m	50 - 100	Cylindrical or buttressed	Straight or interlocked grain	

Timber Species

Common name	*Botanical name*	length of bole (m)	Bole diameter (cm)	shape of bole	Grain	Other comments
Greenheart	*Chlorocardium rodiaei*	10m - 30m	<150	Cylindrical or buttressed	Straight grained	Respiratory effects
Ekki	*Lophira alata*	20m - 40m	100 - 200	not buttressed	Interlocked grain	Skin irritant
Yellow balau	*Shorea* spp.	20m - 40m	50 - 200	Buttressed	Interlocked grain	
Purpleheart	Peltogyne *spp.*	10m - 30m	50 - 150	Buttressed	Straight or interlocked grain	
Douglas fir	*Psuedotsuga menziessii*	10m - 30m	50 - 150	Cylindrical	Straight	
Oak	*Quercus* spp.	10m - 20m	100 - 150	Straight	Straight	Respiratory effects
Karri	*Eucalyptus diversicolor*	*20m - 40m*	250 - 350	Buttressed	Interlocked grain	
Opepe	*Nauclea diderrichii*	20m - 30m	50 - 200	Cylindrical not buttressed	Interlocked grain	Skin irritant

APPENDIX III

Data from the laboratory screening trial to determine resistance to gribble and abrasion

Table 1: Effect of wood species and position on rack in abrasion tester on sample volume loss (arcsine transformed % losses, GLM ANOVA with species and position as fixed factors).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Species	26	1293.9	1306.0	50.2	16.6	<0.0005
Position on rack	5	94.3	94.3	18.9	6.2	<0.0005
Error	136	412.1	412.1	3.0		
Total	167	1800.3				

Table 2: Effect of wood species on feeding rate (one way ANOVA).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Species	27	511.9	511.9	19.0	19.6	<0.0005
Error	308	298.5	298.5	1.0		
Total	335	810.4				

APPENDIX IV

Data from the marine exposure trial

Exposure to *Teredo* spp.
x denotes missing sample

		ASSESSMENT DATE		
SPECIES	CODE	Oct-08	Mar-09	Oct-09
OAK	AL1	4	4	x
	AL2	4	4	x
	AL4	2	4	x
	AL7	4	4	x
	AL9	4	4	x
	AL10	4	4	x
	Avg	**3.6666667**	**4**	**x**
ANGELIM VERMELHO	AV1	0	0	0
	AV2	0	0	0
	AV6	0	0	0
	AV7	0	0	0
	AV8	0	1	0
	AV9	0	0	0
	Avg	**0**	**0.1666667**	**0**
BASRALOCUS	BA3	0	0	x
	BA4	0	0	0
	BA5	0	0	x
	BA6	1	0	0
	BA8	1	0	0
	BA9	0	0	0
	Avg	**0.3333333**	**0**	**0**
BILINGA	BI1	0	0	0
	BI2	1	0	x
	BI4	0	0	0
	BI6	1	0	x
	BI9	0	0	0
	BI10	0	0	0
	Avg	**0.3333333**	**0**	**0**
YELLOW BALAU	BU1	0	0	x
	BU2	0	0	0
	BU5	0	0	0
	BU6	0	0	0
	BU7	0	0	x
	BU10	0	0	0
	Avg	**0**	**0**	**0**

CLOEZIANA	CL3	0	1	1
	CL4	0	1	2
	CL5	0	1	1
	CL6	0	1	3
	CL9	0	1	3
	CL10	0	1	3
	Avg	**0**	**1**	**2.1666667**
CUPUIBA	CU2	0	0	0
	CU3	0	0	0
	CU4	0	1	1
	CU7	0	0	1
	CU8	0	0	0
	CU9	0	0	0
	Avg	**0**	**0.1666667**	**0.3333333**
DABEMA	*DA3*	0	0	0
	DA4	0	1	1
	DA5	1	1	4
	DA6	1	1	4
	DA8	0	1	0
	DA9	0	1	1
	Avg	**0.3333333**	**0.8333333**	**1.6666667**
DOUGLAS FIR	DF2	4	4	x
	DF3	4	4	x
	DF4	4	x	x
	DF7	4	4	x
	DF8	4	4	x
	DF10	4	x	x
	Avg	**4**	**4**	x
EKKI	E2	0	0	0
	E4	0	0	0
	E6	0	0	0
	E7	0	x	x
	E8	0	0	0
	E10	0	0	0
	Avg	**0**	**0**	**0**

EVUESS	EV1	0	0	x	
	EV2	0	0		1
	EV3	0	0		0
	EV4	0	0	x	
	EV6	0	0		0
	EV9	0	0		1
	Avg	**0**	**0**		**0.5**
GARAPA	GA1	0	0		0
	GA2	0	0		1
	GA4	0	0		0
	GA5	0	0		0
	GA9	0	0		0
	GA10	1	0	x	
	Avg	**0.1666667**	**0**		**0.2**
GREENHEART	GH1	0	0		0
	GH3	0	0		0
	GH5	0	0		0
	GH6	0	0		0
	GH8	0	0		0
	GH9	0	0		0
	Avg	**0**	**0**		**0**
KARRI	KA2	3	4	x	
	KA4	4	4	x	
	KA7	3	4	x	
	KA8	4	4	x	
	KA9	4	4	x	
	KA10	4	4	x	
	Avg	**3.6666667**	**4**	**x**	
MASSARANDUBA	MA1	0	0		1
	MA2	0	0	x	
	MA4	0	0		1
	MA5	0	0	x	
	MA8	1	1	x	
	MA9	0	0	x	
	Avg	**0.1666667**	**0.1666667**		**1**

MORA	MO2	1	4	x
	MO3	1	4	x
	MO4	1	4	4
	MO6	1	4	x
	MO7	1	4	4
	MO10	1	4	4
	Avg	**1**	**4**	**4**
MUKULUNGU	MU1	0	0	2
	MU2	0	0	3
	MU4	0	1	1
	MU6	0	0	1
	MU7	0	1	2
	MU8	0	0	2
	Avg	**0**	**0.3333333**	**1.8333333**
NIOVE	NI2	0	2	4
	NI3	0	1	4
	NI4	0	1	3
	NI8	0	2	x
	NI9	0	1	4
	NI10	0	1	4
	Avg	**0**	**1.3333333**	**3.8**
OKAN	OK1	0	0	x
	OK2	0	0	0
	OK3	0	0	0
	OK5	0	0	0
	OK7	0	0	x
	OK8	0	0	0
	Avg	**0**	**0**	**0**
OPEPE	OP4	0	0	1
	OP5	0	0	1
	OP6	0	0	0
	OP7	0	0	0
	OP9	0	0	0
	OP10	0	1	0
	Avg	**0**	**0.1666667**	**0.3333333**

EUROPEAN REDWOOD	P1	4	x		x	
	P2	4	x		x	
	P3	4	x		x	
	P4	4	x		x	
	P5	4	x		x	
	P6	4	x		x	
	Avg	**4**	**x**		**x**	
PIQUIA	PI2	0		1	x	
	PI3	1		1		1
	PI5	0		0		0
	PI6	0		0	x	
	PI7	0		0		1
	PI10	0		1	x	
	Avg	**0.1666667**		**0.5**		**0.6666667**
PURPLEHEART	PU1	2		4		4
	PU2	4		4	x	
	PU3	3		4		4
	PU4	4		4		4
	PU6	2		4		4
	PU9	2		4	x	
	Avg	**2.8333333**		**4**		**4**
SAPUCAIA	SA1	0		0		1
	SA3	0		0	x	
	SA4	1		0		0
	SA6	0		0		0
	SA7	0		0		0
	SA8	0		0		0
	Avg	**0.1666667**		**0**		**0.2**
SOUGE	SO1	0		0		1
	SO2	0		0		1
	SO3	1		0		1
	SO6	0		0		0
	SO7	0		0		0
	SO10	0		0		1
	Avg	**0.1666667**		**0**		**0.6666667**

TALI	TA1	0	0	x	
	TA3	0	0		0
	TA5	1	0		0
	TA7	0	0	x	
	TA8	0	0		0
	TA10	0	0		0
	Avg	**0.1666667**	**0**		**0**
TIMBORANA	TI1	0	1		1
	T13	0	0		0
	TI6	0	0		0
	TI8	0	0	x	
	T19	0	0		0
	TI10	0	0		0
	Avg	**0**	**0.1666667**		**0.2**
TATJUBA	TJ1	0	0		1
	TJ3	0			2
	TJ4	0	1		4
	TJ5	0	1		4
	TJ6	0			3
	TJ10	0	0		2
	Avg	**0**	**0.5**		**2.6666667**

Exposure to *Limnoria* spp.

x denotes missing sample

		ASSESSMENT DATE			
Timber	CODE	Oct-08	Mar-09		Sep-09
OAK	*AL1*	0	3	x	
	AL2	0	2	x	
	AL4	0	2	x	
	AL7	0	2	x	
	AL9	0	2	x	
	AL10	0	2	x	
	Avg	**0**	**2.1666667**	**x**	
ANGELIM VERMELHO	*AV1*	0	0		0
	AV2	0	0		0
	AV6	0	0		0
	AV7	0	0		0
	AV8	0	0		0
	AV9	0	0		0
	Avg	**0**	**0**		**0**
BASRALOCUS	*BA3*	0	0	x	
	BA4	0	0		0
	BA5	0	0	x	
	BA6	0	0		0
	BA8	0	0		1
	BA9	0	0		0
	Avg	**0**	**0**		**0.25**
BILINGA	*BI1*	0	0		0
	BI2	0	0	x	
	BI4	0	0		0
	BI6	0	0	x	
	BI9	0	0		0
	BI10	0	0		0
	Avg	**0**	**0**		**0**
YELLOW BALAU	BU1	0	0	x	
	BU2	0	0		0
	BU5	0	0		0
	BU6	0	0		0
	BU7	0	0	x	
	BU10	0	0		0
	Avg	**0**	**0**		**0**

CLOEZIANA	*CL3*	0		0		0
	CL4	0		0		1
	CL5	0		0		0
	CL6	0		0		0
	CL9	0		0		1
	CL10	0		0		0
	Avg	**0**		**0**		**0.3333333**
CUPUIBA	*CU2*	0		0		0
	CU3	0		0		0
	CU4	0		0		0
	CU7	0		0		0
	CU8	0		0		0
	CU9	0		0		0
	Avg	**0**		**0**		**0**
DABEMA	*DA3*	0		0		0
	DA4	0		0		0
	DA5	0		0		1
	DA6	0		0		1
	DA8	0		0		1
	DA9	0		0		0
	Avg	**0**		**0**		**0.5**
DOUGLAS FIR	DF2	3		4	x	
	DF3	3		4	x	
	DF4	2	x		x	
	DF7	1		4	x	
	DF8	1		4	x	
	DF10	1	x		x	
	Avg	**1.8333333**		**4**	**x**	
EKKI	E2	0		0		0
	E4	0		0		0
	E6	0		0		0
	E7	0	x		x	
	E8	0		0		0
	E10	0		0		0
	Avg	**0**		**0**		**0**

EVUESS	EV1	0	0	x
	EV2	0	0	0
	EV3	0	0	0
	EV4	0	0	x
	EV6	0	0	0
	EV9	0	0	0
	Avg	**0**	**0**	**0**
GARUPA	GA1	0	0	0
	GA2	0	0	0
	GA4	0	0	0
	GA5	0	0	0
	GA9	0	0	0
	GA10	0	0	x
	Avg	**0**	**0**	**0**
GREENHEART	GH1	0	0	0
	GH3	0	0	0
	GH5	0	0	0
	GH6	0	0	0
	GH8	0	0	1
	GH9	0	0	0
	Avg	**0**	**0**	**0.1666667**
KARRI	KA2	0	2	x
	KA4	0	2	x
	KA7	2	3	x
	KA8	0	2	x
	KA9	1	1	x
	KA10	0	1	x
	Avg	0.5	1.8333333	x
MASSARANDUBA	MA1	0	0	0
	MA2	0	0	x
	MA4	0	0	0
	MA5	0	0	x
	MA8	0	0	x
	MA9	0	0	x
	Avg	**0**	**0**	**0**

MORA	MO2	0	0	x	
	MO3	0	0	x	
	MO4	0	0		1
	MO6	0	0	x	
	MO8	0	0		0
	MO10	0	0		1
	Avg				**0.6666667**
MUKULUNGU	MU1	0	0		0
	MU2	0	0		1
	MU4	0	0		0
	MU6	0	0		0
	MU7	0	0		1
	MU8	0	0		1
	Avg	**0**	**0**		**0.5**
NIOVE	NI2	0	0		1
	NI3	0	0		0
	NI4	0	0		0
	NI8	0	0	x	
	NI9	0	0		0
	NI10	0	0		0
	Avg	**0**	**0**		**0.2**
OKAN	OK1	0	0	x	
	OK2	0	0		0
	OK3	0	0		0
	OK5	0	0		0
	OK7	0	0	x	
	OK8	0	0		0
	Avg	**0**	**0**		**0**
OPEPE	OP4	0	0		0
	OP5	0	0		0
	OP6	0	0		0
	OP7	0	0		0
	OP9	0	0		0
	OP10	0	0		0
	Avg	**0**	**0**		**0**

EUROPEAN REDWOOD	P1	1	x		x	
	P2	1	x		x	
	P3	1	x		x	
	P4	2	x		x	
	P5	2	x		x	
	P6	1	x		x	
	Avg	**1.3333333**	**x**		**x**	
PIQUIA	PI2	0		0	x	
	PI3	0		0		0
	PI5	0		0		0
	PI6	0		0	x	
	PI7	0		0		0
	PI10	0		0	x	
	Avg	**0**		**0**		**0**
PURPLEHEART	PU1	0		0		2
	PU2	0		0	x	
	PU3	0		0		1
	PU5	0		0		0
	PU6	0		0		3
	PU9	0		0	x	
	Avg	**0**		**0**		**1.5**
SAPUCAIA	SA1	0		0		0
	SA3	0		0	x	
	SA4	0		0		0
	SA6	0		0		0
	SA7	0		0		0
	SA8	0		0		0
	Avg	**0**		**0**		**0**
SOUGE	SO1	0		0		0
	SO2	0		0		0
	SO3	0		0		0
	SO6	0		0		0
	SO7	0		0		0
	SO10	0		0		0
	Avg	**0**		**0**		**0**

TALI	TA1	0	0	x	
	TA3	0	0		1
	TA5	0	0		0
	TA7	0	0	x	
	TA8	0	0		0
	TA10	0	0		0
	Avg	**0**	**0**		**0.25**
TIMBORANA	TI1	0	0		0
	T13	0	0	x	
	TI6	0	0		0
	TI8	0	0	x	
	T19	0	0		0
	TI10	0	0		0
	Avg	**0**	**0**		**0**
TATJUBA	TJ1	0	0		0
	TJ3	0	0		0
	TJ4	0	0		0
	TJ5	0	0		0
	TJ6	0	0		3
	TJ10	0	0		2
	Avg	**0**	**0**		**0.8333333**

APPENDIX V

Strength test programme data and protocols

For each species in this appendix there is the following set of tables and figures

- Table 1 - Summary data for bending strength $f_{m,12\%}$, bending stiffness $E_{m,12\%}$ and density $\rho_{12\%}$ at 12% moisture content, and moisture content at test ω_{test}
- Table 2 - Specimen grade, bending strength $f_{m,12\%}$, bending stiffness $E_{m,12\%}$ and density $\rho_{12\%}$ at 12% moisture content, and moisture content at test ω_{test}
- Figure 1 - Bending strength ranking
- Figure 2 - Bending strength vs bending stiffness
- Figure 3 - Bending strength vs moisture content
- Figure 4 - Bending stiffness vs moisture content

The subscript “12%” in the Appendices indicates that the corrections described in the section on moisture content have been made. The subscript “m” indicates that the property has been determined from a bending test. The subscript “test” indicates that no adjustment has been made

A1. Angelim Vermelho
A2. Cupiuba
A3. Eveuss
A4. Okan
A5. Tali
A6. EN 408 4-Point Bending Strength Test Procedure
A7. TP028 Four Point Bending Stiffness Test Procedure

A1. Angelim Vermelho

Table A1.1 – Angelim. Summary data for bending strength $f_{m,12\%}$, bending stiffness $E_{m,12\%}$ and density $\rho_{12\%}$ at 12% moisture content, and moisture content at test ω_{test}

Angelim Vermelho		$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
HS Grade	mean	90.1	19265	1082	20.9%
	min	39.8	11302	970	14.1%
	max	128.8	26972	1203	35.9%
	standard deviation (SD)	18.5	2783	42	3.4%
	percentile (EN384 stiffness)	5%	22084	5%	-
	rank (or other factor)	7.35	0.84	70.0	-
	percentile value	60.4	18551	1012	-
	valid test count	147	151	as $E_{m,12\%}$	as $E_{m,12\%}$
	HS Grade count	153	153	-	-
	"No Data" count	6	2	-	-
Reject Grade	mean	50.7	13504	1077	22.2%
	min	36.1	11420	1045	17.6%
	max	86.2	17228	1110	25.3%
	standard deviation (SD)	16.8	2248	31	2.8%
	valid test count	7	7	as $E_{m,12\%}$	as $E_{m,12\%}$
	Reject Grade count	7	7	-	-
	"No Data" count	0	0	-	-

Table A1.2 – Angelim. Specimen grade, bending strength $f_{m,12\%}$, bending stiffness $E_{m,12\%}$ and density $\rho_{12\%}$ at 12% moisture content, and moisture content at test ω_{test}

Angelim Vermelho	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
AN1	HS	119.8	22191	1080	19.1%
AN2	HS	83.8	17681	1084	22.4%
AN3	HS	82.3	16909	1020	19.5%
AN4	HS	81.5	16490	1073	25.8%
AN5	HS	70.8	15657	1045	22.0%
AN6	HS	117.0	21892	1101	21.9%
AN7	HS	84.0	20022	1052	25.1%
AN8	HS	No Data	15045	1057	23.4%
AN9	HS	79.3	18955	1079	31.4%
AN10	HS	71.7	13974	1050	21.6%
AN11	HS	100.9	22321	1094	26.8%
AN12	HS	76.9	15482	1105	18.9%
AN13	HS	116.5	20770	1090	19.6%
AN14	HS	128.8	22257	1141	14.6%
AN15	HS	103.2	21801	1109	18.9%
AN16	HS	101.4	23776	1122	14.9%
AN17	HS	97.3	20922	1154	17.2%
AN18	HS	62.5	15230	1066	18.8%
AN19	HS	96.2	18384	1094	20.1%
AN20	HS	84.2	23430	1174	27.3%
AN21	HS	97.4	21379	1091	32.8%
AN22	HS	No Data	19800	1135	29.1%
AN23	HS	97.9	20486	1143	20.5%

Angelim Vermelho	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
AN24	HS	124.9	23050	1148	16.2%
AN25	HS	114.9	21224	1170	14.6%
AN26	HS	61.7	20041	1152	19.5%
AN27	HS	113.0	21788	1148	18.0%
AN28	HS	65.3	17112	1076	16.8%
AN29	HS	95.0	19022	1013	21.2%
AN30	HS	93.5	21432	1133	20.1%
AN31	HS	88.3	20100	1034	23.0%
AN32	HS	109.0	22177	1150	19.0%
AN33	HS	104.1	19287	1131	17.6%
AN34	HS	60.8	16123	1097	17.6%
AN35	HS	113.5	20758	1097	21.0%
AN36	HS	76.2	20106	1203	19.0%
AN37	HS	96.5	17390	1191	17.2%
AN38	HS	114.5	23446	1162	19.6%
AN39	HS	70.7	16273	1062	16.2%
AN40	HS	105.8	22008	1142	17.6%
AN41	HS	109.3	21678	1131	22.2%
AN42	HS	66.9	16943	1090	18.3%
AN43	HS	63.8	17184	1083	19.2%
AN44	HS	59.3	13901	1116	20.8%
AN45	HS	88.8	19900	1186	21.4%
AN46	HS	83.1	21033	1152	16.8%
AN47	HS	102.2	20517	1124	19.6%
AN48	HS	99.2	23452	1132	19.2%
AN49	HS	104.6	20020	1127	16.1%
AN50	HS	110.4	21085	1055	20.0%
AN51	HS	103.0	19461	1120	19.8%
AN52	HS	96.1	21922	1101	20.8%
AN53	HS	123.3	23376	1112	17.6%
AN54	HS	97.1	23517	1119	19.1%
AN55	HS	117.3	22446	1108	17.5%
AN56	HS	69.0	17534	1057	18.7%
AN57	Reject	48.9	15963	1109	17.6%
AN58	HS	88.1	17855	1134	14.1%
AN59	HS	71.4	16351	1055	24.8%
AN60	HS	72.9	17533	1088	21.2%
AN61	HS	52.4	12579	1081	21.7%
AN62	HS	95.3	18924	1101	18.6%
AN63	HS	73.4	14165	1098	14.6%
AN64	HS	39.8	15881	1081	17.4%
AN65	HS	81.1	14964	1060	21.8%
AN66	HS	112.4	24192	1115	20.9%
AN67	HS	67.0	13310	1023	20.2%
AN68	HS	95.1	18054	1067	20.2%
AN69	HS	80.9	18800	1064	19.5%
AN70	HS	117.1	23443	1088	20.8%
AN71	HS	84.1	18912	1085	20.5%
AN72	HS	85.6	19358	1030	21.8%
AN73	HS	104.5	21997	1028	24.6%
AN74	HS	82.6	20600	1052	24.4%

