



Wood-cement composites— Suitability of Western Australian mallee eucalypt, blue gum and melaleucas

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Foreword

An ambitious program of tree crop development is taking place throughout the wheat growing zone of Western Australia, coordinated largely by the Department of Conservation and Land Management (CALM) in collaboration with several hundred farmers. Tree crops including mallee eucalypts and melaleucas are being assessed in growth trials and established on farms in conjunction with wheat as a means of tackling the growing problem of salinity and land degradation. The trees planted are expected not only to ameliorate soil salinity by reducing the level of the water table over time but also to provide merchantable products such as leaf oils and wood-based products.

Harvesting of fresh leaves from mallee eucalypt and melaleuca trees for leaf oil extraction takes place every three to six years, leaving behind large quantities of small diameter stems as waste which is thought to be suitable for little else apart from biomass fuel. Certain types of reconstituted wood composite panels can utilize such material and it may therefore be possible to convert mallee residues into products such as cement-bonded particulate or flake composite boards. Cement-bonded boards are examined in this project as a potential outlet for such residues because they represent a product with the potential for expansion in Australia. They are made from simple, low cost, inert materials and have high natural resistance to agents that readily destroy solid wood and conventional wood-based composite panels which include termites, fire, borers and rot fungi. Cement-bonded panels are also compatible with smaller-scale, localized manufacturing facilities close to the source of the waste wood residues.

The overall aim of this project was therefore to assess the potential suitability of small diameter waste wood from mallee eucalypt and melaleuca trees for the manufacture of wood-cement composites firstly by measuring the compatibility of the wood with cement and secondly by manufacturing test composites of various types. A principle objective was to demonstrate that good quality cement-bonded boards can be manufactured from eucalypt wood including mallee and blue gum using relatively simple manufacturing techniques. It is hoped that the results will generate further interest in wood-cement composites as building materials suited to the Australian environment.

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Simon Hearn

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Abbreviations

CBP	Cement-bonded particleboard
C_A	Wood-cement compatibility index (Area Ratio method)
h	Hours
ha	Hectares
min	Minutes
MOE	Modulus of Elasticity (Young's modulus)
MOR	Modulus of Rupture
OSB	Oriented strand board
T_{max}	Maximum hydration temperature (°C)
R	Hydration Rate (°C/h)
WA	Western Australia
WWCB	Wood wool cement board

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Executive Summary

This report describes four years of research undertaken with the objective of assessing the suitability of mallee eucalypt, blue gum and melaleuca stem residues for the manufacture of wood-cement composite boards. The project forms part of a wider effort to develop viable utilisation strategies for the potentially enormous quantities of waste stem wood left over from harvesting short-rotation leaf oil-producing tree crops such as mallee eucalypts and melaleucas. The primary aims of this research were to measure and improve the compatibility of mallee and melaleuca wood residues with cement and demonstrate that good quality cement-bonded boards can potentially be manufactured from mallee and other fast-grown plantation eucalypt wood using relatively simple manufacturing techniques. Cement-bonded composite materials have been chosen as the subject of investigation in this project for several reasons; including budget and versatility in manufacture, and enhanced resistance to a range of threats to wood and wood-based composites including rot, borers, termites and fire.

A preliminary assessment of the compatibility of selected commercially important mallee eucalypt woody wastes (with and without bark) indicated that the chipped residues were of ‘moderate’ compatibility with portland cement, and only slightly less compatible than that of wood particles from radiata pine. In contrast to mallee wood, the wood from three potentially important species of melaleuca native to Western Australia was found to be of low compatibility with cement. A subsequent pilot study on the performance of chipped mallee eucalypt residue (converted using a readily available, portable, farm-based chipper) in cement-bonded composite boards showed that although well-consolidated boards could be manufactured from most species, their mechanical properties were very poor. This was caused largely by the production of chips of inappropriate size and geometry necessary to adequately reinforce cement-bonded composite boards. The inclusion of bark greatly increased the absorption of water and thickness swelling of boards, identifying the inclusion of bark in mallee wood-cement composites as problematic unless a manufacturing technique (such as an additive) can be found to reduce its adverse effects on dimensional stability of boards.

Following on from the findings of the pilot study, a series of larger experiments designed to improve the properties of cement-bonded composites made from mallee, blue gum and maritime pine wood resulted in greatly improved board properties through the use of large, thin wood flakes. Compared with pine and blue gum, boards made from mallee were compromised somewhat by the presence of thicker flakes; however, the addition of small amounts of simple, non-toxic cement setting accelerators (either CaCl_2 or MgCl_2) greatly enhanced board quality for all species, eliminating the need to pre-soak the wood flakes. Boards produced from thinner flakes of lower density blue gum wood were of good quality due mainly to the production of fine strands. The ability to produce these from the higher density mallee wood was identified as necessary to enhance the strength and quality of cement-bonded boards made from mallee stem wood.

The project also examined the commercial-scale manufacture of insulating wood wool-cement board (WWCB) from maritime pine and blue gum wood, since the mallee stem wood was too small in diameter to convert into wood wool for this purpose. WWCBs made from maritime pine and blue gum wood were of similar strength to randomly sampled commercial boards made from radiata pine. Factors that reduced board strength across all species included low board density and unevenness in distribution of wood wool in boards. An important finding was that boards made from