Angelim Vermelho	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
AN75	HS	81.6	19420	1023	28.2%
AN76	HS	No Data	23995	1045	28.2%
AN77	HS	82.9	19511	1022	26.5%
AN78	HS	101.0	21047	1076	25.1%
AN79	HS	90.3	20553	1050	21.6%
AN80	HS	86.6	20439	1048	25.7%
AN81	HS	87.8	18340	1045	25.7%
AN82	HS	82.7	17034	1028	22.3%
AN83	HS	108.1	20981	1056	25.3%
AN84	HS	61.7	15896	1056	25.5%
AN85	HS	75.8	17442	1014	21.7%
AN86	HS	122.4	22132	1078	23.0%
AN87	HS	77.7	18648	1054	23.6%
AN88	HS	103.1	21258	1087	25.3%
AN89	HS	99.8	21819	1045	18.1%
AN90	HS	94.0	25907	1041	18.8%
AN91	HS	93.3	17851	1035	17.8%
AN92	HS	102.8	21196	1098	17.2%
AN93	HS	65.1	16523	1059	21.2%
AN94	HS	86.3	19418	1056	20.9%
AN95	HS	107.1	19851	1098	18.8%
AN96	HS	85.4	20396	1068	17.8%
AN97	HS	94.8	19461	1148	18.7%
AN98	HS	64.0	20614	1091	18.7%
AN99	HS	116.3	19775	1102	17.8%
AN100	HS	59.9	18220	1067	19.0%
AN101	HS	106.0	19071	1081	19.0%
AN102	HS	99.3	20155	1097	18.9%
AN103	HS	114.4	21532	1060	17.2%
AN104	HS	89.6	17621	1084	19.8%
AN105	HS	121.2	20587	1070	21.7%
AN106	HS	94.3	18139	1097	20.6%
AN107	HS	71.7	18989	1109	22.6%
AN108	HS	76.3	18767	1041	20.0%
AN109	HS	85.7	20714	1018	19.8%
AN110	HS	98.2	19976	1009	19.6%
AN111	HS	No Data	No Data	No Data	No Data
AN112	HS	60.2	13297	1015	20.0%
AN113	HS	57.9	11302	1097	18.2%
AN114	HS	94.4	20672	1060	17.8%
AN115	HS	101.4	18588	1113	22.0%
AN116	HS	104.4	23752	970	35.9%
AN117	HS	90.2	20130	1019	23.6%
AN118	HS	103.0	20609	1078	21.7%
AN119	HS	102.4	18329	991	20.2%
AN120	HS	67.0	16381	1063	23.8%
AN121	HS	120.3	26972	1104	22.1%
AN122	Reject	37.8	11420	1045	22.3%
AN123	HS	64.7	14163	1038	24.5%
AN124	HS	92.5	20316	1111	18.8%
AN125	HS	71.1	18344	1105	18.7%

Angelim Vermelho	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
AN126	HS	82.1	17564	1041	19.5%
AN127	HS	88.0	19137	1092	23.7%
AN128	HS	51.8	24002	1055	19.8%
AN129	HS	122.7	23955	1086	19.1%
AN130	HS	83.0	17212	1045	23.4%
AN131	HS	120.1	21293	1117	21.4%
AN132	HS	No Data	19010	1074	21.6%
AN133	HS	84.1	16426	1079	19.8%
AN134	HS	76.3	18148	1032	21.2%
AN135	HS	101.6	17809	1099	19.6%
AN136	HS	84.7	16519	1026	21.5%
AN137	HS	73.3	16177	1090	25.4%
AN138	HS	63.4	13665	1054	20.4%
AN139	HS	69.3	20118	1079	23.1%
AN140	HS	67.9	16427	1079	18.9%
AN141	HS	102.0	18754	1123	21.5%
AN142	HS	84.3	14518	1057	23.6%
AN143	HS	83.0	18526	1051	21.4%
AN144	HS	86.4	19693	1099	23.3%
AN145	HS	105.8	18795	1052	20.5%
AN146	HS	100.5	17378	1042	20.8%
AN147	HS	70.0	15900	1085	21.4%
AN148	Reject	86.2	17228	1062	22.9%
AN149	HS	79.6	17177	1033	19.2%
AN150	HS	83.5	18568	1057	22.5%
AN151	HS	79.4	18170	1106	17.8%
AN152	HS	121.3	19278	1105	17.1%
AN153	Reject	44.4	12547	1056	25.3%
AN154	HS	100.9	19738	1085	20.8%
AN155	HS	113.2	20549	1136	21.5%
AN156	Reject	51.9	12268	1110	23.6%
AN157	HS	99.8	21253	1017	19.6%
AN158	Reject	49.5	11601	1110	19.3%
AN159	HS	No Data	No Data	No Data	No Data
AN160	Reject	36.1	13504	1049	24.4%

Figure A1 – Angelim Vermelho graphs

Figure A1.1:
Bending strength ranking

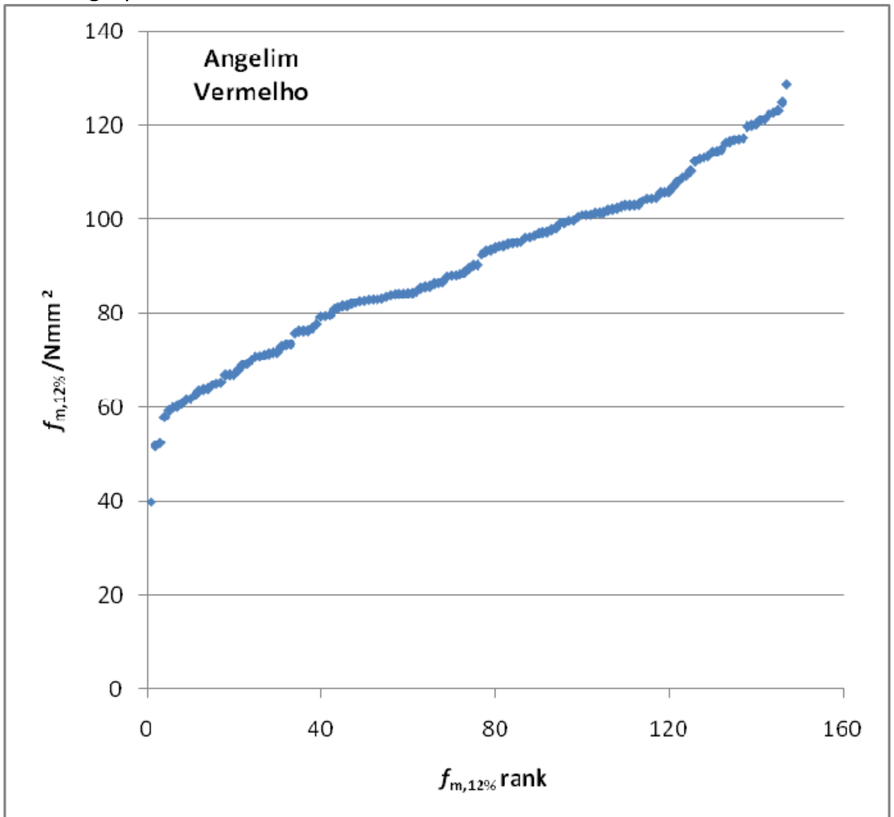


Figure A1.2:
Bending strength vs bending stiffness

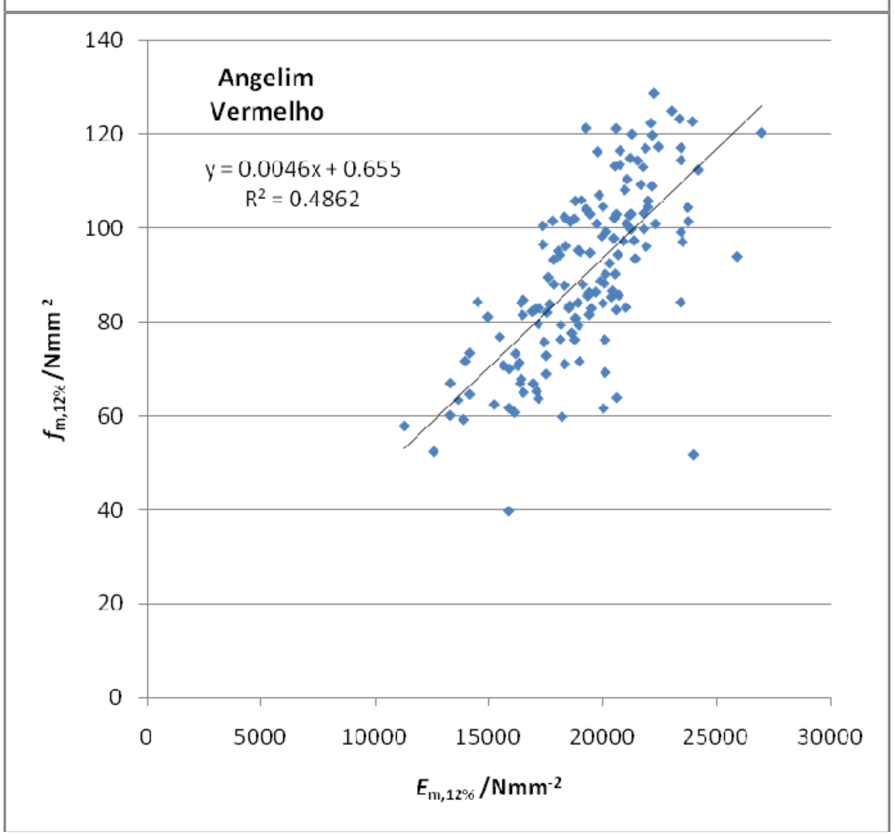


Figure A1.3:
Bending strength vs moisture content

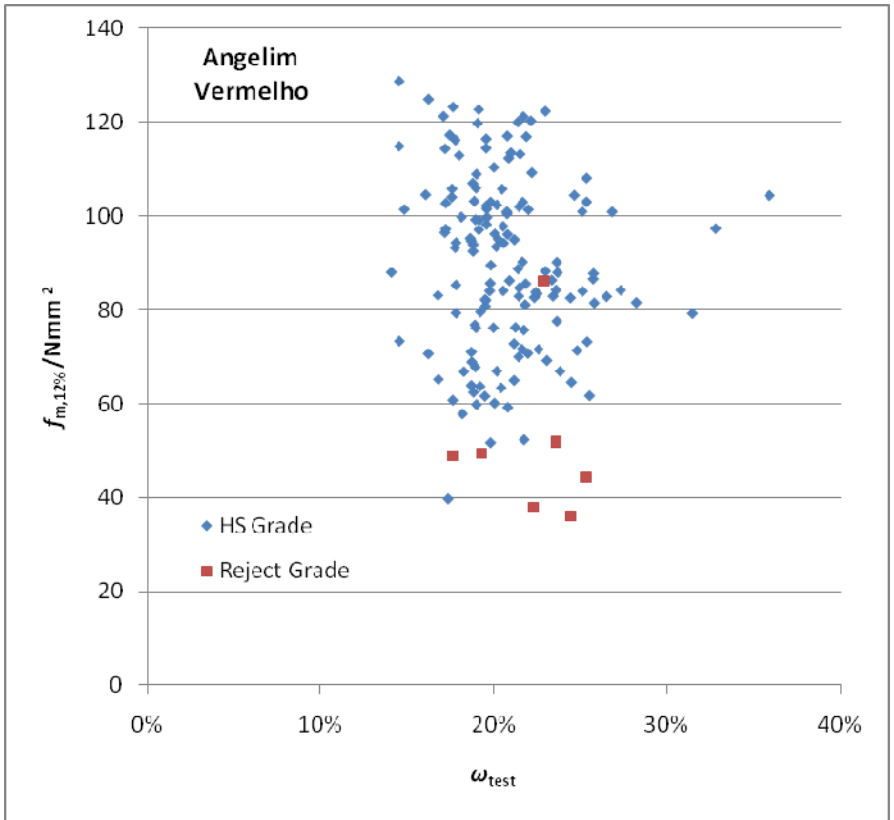
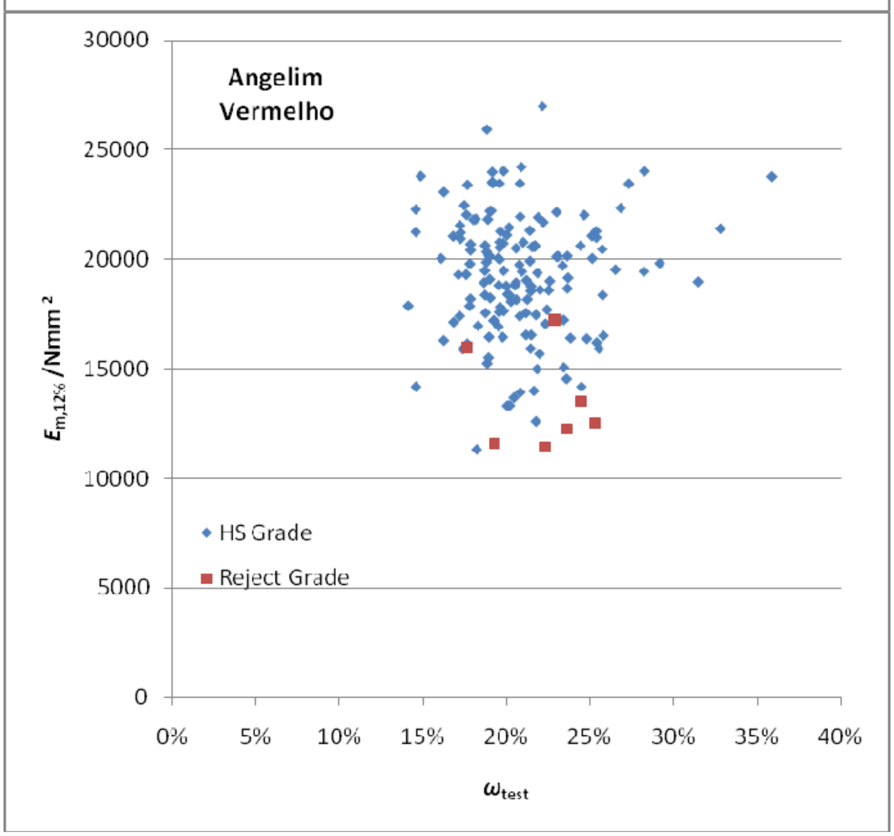


Figure A1.4:
Bending stiffness vs moisture content



A2. Cupiuba

Table A2.1 –Cupiuba. Summary data for bending strength $f_{m,12\%}$, bending stiffness $E_{m,12\%}$ and density $\rho_{12\%}$ at 12% moisture content, and moisture content at test ω_{test}

Cupiuba		$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
HS Grade	mean	75.2	18749	822	29.9%
	min	34.8	10774	591	14.4%
	max	109.2	26993	1029	59.2%
	standard deviation (SD)	15.6	2869	56	9.0%
	percentile (EN384 stiffness)	5%	21414	5%	-
	rank (or other factor)	6.45	0.84	93.1	-
	percentile value	53.1	17987	729	-
	valid test count	129	135	as $E_{m,12\%}$	as $E_{m,12\%}$
	HS Grade count	139	139	-	-
	"No Data" count	10	4	-	-
Reject Grade	mean	43.9	16088	854	26.6%
	min	19.2	8757	714	18.5%
	max	98.7	22454	953	42.1%
	standard deviation (SD)	21.1	3451	59	8.0%
	valid test count	14	14	as $E_{m,12\%}$	as $E_{m,12\%}$
	Reject Grade count	19	19	-	-
	"No Data" count	5	5	-	-

Table A2.2 –Cupiuba. Specimen grade, bending strength $f_{m,12\%}$, bending stiffness $E_{m,12\%}$ and density $\rho_{12\%}$ at 12% moisture content, and moisture content at test ω_{test}

Cupiuba	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
CU01	HS	58.8	14889	826	43.0%
CU02	HS	77.5	17322	784	17.2%
CU03	HS	78.7	17379	944	28.4%
CU04	HS	99.8	18710	773	41.9%
CU05	HS	74.1	16962	803	47.0%
CU06	HS	80.8	17820	775	19.4%
CU07	HS	68.9	21805	816	30.0%
CU08	HS	96.6	16265	808	37.4%
CU09	HS	56.9	15620	826	29.9%
CU10	HS	64.0	17555	897	32.9%
CU11	Reject	24.9	17110	921	23.3%
CU12	HS	72.8	15989	814	33.6%
CU13	HS	58.9	16700	929	29.7%
CU14	HS	81.1	17570	733	32.9%
CU15	Reject	44.3	12982	910	42.1%
CU16	HS	62.7	16731	1029	31.8%
CU17	Reject	45.7	18076	953	38.4%
CU18	Reject	No Data	No Data	No Data	No Data
CU19	Reject	19.2	No Data	No Data	No Data
CU20	HS	60.3	15859	959	36.4%
CU21	HS	83.5	17484	809	26.3%
CU22	Reject	74.4	15648	878	28.2%
CU23	HS	No Data	22480	915	19.3%

Cupiuba	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
CU24	Reject	98.7	22454	848	40.0%
CU25	HS	60.2	18963	836	39.0%
CU26	HS	63.3	13926	748	17.5%
CU27	HS	66.0	18041	885	27.0%
CU28	Reject	43.0	16712	837	25.7%
CU29	HS	72.1	15862	872	37.9%
CU30	HS	83.7	18992	788	42.3%
CU31	Reject	No Data	No Data	No Data	No Data
CU32	Reject	25.6	No Data	No Data	No Data
CU33	HS	75.3	20292	796	19.1%
CU34	HS	78.2	24111	845	31.9%
CU35	HS	87.9	23578	826	33.9%
CU36	HS	64.8	18953	864	33.2%
CU37	HS	88.1	20504	799	39.8%
CU38	HS	63.8	16048	806	32.2%
CU39	HS	No Data	No Data	No Data	No Data
CU40	HS	No Data	No Data	No Data	No Data
CU41	HS	80.9	21018	858	27.6%
CU42	HS	72.2	19149	877	30.5%
CU43	HS	No Data	19684	840	46.7%
CU44	Reject	28.4	15826	819	20.2%
CU45	HS	69.4	14228	857	29.9%
CU46	HS	71.6	20518	807	35.0%
CU47	HS	80.5	19645	778	28.6%
CU48	HS	64.9	22449	791	26.7%
CU49	HS	61.1	19537	852	33.9%
CU50	HS	75.8	20078	926	38.8%
CU51	HS	65.3	17138	814	20.4%
CU52	Reject	36.4	13177	865	23.6%
CU53	HS	85.4	20786	813	20.8%
CU54	Reject	42.1	8757	791	18.5%
CU55	HS	65.5	18951	763	19.5%
CU56	Reject	No Data	12643	880	20.2%
CU57	HS	No Data	No Data	No Data	No Data
CU58	HS	91.4	22753	808	23.7%
CU59	HS	90.9	19704	839	18.8%
CU60	HS	56.9	19119	795	18.1%
CU61	HS	54.9	16460	863	16.0%
CU62	HS	75.9	20889	812	26.0%
CU63	HS	69.7	17057	843	26.4%
CU64	Reject	45.2	15508	714	24.0%
CU65	HS	55.6	13700	812	14.4%
CU66	HS	79.8	19579	879	33.1%
CU67	Reject	53.9	18404	868	29.0%
CU68	HS	74.5	17335	799	16.1%
CU69	HS	102.3	21325	862	18.7%
CU70	HS	63.9	17013	856	31.8%
CU71	HS	54.4	15175	813	34.5%
CU72	HS	67.3	16207	799	18.4%
CU73	HS	No Data	No Data	No Data	No Data
CU74	Reject	32.7	17825	816	19.3%

Cupiuba	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
CU75	HS	73.8	21949	902	29.9%
CU76	HS	42.5	16983	809	28.6%
CU77	HS	67.3	18938	764	22.8%
CU78	HS	83.1	18521	764	18.0%
CU79	HS	No Data	14189	827	17.0%
CU80	HS	55.3	15661	833	35.9%
CU81	HS	52.5	13329	766	16.5%
CU82	HS	77.5	20169	726	20.8%
CU83	HS	71.3	16369	729	24.4%
CU84	HS	63.0	18896	796	39.0%
CU85	HS	64.1	19746	776	25.3%
CU86	HS	35.4	23044	834	23.8%
CU87	HS	60.6	16275	756	16.4%
CU88	HS	No Data	14002	829	27.5%
CU89	HS	70.8	17595	760	18.0%
CU90	HS	86.2	20644	821	31.4%
CU91	HS	58.2	15616	759	30.2%
CU92	HS	84.2	23177	808	19.8%
CU93	HS	58.9	20174	862	22.6%
CU94	HS	93.3	25687	796	49.1%
CU95	HS	No Data	26580	819	28.0%
CU96	HS	71.8	16434	709	18.1%
CU97	HS	89.7	26176	912	32.5%
CU98	HS	53.6	20819	775	38.9%
CU99	HS	75.1	20842	810	28.6%
CU100	Reject	No Data	No Data	No Data	No Data
CU101	HS	109.2	21582	801	42.4%
CU102	HS	57.1	16842	780	23.5%
CU103	HS	No Data	18906	741	38.7%
CU104	HS	100.4	26993	889	29.8%
CU105	HS	97.3	22484	881	34.8%
CU106	HS	83.1	18987	859	29.6%
CU107	HS	81.0	18327	933	35.3%
CU108	HS	62.4	14779	795	45.4%
CU109	HS	103.8	23483	856	32.5%
CU110	HS	81.4	17236	798	16.3%
CU111	HS	88.1	20650	892	32.6%
CU112	HS	56.1	13251	722	21.0%
CU113	HS	64.8	18594	777	43.3%
CU114	HS	34.8	18058	730	36.2%
CU115	HS	82.8	19568	786	40.3%
CU116	HS	61.1	18865	799	26.8%
CU117	HS	76.3	18110	840	19.5%
CU118	HS	69.1	16628	820	42.0%
CU119	HS	82.8	23758	916	34.0%
CU120	HS	80.7	19828	848	32.9%
CU121	HS	96.6	20277	834	19.5%
CU122	HS	101.0	21480	839	35.3%
CU123	HS	94.7	18506	800	28.2%
CU124	HS	92.7	18875	813	36.4%
CU125	HS	87.7	19235	804	44.7%

Cupiuba	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
CU126	HS	89.2	20540	829	40.6%
CU127	HS	69.5	16106	788	23.9%
CU128	HS	56.2	16132	794	19.1%
CU129	HS	70.5	17609	855	33.0%
CU130	HS	102.2	22039	817	29.0%
CU131	HS	82.6	19388	820	30.7%
CU132	HS	70.3	15130	811	27.9%
CU133	HS	102.5	19246	971	34.8%
CU134	Reject	No Data	20112	852	20.4%
CU135	HS	97.9	20234	843	43.5%
CU136	HS	73.0	18295	792	18.3%
CU137	HS	94.6	17183	821	17.7%
CU138	HS	76.6	16592	792	31.0%
CU139	HS	90.4	21251	870	16.4%
CU140	HS	74.3	18660	591	32.6%
CU141	HS	74.0	18119	836	29.6%
CU142	HS	68.1	19365	822	26.2%
CU143	HS	100.4	22712	883	39.0%
CU144	HS	68.0	18918	805	30.4%
CU145	HS	79.7	18247	915	19.2%
CU146	HS	69.5	17362	853	31.9%
CU147	HS	61.2	16570	837	24.9%
CU148	HS	84.2	15722	842	31.7%
CU149	HS	52.8	14184	805	33.8%
CU150	HS	98.4	22925	785	56.4%
CU151	HS	100.8	21167	810	31.8%
CU152	HS	96.0	19094	769	59.2%
CU153	HS	80.6	22491	816	28.7%
CU154	HS	104.7	19524	808	40.0%
CU155	HS	68.9	16263	769	24.3%
CU156	HS	42.7	10774	818	47.1%
CU157	HS	99.5	18141	854	35.9%
CU158	HS	62.9	18097	751	25.1%

Figure A2 – Cupiuba graphs

Figure A2.1:
Bending strength ranking

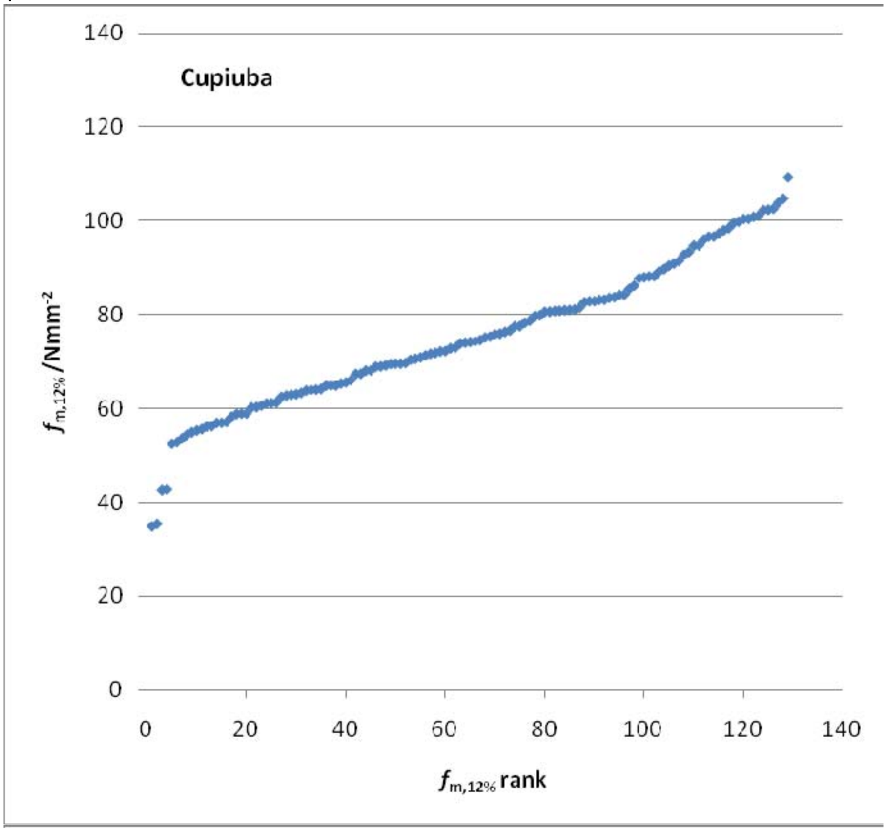


Figure A2.2:
Bending strength vs bending stiffness

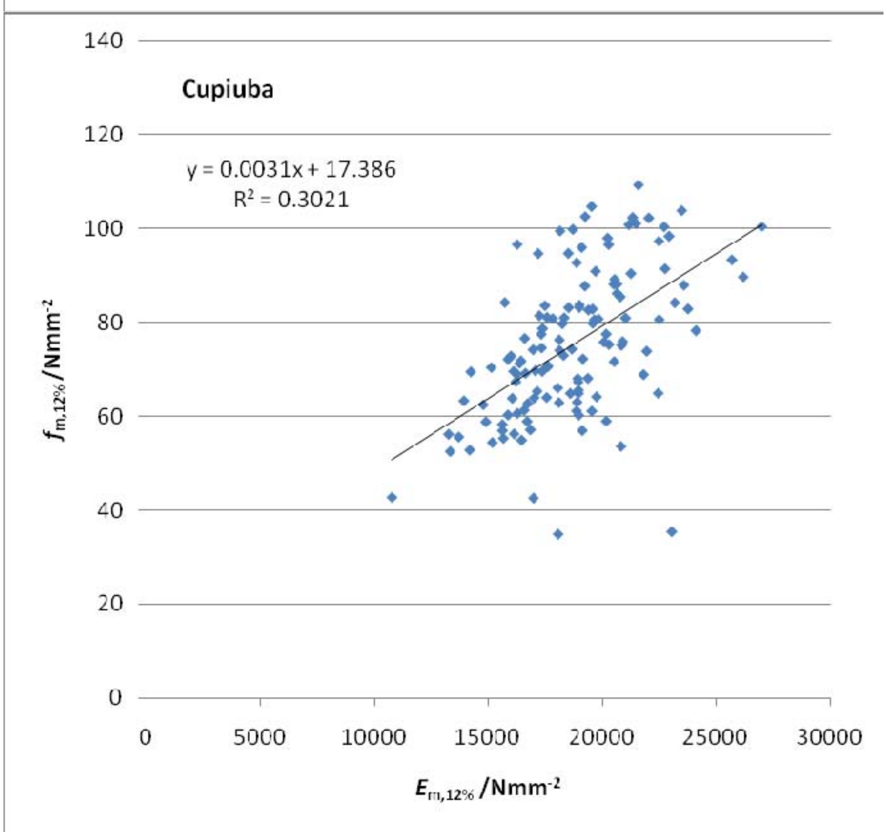


Figure A2.3:
Bending strength vs moisture content

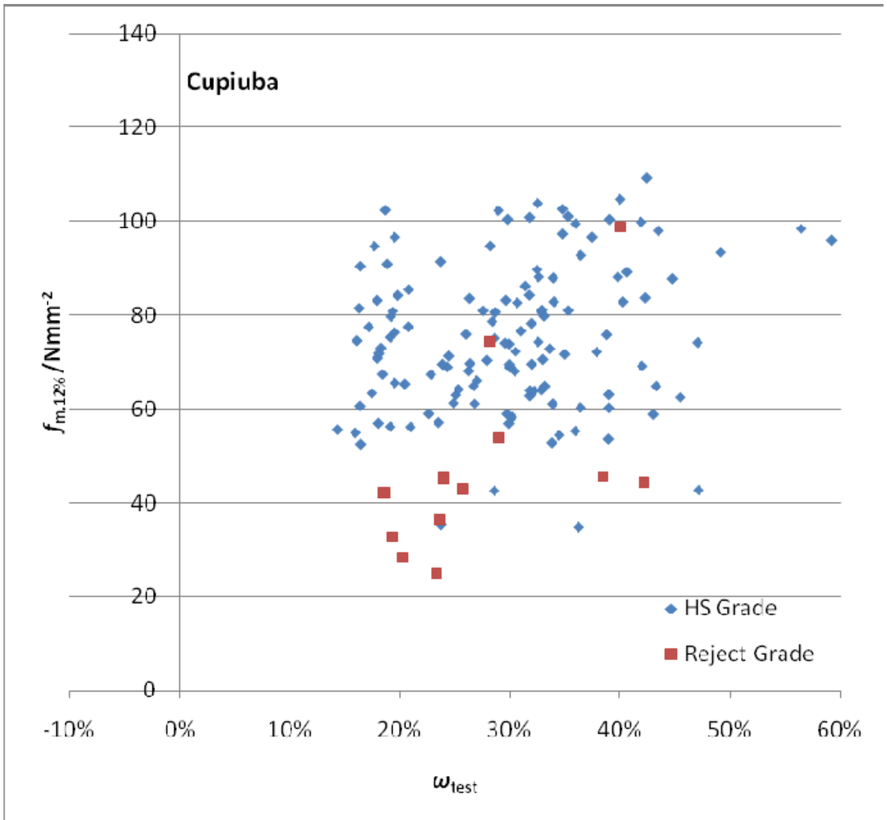
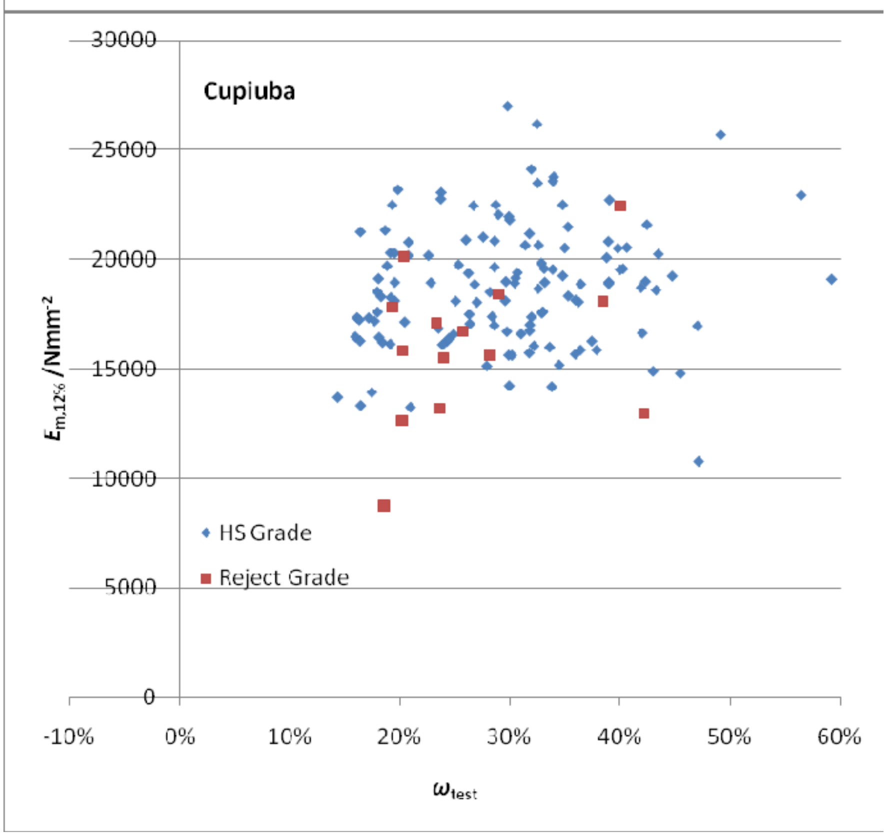


Figure A2.4:
Bending stiffness vs moisture content



A3. Eveuss

Table A3.1 –Eveuss. Summary data for bending strength $f_{m,12\%}$, bending stiffness $E_{m,12\%}$ and density $\rho_{12\%}$ at 12% moisture content, and moisture content at test ω_{test}

Eveuss		$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
HS Grade	mean	83.3	18429	1019	20.9%
	min	32.0	4999	896	17.0%
	max	124.0	27075	1064	28.5%
	standard deviation (SD)	19.0	3658	23	3.1%
	percentile (EN384 stiffness)	5%	20998	5%	-
	rank (or other factor)	7.50	0.84	37.9	-
	percentile value	51.0	17638	981	-
	valid test count	150	151	as $E_{m,12\%}$	as $E_{m,12\%}$
	HS Grade count	151	151	-	-
	"No Data" count	1	0	-	-
Reject Grade	mean	58.1	14769	1032	18.5%
	min	44.3	9111	1018	16.5%
	max	87.8	21802	1047	21.9%
	standard deviation (SD)	13.4	4192	11	1.6%
	valid test count	9	9	as $E_{m,12\%}$	as $E_{m,12\%}$
	Reject Grade count	9	9	-	-
	"No Data" count	0	0	-	-

Table A3.2 –Eveuss. Specimen grade, bending strength $f_{m,12\%}$, bending stiffness $E_{m,12\%}$ and density $\rho_{12\%}$ at 12% moisture content, and moisture content at test ω_{test}

Eveuss	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
EV1	HS	65.0	16345	1035	21.0%
EV2	HS	89.8	20360	1012	23.0%
EV3	HS	77.6	14693	1021	20.1%
EV4	HS	101.4	20628	997	28.1%
EV5	HS	75.5	16583	1003	20.3%
EV6	Reject	66.0	18835	1040	19.2%
EV7	HS	87.4	17728	1035	25.9%
EV8	HS	79.4	15639	1021	20.1%
EV9	HS	79.8	20471	1014	19.8%
EV10	HS	66.6	16317	1015	19.8%
EV11	HS	88.6	13720	1031	19.1%
EV12	HS	100.9	19830	1019	24.2%
EV13	HS	75.8	20995	1004	26.4%
EV14	HS	87.5	23891	1007	25.4%
EV15	HS	77.7	19031	1009	21.0%
EV16	HS	80.5	14092	1036	19.1%
EV17	HS	56.9	13115	1008	18.7%
EV18	HS	38.4	14129	1028	19.5%
EV19	HS	54.8	12283	1006	18.3%
EV20	HS	85.1	19689	1034	18.8%
EV21	HS	56.9	16802	1027	18.8%
EV22	HS	No Data	19194	1009	21.3%
EV23	HS	62.1	13388	1014	18.5%

Eveuss	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
EV24	Reject	87.8	21802	1020	21.9%
EV25	HS	74.8	13982	1032	20.3%
EV26	HS	77.9	14614	1032	19.2%
EV27	HS	88.3	17948	1019	20.1%
EV28	HS	79.4	12650	1026	18.9%
EV29	HS	65.4	17286	1015	18.9%
EV30	HS	93.4	20034	1016	21.8%
EV31	HS	103.7	21248	1009	19.6%
EV32	HS	108.6	20605	1022	19.2%
EV33	HS	102.8	21259	1013	25.8%
EV34	HS	80.1	16510	1033	19.1%
EV35	HS	91.8	20617	1010	19.8%
EV36	HS	102.5	20478	1060	28.5%
EV37	HS	97.5	22679	964	24.0%
EV38	HS	102.2	19875	1003	27.8%
EV39	HS	112.6	25693	1021	25.7%
EV40	Reject	65.7	18452	1022	19.1%
EV41	HS	110.9	25825	1010	21.7%
EV42	HS	124.0	27075	1009	26.4%
EV43	HS	98.0	22590	1025	22.2%
EV44	HS	90.6	21879	1021	26.2%
EV45	HS	108.6	26490	991	26.3%
EV46	HS	88.9	14609	1022	20.4%
EV47	HS	85.7	22025	1008	26.3%
EV48	HS	92.2	20420	1033	20.1%
EV49	HS	94.2	14592	1010	19.7%
EV50	HS	96.6	20354	995	27.4%
EV51	HS	62.1	18364	1019	20.1%
EV52	HS	98.0	23007	1020	27.3%
EV53	HS	61.1	16822	1023	19.8%
EV54	HS	100.0	23819	1016	26.1%
EV55	HS	101.3	21970	1043	27.4%
EV56	HS	87.8	17699	1016	18.7%
EV57	HS	90.2	18791	1028	23.4%
EV58	HS	64.3	16422	1032	18.9%
EV59	HS	88.3	23244	951	24.2%
EV60	HS	60.9	15053	1049	18.8%
EV61	HS	106.5	22885	1029	19.5%
EV62	HS	110.6	21614	1032	23.6%
EV63	HS	119.3	23682	972	19.5%
EV64	HS	114.0	24806	1031	25.4%
EV65	HS	80.1	17762	1034	18.8%
EV66	HS	80.4	18257	1030	19.3%
EV67	HS	91.5	20975	1016	23.7%
EV68	HS	93.0	19800	1011	24.9%
EV69	HS	90.5	19588	1034	18.7%
EV70	HS	63.8	18799	1014	19.8%
EV71	HS	90.4	23692	1029	26.2%
EV72	HS	119.0	25299	970	20.9%
EV73	HS	84.9	19110	1034	19.4%
EV74	HS	64.6	14861	1051	19.1%

Eveuss	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
EV75	HS	81.2	18538	1011	18.2%
EV76	HS	101.7	21815	1034	26.9%
EV77	HS	65.1	16146	1038	18.1%
EV78	HS	50.9	11933	1044	18.3%
EV79	HS	87.7	19396	1013	24.1%
EV80	HS	113.9	22764	967	20.3%
EV81	HS	54.7	12827	1014	18.8%
EV82	HS	53.7	17749	1024	18.7%
EV83	HS	98.1	20722	1009	18.2%
EV84	HS	74.8	18453	1025	19.9%
EV85	HS	83.9	17010	1009	20.5%
EV86	HS	79.1	16480	1035	18.3%
EV87	HS	105.0	22261	975	27.4%
EV88	HS	32.2	4999	1044	18.8%
EV89	HS	57.5	14490	1020	19.7%
EV90	HS	104.5	22629	1002	25.7%
EV91	HS	75.4	20408	1013	24.3%
EV92	HS	115.4	22388	999	25.8%
EV93	Reject	48.6	12894	1039	19.2%
EV94	HS	112.8	23101	1020	25.4%
EV95	HS	73.6	16503	1056	17.9%
EV96	HS	72.2	15061	1037	17.8%
EV97	HS	96.1	23556	951	18.0%
EV98	HS	111.3	24298	981	20.9%
EV99	HS	94.5	21433	975	23.2%
EV100	HS	32.0	16007	1042	17.9%
EV101	HS	94.9	20475	1019	22.2%
EV102	HS	93.0	20538	1046	17.8%
EV103	HS	105.1	20576	989	23.0%
EV104	HS	79.4	17283	1034	18.1%
EV105	HS	84.1	16938	1040	18.5%
EV106	HS	109.4	21325	971	19.0%
EV107	HS	80.8	20039	1017	20.3%
EV108	HS	104.8	22604	976	22.2%
EV109	HS	74.6	15238	1011	18.2%
EV110	HS	52.1	13313	1033	17.3%
EV111	HS	63.2	13805	1058	18.4%
EV112	HS	77.0	16475	1037	17.6%
EV113	Reject	57.8	15865	1045	17.8%
EV114	HS	69.2	19507	1064	18.3%
EV115	Reject	50.6	11877	1018	17.6%
EV116	HS	89.1	16841	1040	18.5%
EV117	HS	72.1	17662	1023	19.2%
EV118	Reject	53.5	12760	1028	17.4%
EV119	HS	87.2	17448	1002	18.7%
EV120	HS	97.4	21348	1005	26.1%
EV121	HS	83.6	17203	1039	18.2%
EV122	HS	76.2	14788	1033	18.1%
EV123	HS	102.4	22411	995	26.1%
EV124	HS	75.1	18667	1010	24.5%
EV125	HS	47.9	13189	1026	18.6%

Eveuss	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
EV126	Reject	44.3	11324	1047	17.5%
EV127	HS	79.8	17839	1014	19.8%
EV128	HS	78.1	17752	1020	21.3%
EV129	HS	96.1	17927	1007	17.9%
EV130	HS	91.1	20375	999	23.0%
EV131	HS	108.3	23798	896	23.3%
EV132	HS	102.1	20298	1024	17.9%
EV133	HS	75.9	17945	1041	18.6%
EV134	HS	92.4	18479	1022	22.3%
EV135	HS	86.7	17086	1012	18.8%
EV136	HS	73.6	17049	1031	19.4%
EV137	HS	102.4	22281	1025	24.6%
EV138	HS	61.2	12106	1034	18.2%
EV139	HS	77.2	17275	1014	17.7%
EV140	HS	78.0	15060	1040	18.9%
EV141	HS	102.6	21015	1015	24.2%
EV142	HS	73.7	15182	1036	18.0%
EV143	HS	71.1	14195	1039	18.3%
EV144	HS	79.4	15188	1045	17.0%
EV145	HS	57.8	13942	1034	17.8%
EV146	HS	89.7	19290	993	23.2%
EV147	HS	84.1	15666	1054	17.8%
EV148	HS	89.9	17781	1026	18.0%
EV149	HS	69.6	13685	1024	17.9%
EV150	HS	102.3	21677	1018	25.1%
EV151	HS	52.3	16011	1017	17.5%
EV152	HS	87.4	18104	1025	18.5%
EV153	HS	42.2	15031	1055	17.5%
EV154	HS	68.1	13432	1030	18.3%
EV155	HS	51.2	12713	1037	19.7%
EV156	Reject	48.7	9111	1026	16.5%
EV157	HS	40.4	13050	1031	18.7%
EV158	HS	58.3	16794	1033	18.5%
EV159	HS	81.3	15970	1051	17.9%
EV160	HS	71.4	13569	1033	18.6%

Figure A3 – Eveuss graphs

Figure A3.1:
Bending strength ranking

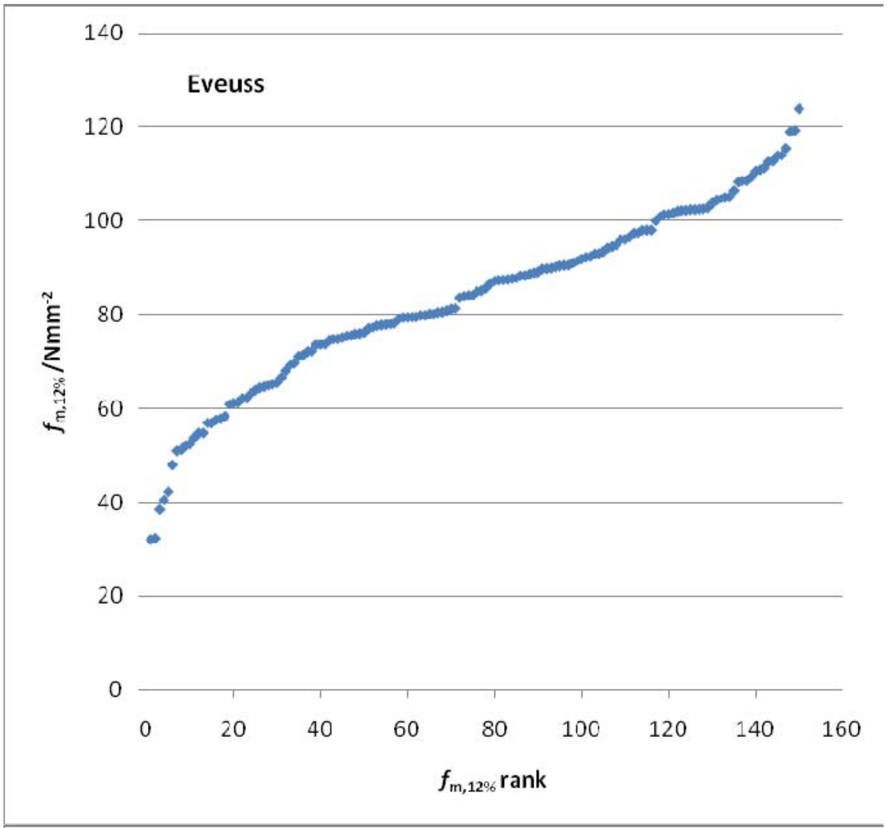


Figure A3.2:
Bending strength vs bending stiffness

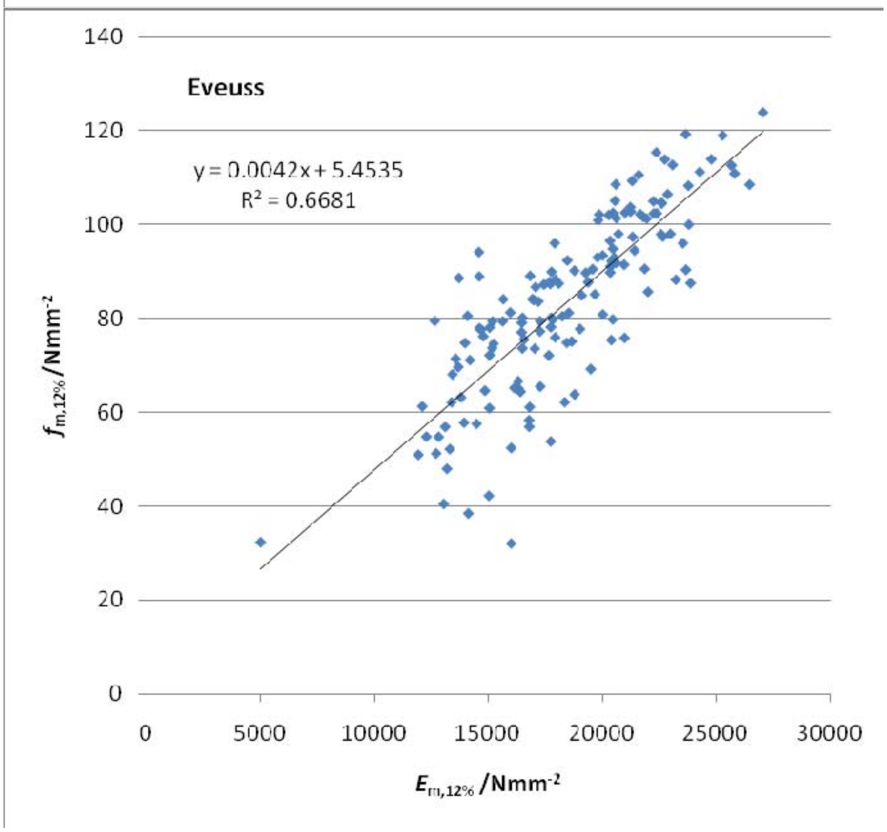


Figure A3.3:
Bending strength vs moisture content

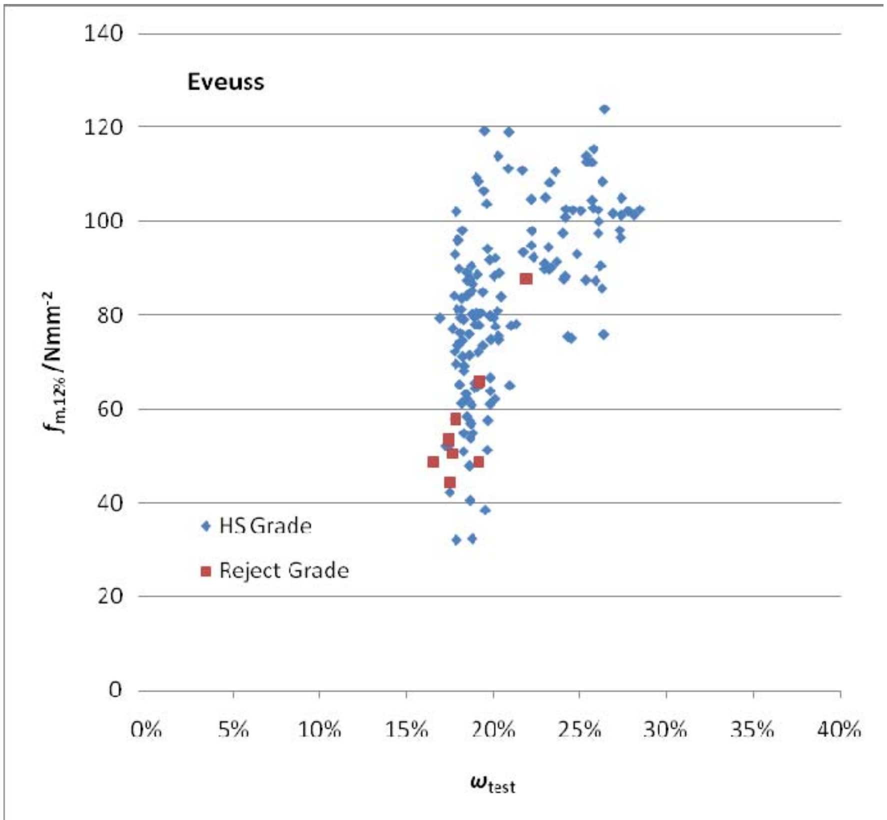
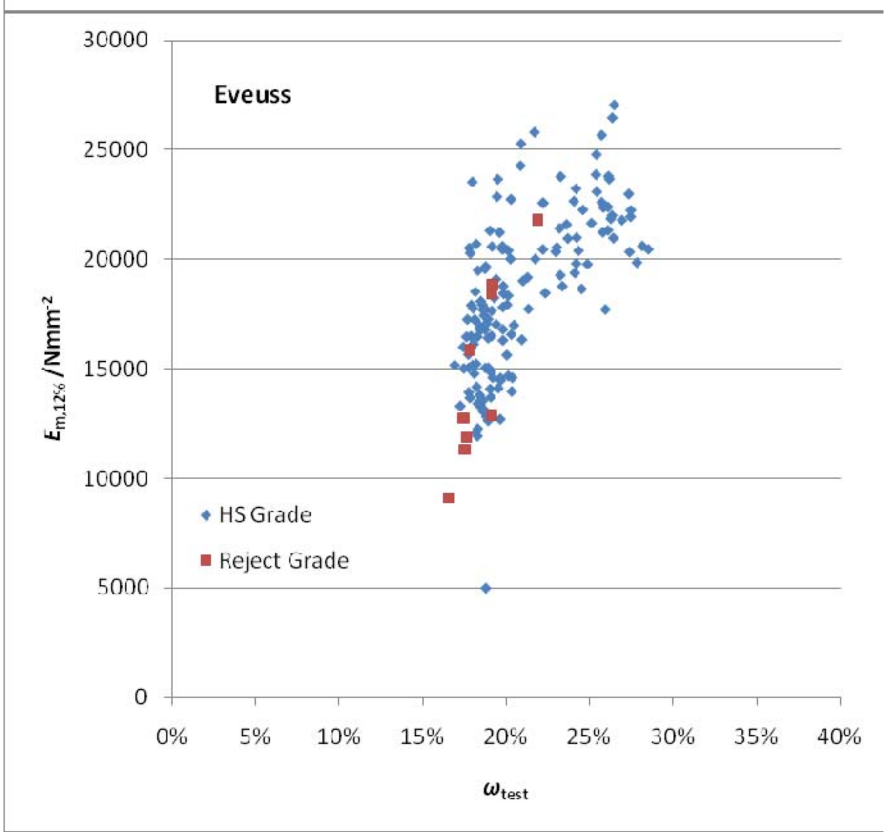


Figure A3.4:
Bending stiffness vs moisture content



A4. Okan test data

Table A4.1 –Okan. Summary data for bending strength $f_{m,12\%}$, bending stiffness $E_{m,12\%}$ and density $\rho_{12\%}$ at 12% moisture content, and moisture content at test ω_{test}

Okan		$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
HS Grade	mean	81.5	17137	998	20.4%
	min	35.8	7464	779	16.7%
	max	123.8	21195	1118	31.2%
	standard deviation (SD)	17.1	2322	61	2.0%
	percentile (EN384 stiffness)	5%	19318	5%	-
	rank (or other factor)	6.75	0.84	100.4	-
	percentile value	47.3	16227	898	-
	valid test count	135	137	as $E_{m,12\%}$	as $E_{m,12\%}$
	HS Grade count	139	139	-	-
	"No Data" count	4	2	-	-
Reject Grade	mean	56.2	15397	962	20.5%
	min	29.2	7707	782	18.0%
	max	104.4	18988	1069	25.4%
	standard deviation (SD)	21.7	2820	83	1.9%
	valid test count	19	20	as $E_{m,12\%}$	as $E_{m,12\%}$
	Reject Grade count	22	22	-	-
	"No Data" count	3	2	-	-

Table A4.2 –Okan. Specimen grade, bending strength $f_{m,12\%}$, bending stiffness $E_{m,12\%}$ and density $\rho_{12\%}$ at 12% moisture content, and moisture content at test ω_{test}

Okan	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
OK1	HS	72.7	16302	865	21.4%
OK2	HS	82.2	17986	991	18.2%
OK3	HS	87.5	18594	1042	20.7%
OK4	HS	83.7	18001	1001	24.3%
OK5	HS	77.4	19431	995	17.3%
OK6	HS	77.1	18699	948	24.2%
OK7	Reject	40.9	13434	1001	19.8%
OK8	HS	96.0	17027	1118	19.0%
OK9	HS	54.1	19808	1048	22.2%
OK10	HS	98.1	17447	1069	20.1%
OK11	HS	84.7	20195	1055	18.8%
OK12	HS	91.9	17018	1051	19.1%
OK13	HS	74.5	16771	1081	19.5%
OK14	Reject	76.3	17425	951	18.8%
OK15	HS	73.5	16528	1010	18.7%
OK16	HS	44.4	17880	1053	18.5%
OK17	HS	37.9	12692	892	23.6%
OK18	HS	96.8	14872	973	19.3%
OK19	HS	91.1	17512	998	18.4%
OK20	HS	83.0	19135	974	18.4%
OK21	HS	91.0	20589	1000	17.9%
OK22	HS	54.3	14361	1014	21.7%
OK23	HS	86.9	19325	1067	21.2%

Okan	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
OK24	HS	57.5	14751	1080	20.6%
OK25	HS	91.2	19205	1055	20.8%
OK26	HS	101.6	15723	1008	21.8%
OK27	HS	72.9	17058	1058	18.8%
OK28	HS	82.0	16522	999	19.1%
OK29	HS	64.6	17211	1049	22.0%
OK30	HS	100.3	20166	989	23.3%
OK31	HS	55.4	18334	1057	20.1%
OK32	HS	95.8	20564	1063	18.8%
OK33	Reject	32.6	7707	1009	19.8%
OK34	HS	No Data	15546	1039	20.7%
OK35	HS	80.7	18463	1002	19.0%
OK36	HS	91.3	17355	1020	22.2%
OK37	Reject	No Data	No Data	No Data	No Data
OK38	HS	40.4	7464	972	25.7%
OK39	HS	62.7	20782	981	19.1%
OK40	Reject	No Data	No Data	No Data	No Data
OK41	HS	No Data	9734	1025	22.2%
OK42	HS	84.7	16611	1084	19.3%
OK43	HS	81.3	15100	973	19.8%
OK44	HS	82.9	16709	1061	20.2%
OK45	HS	73.7	17025	1013	24.8%
OK46	HS	86.9	18733	1026	21.3%
OK47	HS	84.0	14031	1071	19.9%
OK48	HS	90.6	17259	954	20.9%
OK49	Reject	49.3	14201	1058	18.5%
OK50	HS	92.5	14776	1070	21.7%
OK51	HS	70.0	13751	975	24.7%
OK52	HS	98.7	17315	1068	21.3%
OK53	HS	45.9	13133	991	24.7%
OK54	Reject	No Data	16124	1040	19.6%
OK55	HS	73.2	15570	1075	18.8%
OK56	HS	53.7	14843	1007	18.6%
OK57	Reject	38.2	13743	1006	18.2%
OK58	HS	117.8	16102	1017	20.3%
OK59	HS	84.3	16688	977	19.5%
OK60	HS	62.3	13968	1078	19.1%
OK61	HS	79.1	15061	987	21.4%
OK62	HS	83.3	17016	1059	20.3%
OK63	HS	77.7	16309	973	19.8%
OK64	HS	71.1	15603	1038	19.0%
OK65	HS	80.9	16004	1073	19.9%
OK66	HS	No Data	No Data	No Data	No Data
OK67	Reject	37.8	14596	910	25.4%
OK68	HS	77.5	15751	980	19.2%
OK69	HS	100.1	17533	1064	19.0%
OK70	HS	75.1	16155	999	18.3%
OK71	HS	53.7	13764	890	25.0%
OK72	HS	73.0	15307	954	20.6%
OK73	HS	88.4	16082	964	21.5%
OK74	HS	47.8	15520	1088	22.4%

Okan	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
OK75	HS	79.1	15419	1016	19.9%
OK76	HS	109.2	16505	1017	20.5%
OK77	HS	84.6	15674	1034	19.8%
OK78	HS	55.3	14516	1080	19.8%
OK79	HS	77.8	16500	958	23.1%
OK80	Reject	41.6	12087	815	20.3%
OK81	Reject	93.4	18988	1069	18.9%
OK82	HS	78.4	16897	961	19.9%
OK83	HS	123.8	20733	981	18.5%
OK84	HS	94.8	15006	891	23.0%
OK85	HS	71.7	15540	1027	18.5%
OK86	Reject	44.0	13583	995	22.0%
OK87	HS	94.0	20290	970	21.4%
OK88	HS	88.1	17554	966	20.8%
OK89	HS	93.1	19415	990	18.9%
OK90	HS	86.9	16909	1061	19.7%
OK91	HS	94.7	16438	1104	18.4%
OK92	HS	No Data	No Data	No Data	No Data
OK93	Reject	76.6	17692	1059	21.3%
OK94	Reject	76.1	14491	979	19.3%
OK95	HS	99.3	19350	1004	19.4%
OK96	HS	78.4	14927	1014	18.8%
OK97	HS	115.1	14277	987	19.2%
OK98	HS	108.5	20047	1046	21.1%
OK99	HS	91.0	19386	992	19.3%
OK100	HS	92.5	18962	862	16.7%
OK101	HS	68.7	12578	1061	19.3%
OK102	HS	107.5	18743	1033	18.1%
OK103	HS	83.8	17864	1100	20.7%
OK104	HS	95.8	18121	779	18.0%
OK105	HS	79.2	14052	1024	19.7%
OK106	HS	93.4	21195	954	19.1%
OK107	HS	40.1	17296	1045	19.6%
OK108	HS	95.1	19175	958	18.1%
OK109	Reject	81.7	17435	1055	18.0%
OK110	HS	78.2	13629	896	31.2%
OK111	Reject	55.3	13119	922	20.5%
OK112	HS	87.9	15186	882	18.1%
OK113	HS	99.4	19855	986	20.2%
OK114	HS	89.3	18673	1070	20.7%
OK115	HS	87.1	17519	1029	19.3%
OK116	HS	75.7	18484	987	17.4%
OK117	HS	89.2	14725	990	20.4%
OK118	Reject	104.4	18823	959	19.7%
OK119	HS	78.2	14416	987	18.8%
OK120	HS	48.8	18588	863	20.4%
OK121	HS	101.6	20427	989	21.6%
OK122	HS	101.3	17246	978	21.2%
OK123	HS	72.0	14968	968	23.1%
OK124	HS	70.6	15291	781	21.9%
OK125	HS	97.5	20859	883	23.2%

Okan	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
OK126	HS	89.5	20575	955	23.9%
OK127	HS	65.2	18168	863	20.1%
OK128	HS	80.6	17349	901	18.3%
OK129	Reject	44.4	17320	851	21.1%
OK130	HS	84.7	19047	1002	20.3%
OK131	HS	81.9	18399	989	18.6%
OK132	HS	35.8	13666	835	20.4%
OK133	HS	54.7	18741	975	23.1%
OK134	HS	94.5	19468	992	18.5%
OK135	HS	89.1	16171	965	19.2%
OK136	Reject	29.2	16122	979	22.7%
OK137	HS	77.6	17492	995	20.6%
OK138	HS	101.3	20613	977	19.5%
OK139	HS	114.6	18869	980	19.9%
OK140	HS	74.0	19250	996	22.4%
OK141	HS	70.7	17436	1006	20.8%
OK142	HS	86.5	20398	999	18.5%
OK143	HS	105.6	19527	996	19.3%
OK144	HS	53.4	14390	1057	19.9%
OK145	HS	85.2	16786	962	21.6%
OK146	HS	79.5	13653	966	18.3%
OK147	HS	86.0	19243	1004	20.4%
OK148	HS	82.8	18987	972	18.5%
OK149	Reject	48.3	18135	897	21.4%
OK150	HS	79.0	15481	995	21.0%
OK151	HS	71.8	19302	1042	17.4%
OK152	HS	53.8	19246	954	22.1%
OK153	HS	75.7	18148	984	20.6%
OK154	HS	83.7	18500	1010	23.1%
OK155	HS	69.6	19958	998	19.1%
OK156	HS	96.5	18595	997	22.2%
OK157	Reject	51.2	14177	782	23.4%
OK158	Reject	46.1	18740	895	22.1%
OK159	HS	95.5	18352	1003	20.7%
OK160	HS	98.5	18891	1022	20.4%
OK161	HS	102.2	19040	1029	19.0%

Figure A4 – Okan graphs

Figure A4.1:
Bending strength ranking

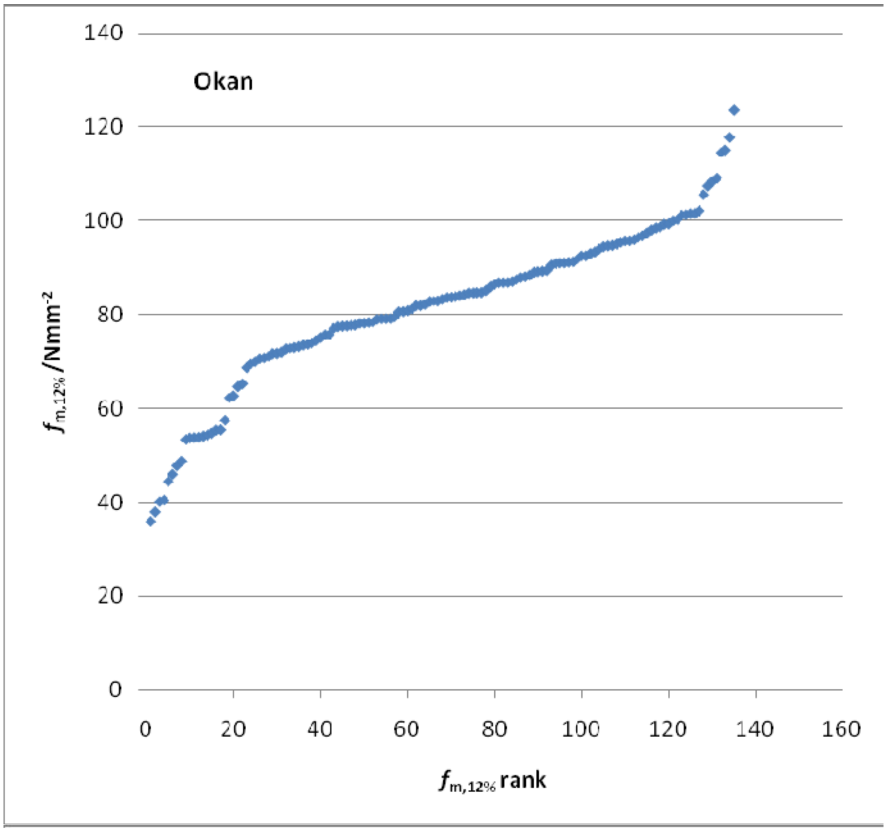


Figure A4.2:
Bending strength vs bending stiffness

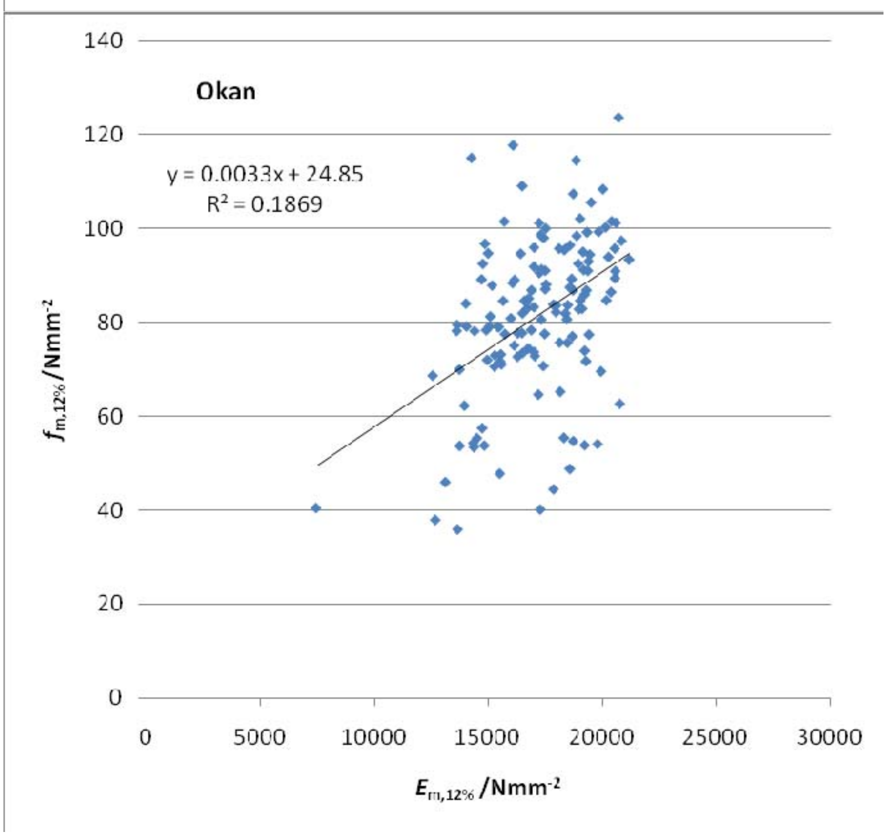


Figure A4.3:
Bending strength vs moisture content

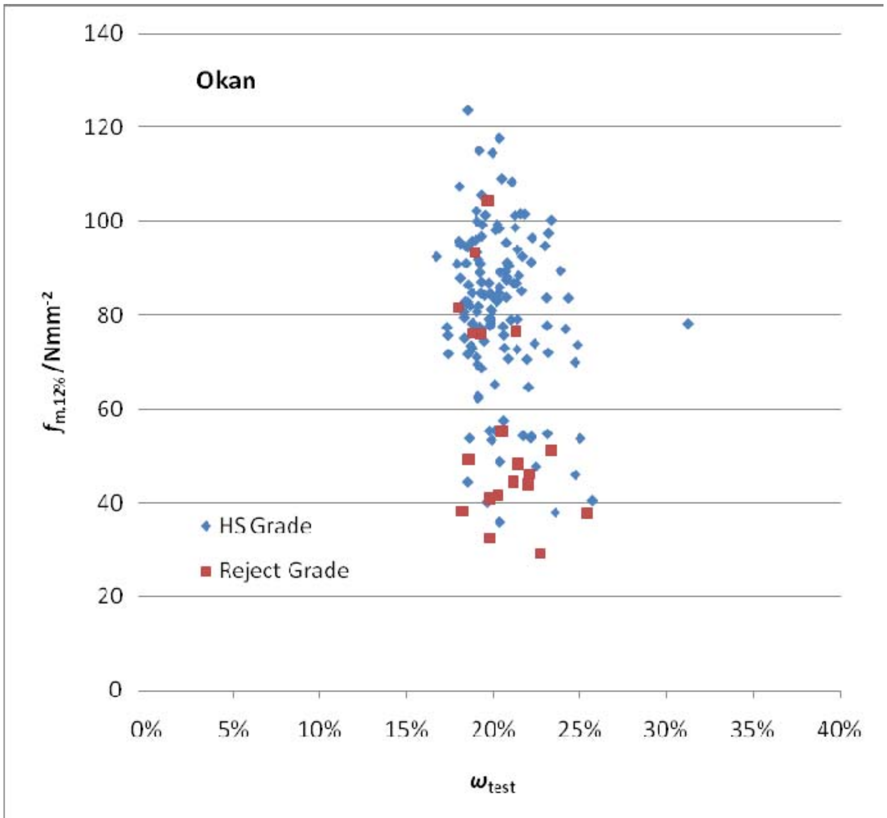
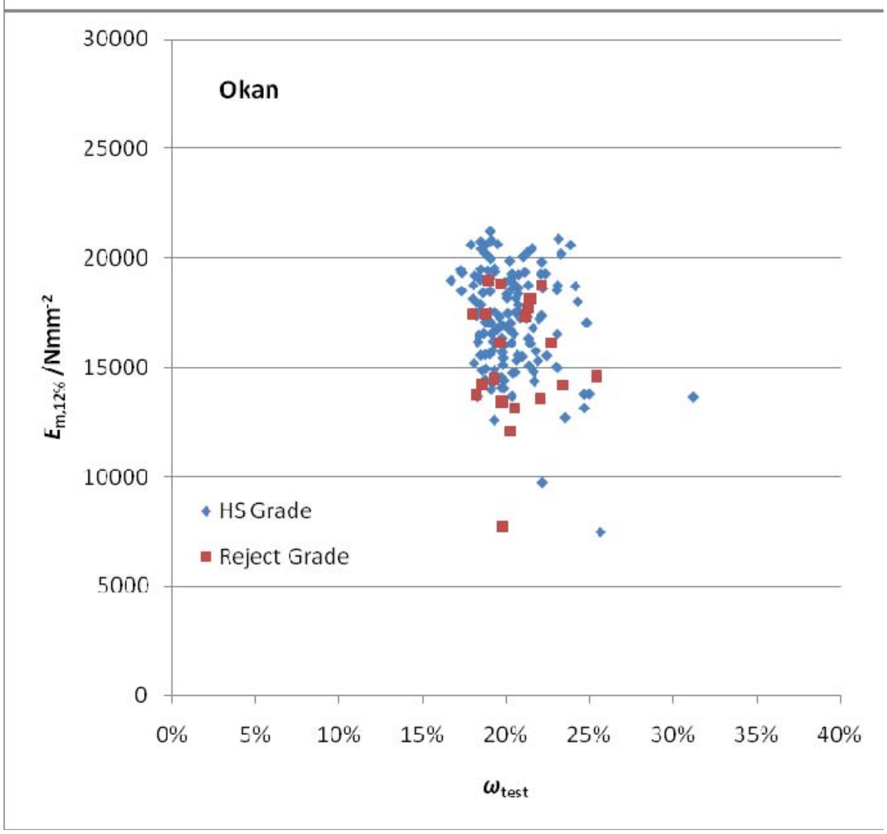


Figure A4.4:
Bending stiffness vs moisture content



A5. Tali test data

Table A5.1 –Tali. Summary data for bending strength $f_{m,12\%}$, bending stiffness $E_{m,12\%}$ and density $\rho_{12\%}$ at 12% moisture content, and moisture content at test ω_{test}

Tali		$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
HS Grade	mean	70.3	15508	815	33.0%
	min	29.8	10441	647	16.9%
	max	110.9	25866	1097	54.3%
	standard deviation (SD)	17.9	2958	87	7.5%
	percentile (EN384 stiffness)	5%	17200	5%	-
	rank (or other factor)	6.60	0.84	143.0	-
	percentile value	40.5	14448	672	-
	valid test count	132	133	as $E_{m,12\%}$	as $E_{m,12\%}$
	HS Grade count	142	142	-	-
	"No Data" count	10	9	-	-
Reject Grade	mean	62.7	15233	825	33.7%
	min	30.5	9788	687	17.6%
	max	104.7	23317	1037	44.7%
	standard deviation (SD)	23.3	3558	96	7.8%
	valid test count	16	18	as $E_{m,12\%}$	as $E_{m,12\%}$
	Reject Grade count	18	18	-	-
	"No Data" count	2	0	-	-

Table A5.2 –Tali. Specimen grade, bending strength $f_{m,12\%}$, bending stiffness $E_{m,12\%}$ and density $\rho_{12\%}$ at 12% moisture content, and moisture content at test ω_{test}

Tali	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
TA1	HS	72.1	17832	1097	25.0%
TA2	HS	76.7	17965	891	35.7%
TA3	Reject	100.2	18964	990	32.4%
TA4	HS	56.0	14332	892	39.0%
TA5	Reject	62.3	16545	890	30.5%
TA6	HS	76.3	16606	766	38.3%
TA7	HS	79.5	19282	981	27.2%
TA8	Reject	104.7	23317	1037	28.3%
TA9	HS	No Data	No Data	No Data	No Data
TA10	HS	104.8	19529	1066	25.2%
TA11	HS	73.7	15312	881	20.5%
TA12	HS	78.8	15946	774	34.9%
TA13	HS	No Data	No Data	No Data	No Data
TA14	HS	57.0	16198	838	21.7%
TA15	HS	88.2	17415	899	18.8%
TA16	HS	49.9	14650	841	34.7%
TA17	HS	72.3	13650	737	24.3%
TA18	Reject	No Data	9788	687	36.0%
TA19	HS	95.6	18875	979	37.3%
TA20	HS	90.3	18929	807	25.7%
TA21	HS	76.9	15145	750	32.0%
TA22	HS	No Data	No Data	No Data	No Data
TA23	HS	94.4	25810	928	28.6%

Tali	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
TA24	HS	42.7	14296	658	26.6%
TA25	HS	50.0	14216	699	43.5%
TA26	HS	103.1	17218	968	33.3%
TA27	HS	77.6	14597	750	35.0%
TA28	HS	91.6	19953	834	37.5%
TA29	HS	76.5	16153	774	33.0%
TA30	HS	92.6	19671	952	33.0%
TA31	HS	103.3	25866	980	35.2%
TA32	HS	36.4	11331	733	33.7%
TA33	HS	73.4	18310	936	30.3%
TA34	HS	78.2	18191	862	24.8%
TA35	HS	71.2	13727	872	16.9%
TA36	HS	77.8	13266	962	26.3%
TA37	HS	58.6	15217	822	25.8%
TA38	Reject	70.1	15644	881	17.6%
TA39	HS	40.2	11351	683	54.3%
TA40	HS	60.7	15084	889	20.5%
TA41	HS	93.7	19388	988	26.9%
TA42	HS	80.9	14718	801	32.9%
TA43	HS	68.2	15247	952	28.0%
TA44	HS	78.8	17980	886	20.8%
TA45	HS	50.1	11979	709	22.8%
TA46	HS	91.6	16028	904	21.1%
TA47	HS	80.5	15946	760	36.1%
TA48	HS	36.5	15083	984	27.7%
TA49	HS	72.5	15177	772	33.1%
TA50	HS	75.5	17376	935	29.6%
TA51	HS	74.2	16035	724	34.3%
TA52	HS	51.7	13845	712	42.9%
TA53	HS	77.9	14970	718	26.5%
TA54x	Reject	83.4	18359	883	29.1%
TA55	HS	99.5	19957	815	39.8%
TA56	HS	71.6	14352	732	24.4%
TA57	HS	106.8	21415	866	28.7%
TA58	HS	73.0	14440	791	34.7%
TA59	HS	104.9	22415	902	37.2%
TA60	HS	86.9	14964	782	29.0%
TA61	HS	82.5	15326	739	48.5%
TA62	HS	29.8	12484	697	49.7%
TA63	HS	107.1	22710	857	31.7%
TA64	HS	61.5	18289	883	40.2%
TA65	HS	79.7	15260	772	52.1%
TA66	HS	74.6	15254	760	39.7%
TA67	HS	77.9	15016	714	36.7%
TA68	HS	65.6	13152	715	41.1%
TA69	HS	59.4	13773	775	37.3%
TA70	HS	68.0	14147	862	19.3%
TA71	HS	67.4	12131	783	32.2%
TA72	HS	71.4	14818	786	30.7%
TA73	HS	No Data	No Data	No Data	No Data
TA74	HS	41.8	11192	647	28.4%

Tali	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
TA75	HS	67.4	16876	908	31.0%
TA76	HS	62.4	11813	788	35.2%
TA77	HS	64.5	13079	775	35.8%
TA78	HS	67.8	12546	724	41.8%
TA79	HS	62.3	12641	793	32.6%
TA80	HS	53.5	10904	816	44.6%
TA81	HS	49.3	13824	716	37.6%
TA82	HS	104.0	19615	885	26.5%
TA83	HS	80.7	20660	974	27.3%
TA84	HS	67.2	13220	739	48.2%
TA85	HS	No Data	No Data	No Data	No Data
TA86	HS	83.8	16027	751	37.4%
TA87	HS	43.5	12689	715	33.7%
TA88	HS	73.9	15169	720	26.7%
TA89	HS	No Data	No Data	No Data	No Data
TA90	HS	63.7	11013	735	39.1%
TA91	HS	56.9	14076	709	45.4%
TA92	HS	No Data	No Data	No Data	No Data
TA93	HS	59.2	13272	685	48.3%
TA94	HS	63.4	13389	736	34.6%
TA95	HS	54.9	13385	778	30.3%
TA96	HS	60.2	13601	808	42.9%
TA97	Reject	58.8	13729	742	36.5%
TA98	HS	73.3	18255	835	32.4%
TA99	HS	47.8	14083	873	27.7%
TA100	Reject	43.9	12219	717	26.8%
TA101	HS	82.9	15478	724	25.7%
TA102	HS	77.2	14363	748	35.3%
TA103	HS	No Data	No Data	No Data	No Data
TA104	HS	55.3	13811	751	36.3%
TA105	HS	70.3	18843	879	26.2%
TA106	HS	76.3	13961	807	39.7%
TA107x	Reject	44.3	12442	713	44.7%
TA108	HS	46.8	15654	822	19.8%
TA109x	Reject	72.5	14057	863	18.6%
TA110	HS	63.6	13554	794	34.9%
TA111	Reject	44.1	15827	896	30.7%
TA112	HS	56.5	12877	776	24.2%
TA113	HS	72.5	18469	833	33.1%
TA114	HS	60.1	14931	878	26.1%
TA115	HS	67.4	13856	787	32.0%
TA116	HS	82.3	16788	779	39.6%
TA117	HS	40.9	12801	687	21.3%
TA118	HS	55.1	12667	823	43.7%
TA119	HS	No Data	No Data	No Data	No Data
TA120	HS	99.3	20439	857	36.9%
TA121	Reject	36.3	16962	847	39.5%
TA122	HS	48.9	11684	816	40.1%
TA123	HS	74.9	14684	780	30.8%
TA124	HS	82.0	18515	825	27.6%
TA125	HS	110.9	19373	881	42.1%

Tali	BS5756 grade	$f_{m,12\%}$ /Nmm^{-2}	$E_{m,12\%}$ /Nmm^{-2}	$\rho_{12\%}$ /kgm^{-3}	ω_{test}
TA126	Reject	71.5	13767	785	34.0%
TA127	HS	94.2	14230	793	35.9%
TA128x	Reject	88.5	21723	837	42.2%
TA129x	Reject	59.1	13452	751	42.4%
TA130	HS	96.5	19053	847	37.1%
TA131	HS	63.5	14248	699	30.0%
TA132	HS	90.4	18484	865	30.6%
TA133	HS	40.9	11820	809	33.8%
TA134x	Reject	30.5	12383	780	37.6%
TA135	HS	65.3	14772	759	36.2%
TA136	HS	55.9	15460	1028	21.7%
TA137	HS	53.2	11791	799	33.6%
TA138	HS	37.7	11449	804	36.3%
TA139	HS	93.3	20508	887	29.1%
TA140	HS	86.8	17728	799	42.2%
TA141	HS	40.8	12286	725	35.5%
TA142	HS	No Data	10441	893	35.8%
TA143	HS	64.1	15255	750	37.3%
TA144	HS	65.1	14467	773	25.5%
TA145	HS	51.8	12736	731	51.5%
TA146x	Reject	33.6	12104	774	34.6%
TA147	HS	58.6	12883	789	30.8%
TA148	HS	56.1	13376	778	38.2%
TA149	HS	65.9	14087	741	25.4%
TA150	HS	48.7	15111	824	34.8%
TA151	HS	88.6	20315	864	25.6%
TA152	HS	64.0	12758	811	37.9%
TA153	HS	64.2	13818	818	34.2%
TA154	HS	39.2	13879	813	42.2%
TA155	HS	63.9	14030	806	31.8%
TA156	HS	68.5	14483	777	31.3%
TA157	HS	82.7	15833	765	32.4%
TA158x	Reject	No Data	12905	766	44.2%
TA159	HS	55.6	14003	845	29.8%
TA160	HS	97.4	19552	866	29.3%

Figure A5 – Tali graphs

Figure A5.1: Bending strength ranking

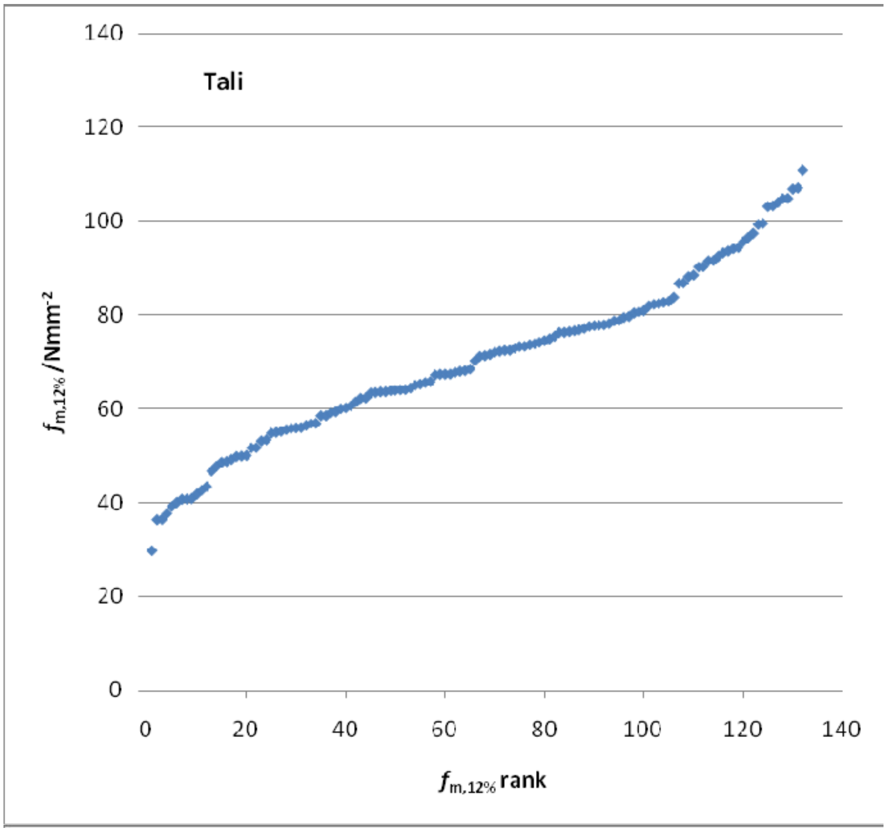


Figure A5.2: Bending strength vs bending stiffness

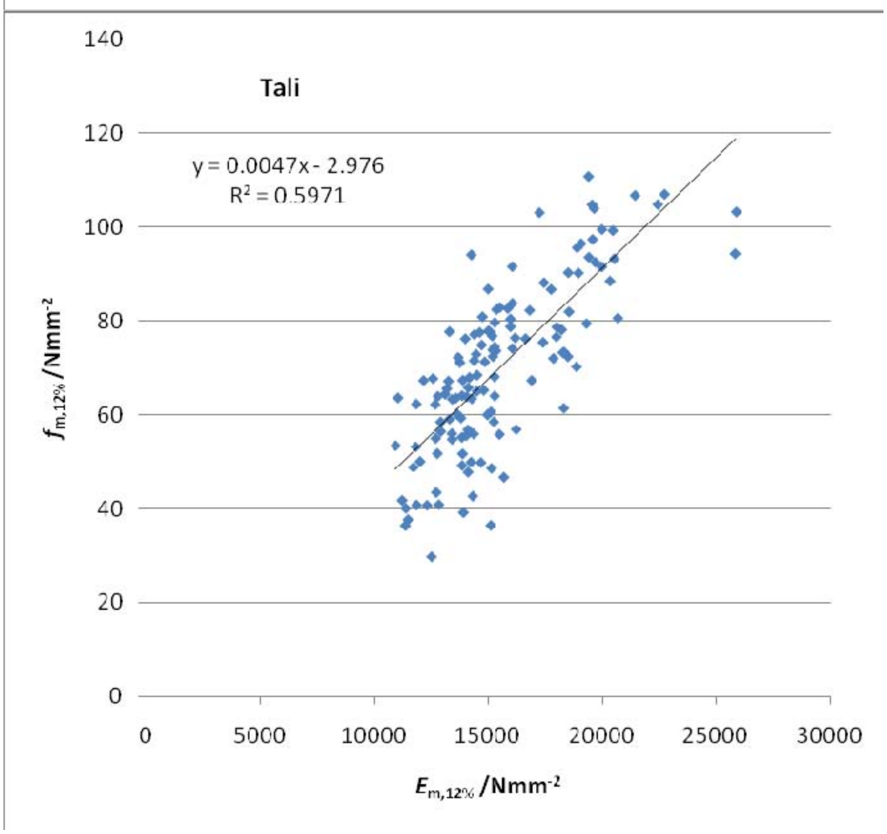


Figure A5.3: Bending strength vs moisture content

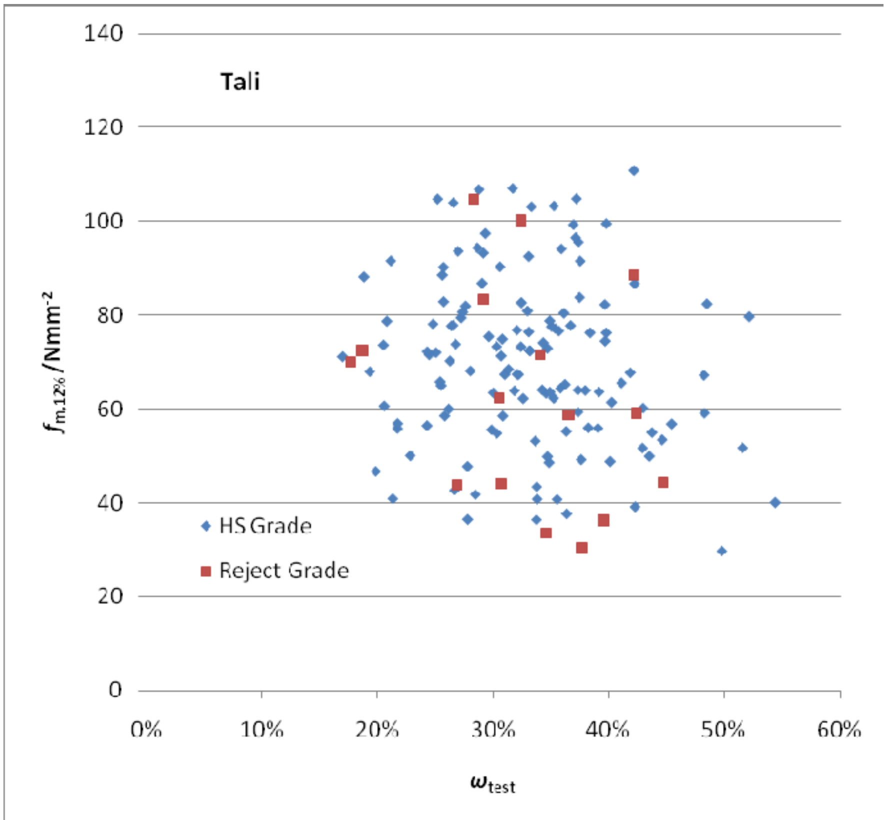
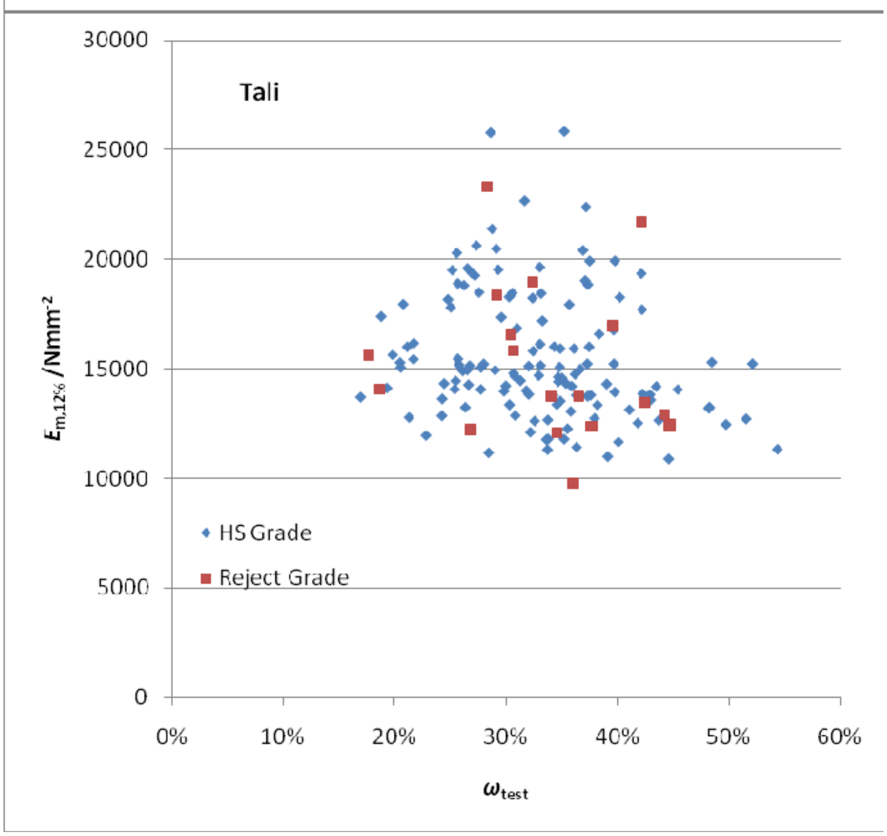
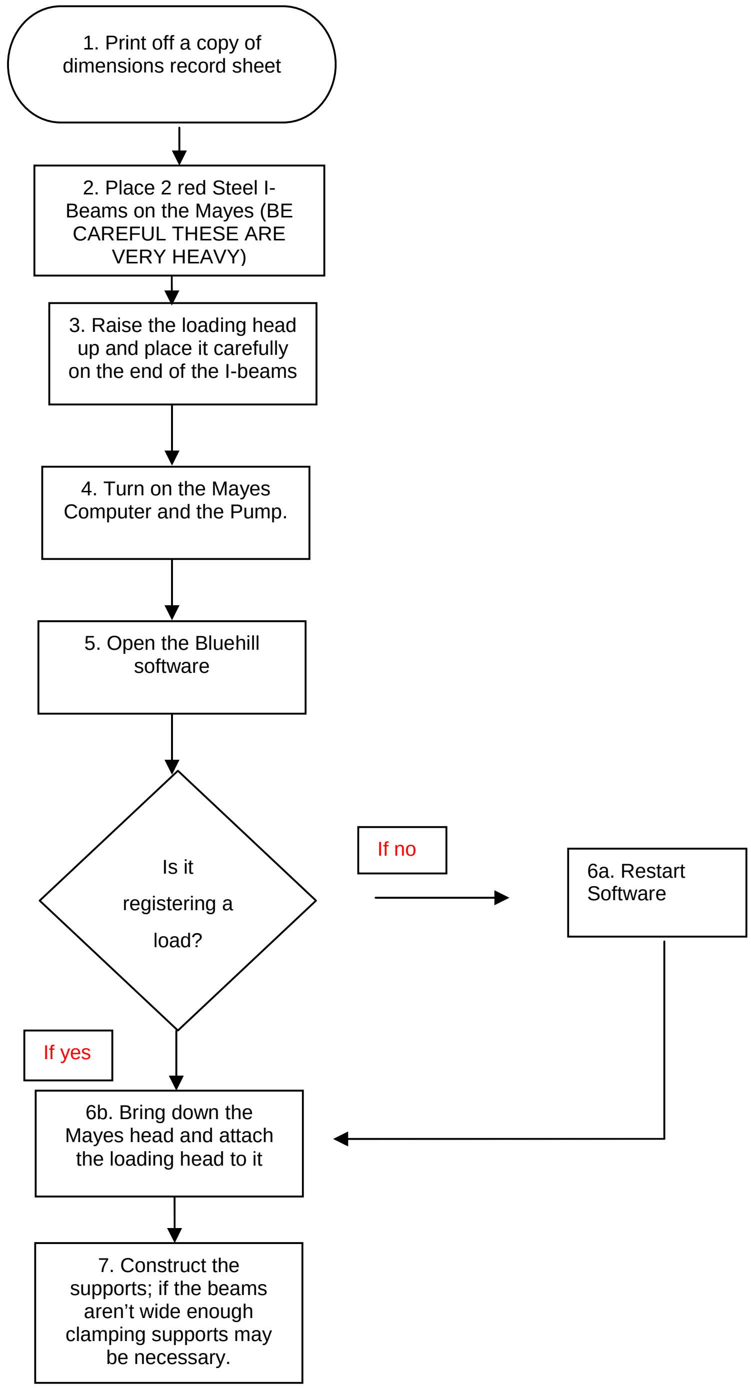
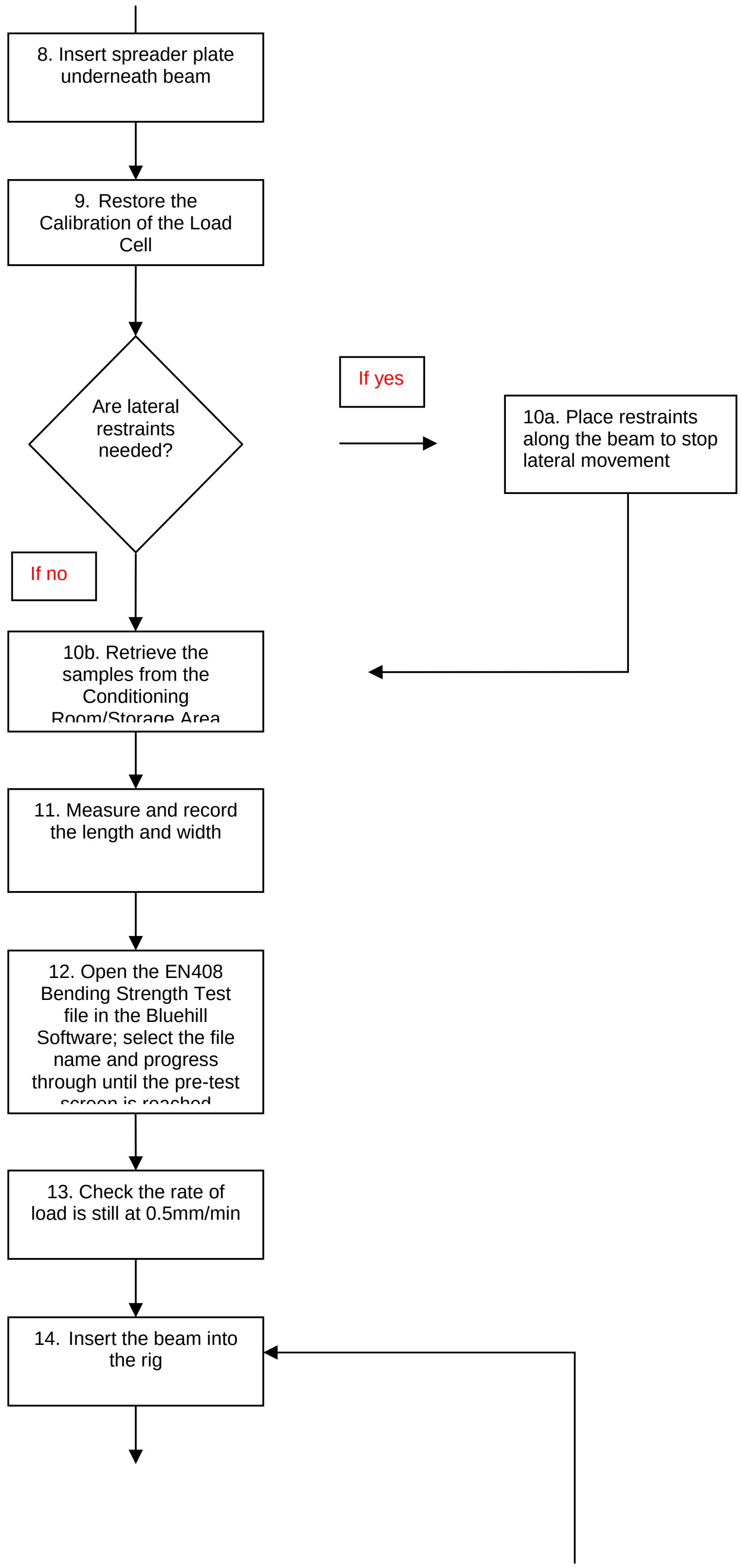


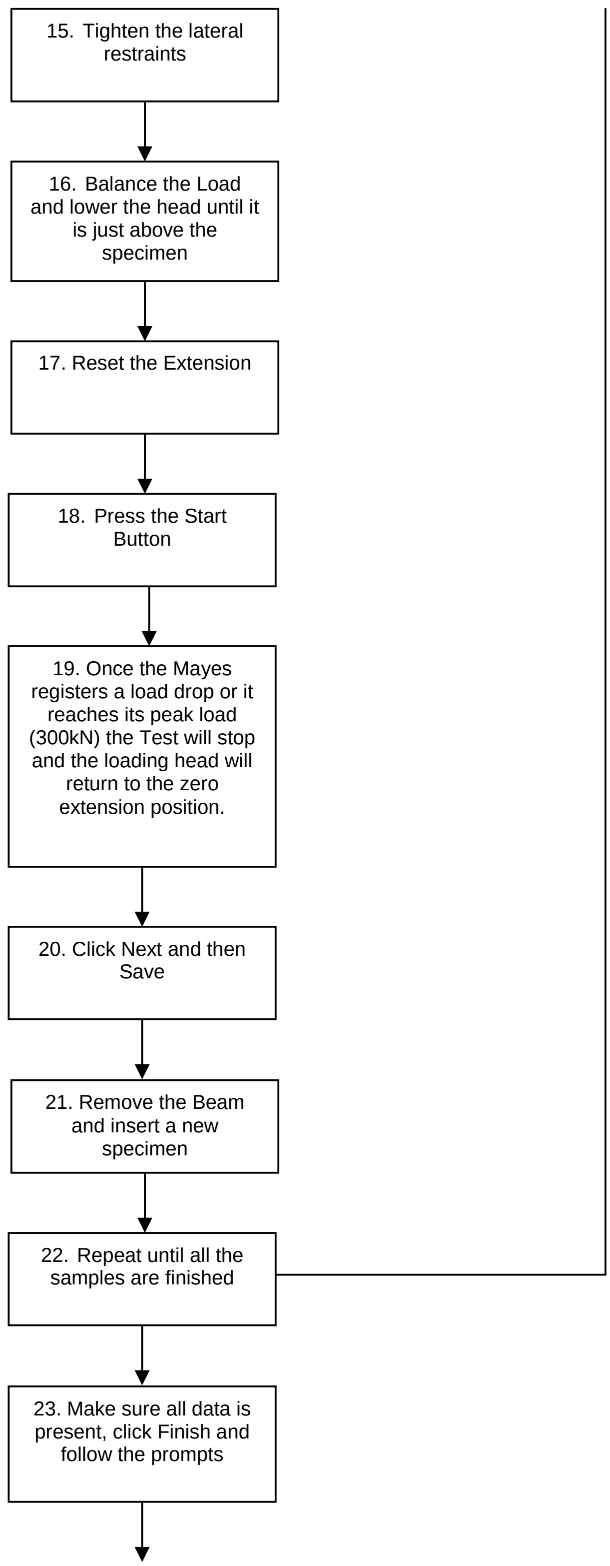
Figure A5.4: Bending stiffness vs moisture content

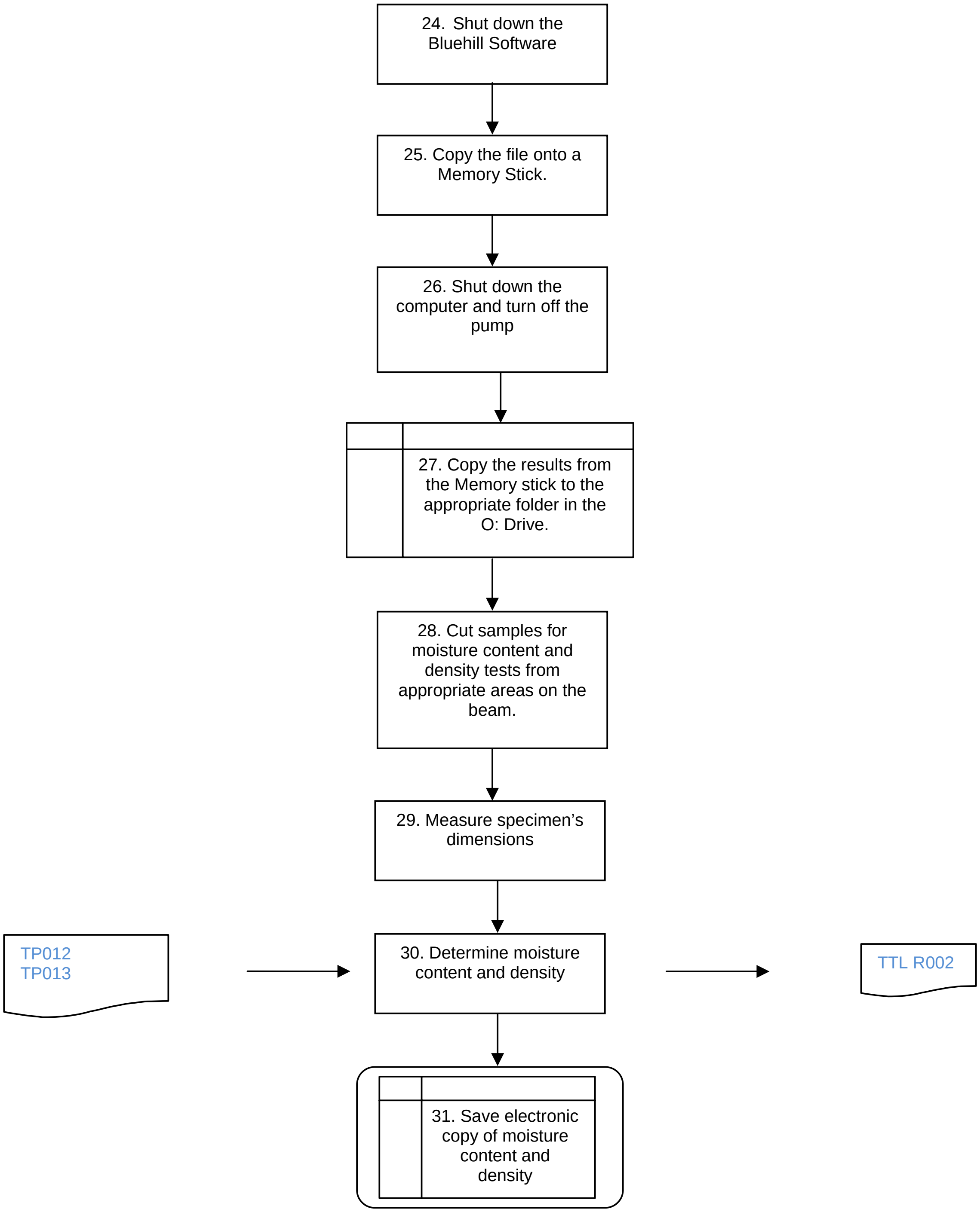


A6. EN 408 4-Point Bending Strength Test Procedure




8. Insert spreader plate underneath beam
9. Restore the Calibration of the Load Cell
Are lateral restraints needed?
If yes
10a. Place restraints along the beam to stop lateral movement
If no
10b. Retrieve the samples from the Conditioning Room/Storage Area
11. Measure and record the length and width
12. Open the EN408 Bending Strength Test file in the Bluehill Software; select the file name and progress through until the pre-test
13. Check the rate of load is still at 0.5mm/min
14. Insert the beam into the rig


15. Tighten the lateral restraints
16. Balance the Load and lower the head until it is just above the specimen
17. Reset the Extension
18. Press the Start Button
19. Once the Mayes registers a load drop or it reaches its peak load (300kN) the Test will stop and the loading head will return to the zero extension position.
20. Click Next and then Save
21. Remove the Beam and insert a new specimen
22. Repeat until all the samples are finished
23. Make sure all data is present, click Finish and follow the prompts


24. Shut down the Bluehill Software
25. Copy the file onto a Memory Stick.
26. Shut down the computer and turn off the pump
27. Copy the results from the Memory stick to the appropriate folder in the O: Drive.
28. Cut samples for moisture content and density tests from appropriate areas on the beam.
29. Measure specimen's dimensions
TP012
TP013
30. Determine moisture content and density
TTL R002
31. Save electronic copy of moisture content and density

Action	By whom	How
1. Print off a copy of dimensions record sheet	Level 1, 2 or 3 competent staff	This can be found in the Record Sheet folder on the O:Drive.
2 .Place 2 red Steel I-Beams on the Mayes (CAUTION! THESE ARE VERY HEAVY)	Level 1 competent staff	The 2 red Steel I-Beams need to be placed on the Mayes (CAUTION! THESE ARE VERY HEAVY). Using the Forklift and the Hoist the beams can be manoeuvred onto the Mayes bed, keep them supported with the hoist and a roller until the centre line drawn on the beam lines up with that drawn on the Mayes bed.
3. Raise the loading head up and place it carefully on the end of the I-beams	Level 1 competent staff	Using the forklift, raise the loading head up and place it carefully on the end of the I-beams (again this is very heavy, be careful), with the roller under the beam there is little risk of unbalancing them. Slide the loading head along until it is directly under the load cell of the Mayes.
4. Turn on the Mayes Computer and the Pump.	Level 1 or 2 competent staff	Switch on the Data Logger and the Computer. Turn on the pump at the wall. If possible turn the pump on using the controller on the Mayes.
5. Open the Bluehill software	Level 1 or 2 competent staff	Open the Bluehill software; make sure it is registering a load.
6a. Restart Software	Level 1 or 2 competent staff	If a load isn't being registered, restart the software.
6b. Bring down the Mayes head and attach the loading head to it.	Level 1 or 2 competent staff	Bring down the Mayes head until bolts can be inserted from the loading head to the plate attached to the loading cell. Make sure the nuts are tightened and the loading head and Mayes are firmly attached before raising the loading head up off the beams.
7. Construct the supports; if the beams aren't wide enough clamping supports may be necessary.	Level 1 or 2 competent staff	Construct the supports; if the Beams aren't wide enough clamping supports maybe necessary. Place the supports in the appropriate positions, dictated by the depth of the beam, and secure them in position using the threaded rod and plates. Make sure the set up is symmetrical about the centre of the Mayes.
8. Insert spreader plate underneath beam	Level 1, 2 or 3 competent staff	Restore the Calibration of the Load Cell (the transducers also require the restoration of their calibration to start the test although they are not used).
9. Restore the Calibration of the Load Cell	Level 1 competent staff	Restore the Calibration of the Load Cell (the transducers also require the restoration of their calibration to start the test although they are not used).
10a. Place restraints along the beam to stop lateral movement	Level 1, 2 or 3 competent staff	Lateral supports might also be necessary for narrow beams, these should be placed all along the beam and stop the beam from moving laterally

10b. Retrieve the samples from the Conditioning Room/Storage Area	Level 1, 2 or 3 competent staff	
11. Measure and record the length and width	Level 1, 2 or 3 competent staff	Measure and record the length and width in millimetres using the tape measure and measure the thickness of the prism in millimetres using the Callipers to 2 decimal places.
12. Open the EN408 Bending Strength Test file in the Bluehill Software; select the file name and progress through until the pre-test screen is reached	Level 1 or 2 competent staff	Open the EN408 Bending Strength Test file in the Bluehill Software; select the file name and where to save the data and progress through entering any necessary data until to reach the pre-test screen.
13. Check the rate of load is still at 0.5mm/min	Level 1 competent staff	Click on the Method Tab and in Control Menu, under Test, check the rate of load has not reset itself to zero and is still at 0.5mm/min or close to that value.
14. Insert the beam into the rig	Level 1, 2 or 3 competent staff	Insert the beam into the rig; if necessary secure the ends in the clamping supports. If there is a central finger joint make sure it is not directly under a loading head.
15. Tighten the lateral restraints	Level 1, 2 or 3 competent staff	Move the restraints to support the sample and prevent it from twisting or moving laterally.
16. Balance the Load and lower the head until it is just above the specimen	Level 1 or 2 competent staff	Right click the Load Cell Icon and select Balance. Lower the head down using the controller until it is just above the beam, the closer the better.
17. Reset the Extension	Level 1 or 2 competent staff	Press the Reset Extension button to zero the extension and define the return point.
18. Press the Start Button	Level 1, 2 or 3 competent staff	Press the Start Button and the loading head will begin to move downward.
19. Once the Mayes registers a load drop or it reaches its peak load (300kN) the Test will stop and the loading head will return to the zero extension position.	N/A	As soon as the Mayes registers a load drop of 40% of the maximum load recorded it will stop and automatically return to its zero extension position. This will also happen in the unlikely event the load reaches 300kN which is the maximum the load cell can record.

20. Click Next and then Save	Level 1 or 2 competent staff	Click Next and follow the prompts onscreen, then click Save to make sure the Data will not be lost.
21. Remove the Beam and insert a new specimen	Level 1, 2 or 3 competent staff	Carefully remove the beam and insert another sample as before.
22. Repeat until all the samples are finished	Level 1 or 2 competent staff	Repeat the procedure until all samples are finished.
23. Make sure all data is present, click Finish and follow the prompts	Level 1 or 2 competent staff	Once finished, make sure all data is present, click Finish and follow the prompts. When asked if you want to start a new test with the same parameters click No. The Data will be outputted into HTML and CSV format.
24. Shut down the Bluehill Software	Level 1, 2 or 3 competent staff	Close the Bluehill program
25. Copy the file onto a Memory Stick.	Level 1, 2 or 3 competent staff	Copy all the data from the file on the Mayes computer to a memory stick.
26. Shut down the computer and turn off the pump	Level 1 or 2 competent staff	Close down the computer, shut off the power to the Data Logger and switch both the computer and the pump off at the mains.
27. Copy the results from the Memory stick to the appropriate folder in the O: Drive.	Level 1, 2 or 3 competent staff	When back in the office, copy of the results from the Memory stick to the appropriate folder in the O: Drive.
28. Cut samples for moisture content and density tests from appropriate areas on the beam.	Level 1 or 2 competent staff	If necessary cut samples for moisture content and density tests from appropriate areas on the beam.
29. Measure specimen's dimensions, and weigh	Level 1, 2 or 3 competent staff	The specimen is measured in its three directions with a calliper and weighed with a four-digit scale
30. Determine moisture content and density	Level 1 or 2 competent staff	The samples are then oven dried at 103 ºC until their weight does not vary more than 0.1 % in 6 hours. Density and moisture content (MC) are then derived according to TP insert test procedure here
31. Save electronic copy of moisture content and density	Level 1 or 2 competent staff	Moisture content and density measurements must be recorded electronically in the job file.

Photographic instructions can be found below to further aid understanding

Figure 1: Red Steel I Beams on Mayes

Figure 2:Adjustable Twin Loading Head

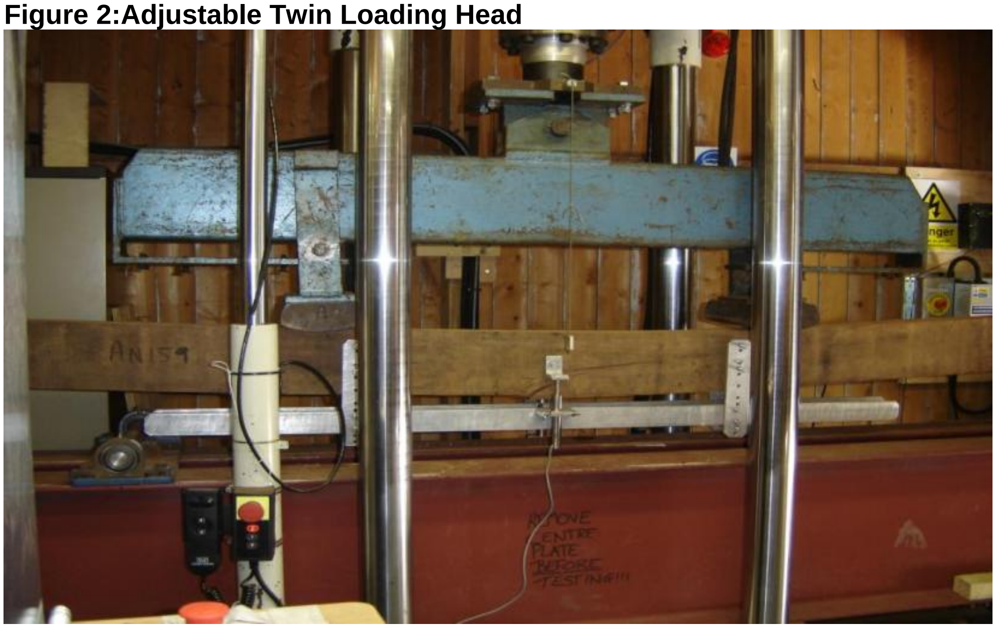


Figure 3: Support Method

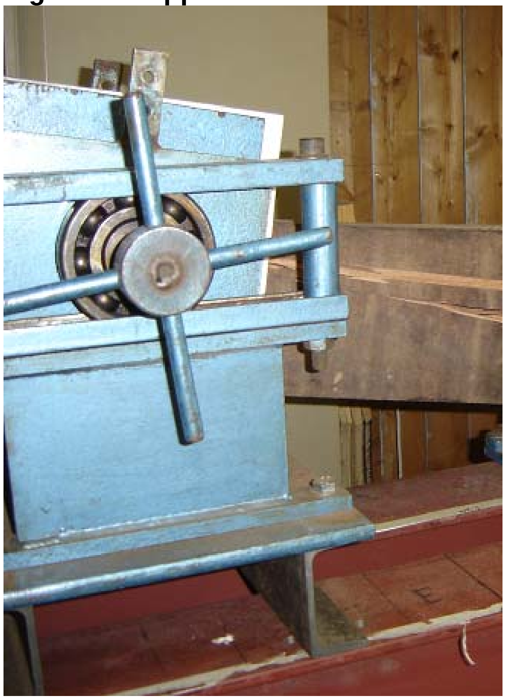


Figure 4: Support Secured Beneath I-Beam

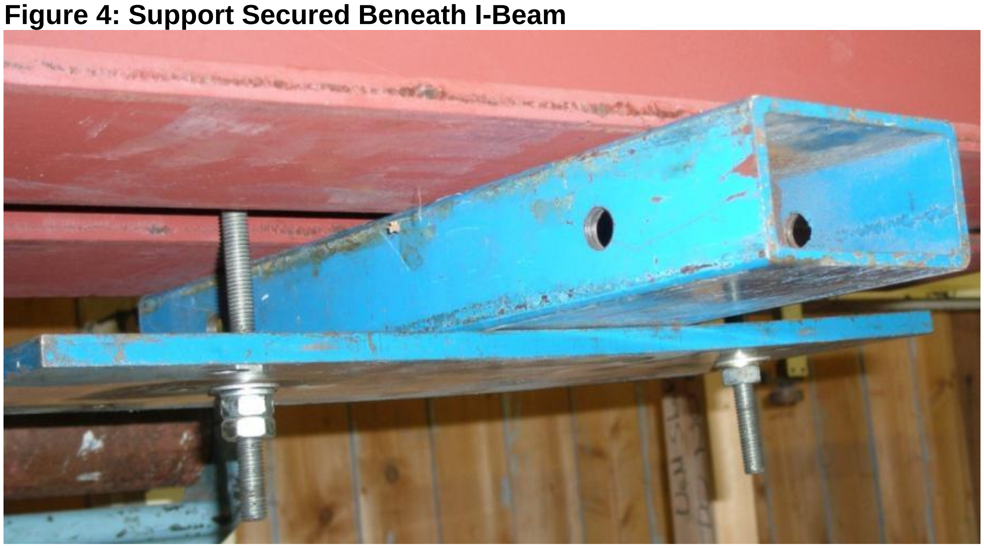


Figure 5: Diagram of 4 Point Bending Set Up

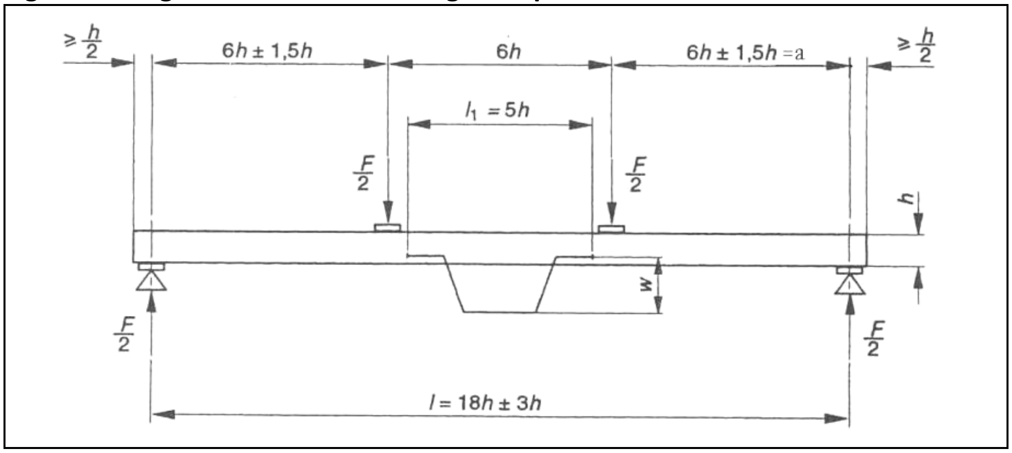
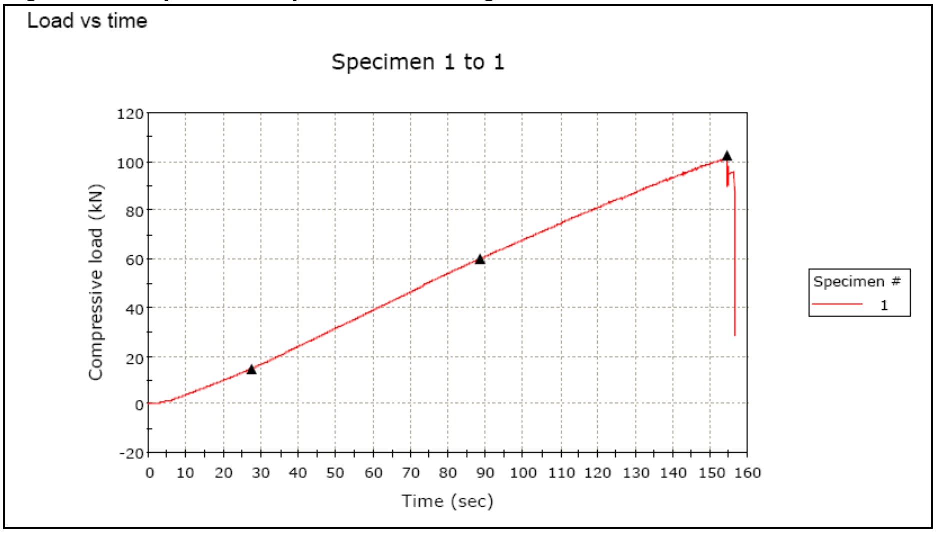
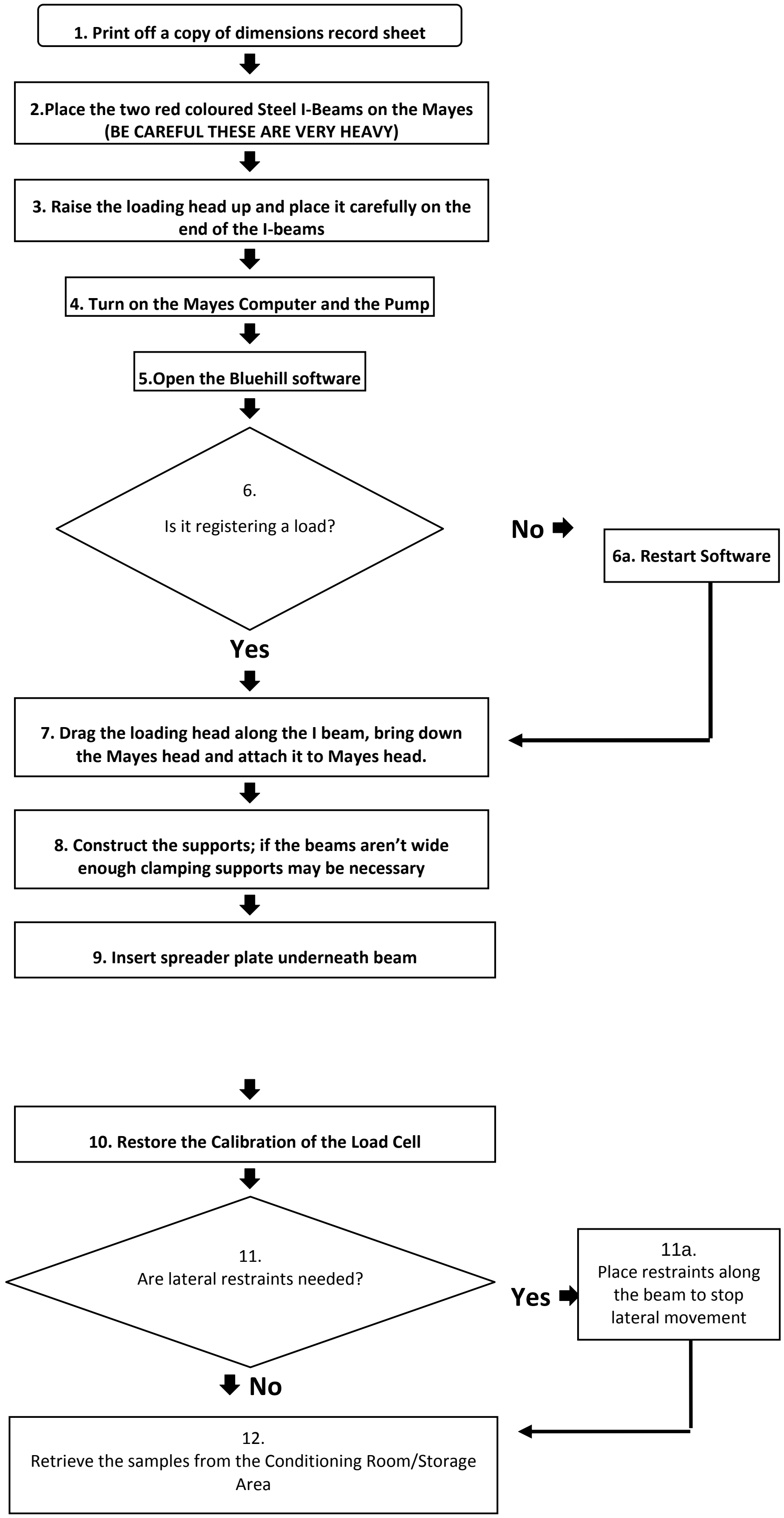


Figure 6: Graph of Compressive Load against Time



A7. TP028 Four Point Bending Stiffness Test Procedure



13.
Measure and record the length and width

↓

14.
Open the EN408 Bending Stiffness Test file in the Bluehill Software; select the file name and progress through until the pre-test screen is reached

↓

15.
Check the rate of load is still at 0.5mm/min

↓

16.
Label the beam and drill 3 holes on the beam using template in order to fix deflection transducer mounts to the beam

↓

17.
Insert the beam into the rig

↓

18.
Tighten the lateral restraints

↓

19.
Fix two transducer mounts into either side of the beam

↓

20.
Mount two transducers on each transducer mount

↓

21.
Balance the load and transducer deflection and lower the head until it is just above the specimen

↓

22.
Reset the Extension

↓

23.
Press the Start Button

↓

24.
Once the Mayes reach the set load (this is normally 40% of the estimated maximum load) the test will stop and the loading head will return to the zero extension position

↓

25.
Click Next and then Save

↓

26.
Dismantle the deflection transducers and transducer mounts

↓

27.
Remove the beam and insert a new specimen

↓

28.
Repeat until all the samples are finished

↓

29.
Make sure all data is present, click Finish and follow the prompts

↓

30.
Shut down the Bluehill Software

↓

31.
Copy the file onto a Memory Stick

↓

32.
Shut down the computer and turn off the pump

↓

33.
Copy the results from the Memory stick to the appropriate folder in the O: Drive

Procedure

Action	**By whom**	**How**
1. Print off a copy of dimensions record sheet	Level 1, 2 or 3 competent staff	This can be found in the Record Sheet folder on the O:Drive.
2 . Place the two red coloured Steel I-Beams on the Mayes (BE CAREFUL THESE ARE VERY HEAVY)	Level 1 competent staff	The two red Steel I-Beams need to be placed on the Mayes (CAUTION! THESE ARE VERY HEAVY). Using the Forklift and the Hoist the beams can be manoeuvred onto the Mayes bed, keep them supported with the hoist and a roller until the centre line drawn on the beam lines up with that drawn on the Mayes bed.
3. Raise the loading head up and place it carefully on the end of the I-beams	Level 1 competent staff	Using the forklift, raise the loading head up and place it carefully on the end of the I-beams (again this is very heavy, be careful), with the roller under the beam there is little risk of unbalancing them. Slide the loading head along until it is directly under the load cell of the Mayes.

4. Turn on the Mayes Computer and the Pump.	Level 1 or 2 competent staff	Switch on the Data Logger and the Computer. Turn on the pump at the wall. If possible turn the pump on using the controller on the Mayes.
5. Open the Bluehill software	Level 1 or 2 competent staff	Open the Bluehill software; make sure it is registering a load.
6a. Restart Software	Level 1 or 2 competent staff	If a load isn't being registered, restart the software.
7. Drag the loading head along the I beam, bring down the Mayes head and attach it to Mayes head.	Level 1 or 2 competent staff	Drag the loading head along the I beam and bring down the Mayes head until bolts can be inserted from the loading head to the plate attached to the loading cell. Make sure the nuts are tightened and the loading head and Mayes are firmly attached before raising the loading head up off the beams.
8. Construct the supports; if the beams aren't wide enough clamping supports may be necessary.	Level 1 or 2 competent staff	Construct the supports; if the Beams aren't wide enough clamping supports maybe necessary. Place the supports in the appropriate positions, dictated by the depth of the beam, and secure them in position using the threaded rod and plates. Make sure the set up is symmetrical about the centre of the Mayes.
9. Insert spreader plate underneath beam	Level 1, 2 or 3 competent staff	Restore the Calibration of the Load Cell (the transducers also require the restoration of their calibration to start the test).
10. Restore the Calibration of the Load Cell	Level 1 competent staff	Restore the Calibration of the Load Cell (the transducers also require the restoration of their calibration to start the test).
11a. Place restraints along the beam to stop lateral movement	Level 1, 2 or 3 competent staff	Lateral supports might also be necessary for narrow beams, these should be placed all along the beam and stop the beam from moving laterally
12. Retrieve the samples from the Conditioning Room/Storage Area	Level 1, 2 or 3 competent staff	
13. Measure and record the length and width	Level 1, 2 or 3 competent staff	Measure and record the length and width in millimetres using the tape measure and measure the thickness of the prism in millimetres using the Callipers to 2 decimal places.
14. Open the EN408 Bending stiffness Test file in the Bluehill Software; select the file name and progress through until the pre-test screen is reached	Level 1 or 2 competent staff	Open the EN408 Bending Stiffness Test file in the Bluehill Software; select the file name and where to save the data and progress through entering any necessary data until to reach the pre-test screen.

15. Check the rate of load is still at 0.5mm/min	Level 1 competent staff	Click on the Method Tab and in Control Menu, under Test, check the rate of load has not reset itself to zero and is still at 0.5mm/min or close to that value.
16. Label the beam and drill 3 holes on the beam using template in order to fix deflection transducer mounts to the beam	Level 1 or 2 competent staff	Label the beam and drill 3 holes on the beam using template in order to fix deflection transducer mounts to the beam.
17. Insert the beam into the rig	Level 1, 2 or 3 competent staff	Insert the beam into the rig; if necessary secure the ends in the clamping supports. If there is a central finger joint make sure it is not directly under a loading head.
18. Tighten the lateral restraints	Level 1, 2 or 3 competent staff	Move the restraints to support the sample and prevent it from twisting or moving laterally.
19. Fix two transducer mounts into either side of the beam	Level 1, 2 or 3 competent staff	Fix two transducer mounts into either side of the beam.
20. Mount two transducers on each transducer mount.	Level 1, 2 or 3 competent staff	Mount two transducers on each transducer mount.
21. Balance the load and transducer deflection and lower the head until it is just above the specimen	Level 1 or 2 competent staff	Right click the Load Cell Icon and select Balance. Do the same for transducers. Lower the head down using the controller until it is just above the beam, the closer the better.
22. Reset the Extension	Level 1 or 2 competent staff	Press the Reset Extension button to zero the extension and define the return point.
23. Press the Start Button	Level 1, 2 or 3 competent staff	Press the Start Button and the loading head will begin to move downward.
24. Once the Mayes reach the set load (this is normally 40% of the estimated maximum load) the test will stop and the loading head will return to the zero extension position	N/A	As soon as the Mayes reach the set load of 40% of the estimated maximum load it will stop and automatically return to its zero extension position.
25. Click Next and then Save	Level 1 or 2 competent staff	Click Next and follow the prompts onscreen, then click Save to make sure the Data will not be lost.
26. Dismantle the deflection transducers and transducer mounts.	Level 1, 2 or 3 competent staff	Dismantle the deflection transducers and transducer mounts.

27. Remove the Beam and insert a new specimen	Level 1, 2 or 3 competent staff	Carefully remove the beam and insert another sample as before.
28. Repeat until all the samples are finished	Level 1 or 2 competent staff	Repeat the procedure until all samples are finished.
29. Make sure all data is present, click Finish and follow the prompts	Level 1 or 2 competent staff	Once finished, make sure all data is present, click Finish and follow the prompts. When asked if you want to start a new test with the same parameters click No. The Data will be outputted into HTML and CSV format.
30. Shut down the Bluehill Software	Level 1, 2 or 3 competent staff	Close the Bluehill program
31. Copy the file onto a Memory Stick.	Level 1, 2 or 3 competent staff	Copy all the data from the file on the Mayes computer to a memory stick.
32. Shut down the computer and turn off the pump	Level 1 or 2 competent staff	Close down the computer, shut off the power to the Data Logger and switch both the computer and the pump off at the mains.
33. Copy the results from the Memory stick to the appropriate folder in the O: Drive.	Level 1, 2 or 3 competent staff	When back in the office, copy of the results from the Memory stick to the appropriate folder in the O: Drive.

APPENDIX VI

Summary of the wood working properties of :

1. Angelim Vermelho
2. Cupiuba
3. Evuess
4. Okan
5. Tali

Results of informal tests undertaken at Environment Agency's Osney workshop

Timber Species	Bouyancy	Weight of 980 x 145 x 42 Block	Performance comparison	Blunting	Sawing	Machining	Nailing	Gluing	Morticing	Comments/observations
Cupiuba	Bouyant	5kg	Vs. GH	Worse	Equal	Equal	Nails bend or timber splits. Will need pre-drilling	Dependant on glue, timber function & internal/external use	Easier than Greenhart & Ekki. Same As Oak.	Less odour - antiseptic smell. Easier than Greenheart, harder than Oak. Grain contains softer sections which may abrade/degrade faster.
			Vs. Ekki	Better	Better	Better				
			Vs. Oak	Better	Worse	Better				
Angelim Vermelho	Sinks	6.8kg	Vs. GH	Equal	Worse	Better			Hard to mortice. Same As Ekki, harder than Greenheart	Malodorous, but good workability. Similar to Ekki. Harder than Oak
			Vs. Ekki	Equal	Worse	Better				
			Vs. Oak	Worse	Worse	Worse				
Okan	Sinks	6.4kg	Vs. GH	Better	Better	Better			Harder than Oak, easier than Ekki and Greenheart	Mixed grain, similar to Opepe & Iroko. Drills well and easier than others
			Vs. Ekki	Equal	Better	Better				
			Vs. Oak	Worse	Equal	Better				
Evuess	Sinks	6.5kg	Vs. GH	Equal	Better	Equal			Hard to mortice. Easier than Ekki, harder than Oak, similar to Greenheart	Irregular grain. Works similar to Greenheart, easier than Ekki, harder than Oak.
			Vs. Ekki	Equal	Equal	Equal				
			Vs. Oak	Worse	Worse	Worse				
Tali	Bouyant	5.3kg	Vs. GH	Better	Better	Better			Easy to mortice. Easier than Ekki, Greenheart and Oak.	Open grain. Hard to get smooth machined finished. Drills easy.
			Vs. Ekki	Better	Better	Better				
			Vs. Oak	Equal	Worse	Better				

	WORKABILITY (HAND TOOLS)
	Comparable to oak and easier to work than ekki and greenheart
	Difficult to work across the grain. Comparable to GH and Ekki and harder than oak
	Difficult to work across the grain. Comparable to GH and Ekki and harder than oak
	Difficult to work across the grain. Comparable to GH and Ekki and harder than oak
	Comparable to oak and easier to work than ekki and greenheart

Results of informal tests undertaken at British Waterway's workshop

	MACHINABILITY TEST					WORKABILITY TEST - HAND TOOLS		
NAME OF TIMBER	MORTISE	PLANER	SAW	DRILL 8mm	DRILL AUGER 50mm	HAND PLANER	HAND SAW	HAND CHISEL
ANGELIM VERMELHO	VERY HARD GRADE 5 THE HARDIEST OF ALL THE WOODS TESTED, WILL NEED DRILLING BEFORE MORTISING.	VERY HARD GRADE 5,BUT OK.	GRADE 5 VERY HARD, LOTS OF FINE DUST.	GRADE 4 OK.	GRADE 5 VERY HARD, THIS IS THE HARDIEST OF ALL THE TIMBERS, BITS WILL NOT LAST LONG	GRADE 5 VERY HARD, THE HARDIEST OF ALL TIMBERS, SHINES THE SURFACE WHICH MAKE THE PLANE SLIDE.	GRADE 4 OK	GRADE 5. VERY HARD ACROSS GRAIN, OK WITH GRAIN. GRAIN GOES IN DIFFERENT DIRECTION
OKAN	VERY HARD GRADE 5 WILL NEED GRILLING BEFORE MORTISING.	VERY HARD GRADE 5,SMOOTH FINISH.	GRADE 4,LOTS OF FINE DUST.	GRADE 4 OK.	GRADE 5 VERY HARD	GRADE 5 VERY HARD, TEARS IN ONE DIRECTION.	GRADE 5 VERY HARD	GRADE 4. HARD STRAIGHT GRAIN, HARD TO CHISEL ACROSS GRAIN AND INTO TIMBER
EVEUSS	GRADE 4 VERY HARD WILL NEED DRILLING BEFORE MORTISING.	VERY HARD GRADE 5, SMOOTH IN ONE DIRECTION TEARS IN OTHER.	GRADE 5 HARD, LOTS OF FINE DUST.	GRADE 4 OK.	GRADE 5 HARD	GRADE 5 VERY HARD.	GRADE 5 VERY HARD	GRADE 5. VERY HARD STRAIGHT GRAIN, HARD TO CHISEL ACROSS AND INTO THE TIMBER.
CUPIUBA	VERY HARD GRADE 4, WILL NEED DRILLING BEFORE MORTISING.	GRADE 4 OK SMOOTH FINISH.	GRADE 4 OK	GRADE 3 SAME AS OAK	GRADE 4 EASIEST OF THE WOODS TESTED	GRADE 4 GET A SMOOTH FINISH	GRADE 3 OK	GRADE 3. ACROSS GRAIN OK, WITH GRAIN, GRAIN GOES IN DIFFERENT DIRECTION. CHISEL INTO OK, DIFFICULT TO ROUND
TALI	GRADE 4 EASIEST OF ALL TIMBER TESTED.	GRADE 4 CAN NOT GET IT COMPLETELY SMOOTH, TEARS.	GRADE 3 SAME AS OAK.	GRADE 3 SAME AS OAK	GRADE 5 HARD	GRADE 3	GRADE 3 OK SAME AS OAK	GRADE 3 ACROSS GRAIN OK,WITH GRAIN, GRAIN GOES IN DIFFERENT DIRECTION. CHISEL INTO OK ,DIFFICULT TO ROUND
EKKI	VERY HARD GRADE 5 THE VERY HARD, WILL NEED DRILLING BEFORE MORTISING.	VERY HARD GRADE 5, BUT OK.	GRADE 5 VERY HARD, LARGE AMMOUNTS OF RED FINE DUST.	GRADE 4 OK.	GRADE 5 VERY HARD, THIS IS ONE OF THE HARDIEST OF ALL THE TIMBERS TESTED, BITS WILL NOT LAST LONG	GRADE 5 VERY HARD, BETTER WHEN GREEN, OLDER TIMBER SHINES THE SURFACE WHICH MAKE THE PLANE SLIDE.	GRADE 4 OK	GRADE 5. EXTREMELY HARD ACROSS GRAIN NOT MUCH BETTER WITH GRAIN. GRAIN GOES IN DIFFERENT DIRECTION
GH	VERY HARD GRADE 5 WILL NEED DRILLING BEFORE MORTISING.	VERY HARD GRADE 5, TENDENCY TO MOVE ON THE MACHINE AS THE STRESSES ARE REALISED, SMOOTH FINISH BUT GRAIN LIFTS SHORTLY AFTER.	GRADE 4, LOTS OF FINE GRITTY DUST.	GRADE 4 OK.	GRADE 5 VERY HARD	GRADE 5 VERY HARD, BETTER WHEN GREEN.	GRADE 5 VERY HARD	GRADE 4. HARD STRAIGHT GRAIN, HARD TO CHISEL ACROSS GRAIN AND INTO TIMBER

Notes:
1) The following grading has been adopted: 1 = very good, 2 = good, 3 = fair, 4 = poor, 5 = bad.
2) For comparison (benchmark) purposes, Oak is considered to be Grade 3 (Fair)

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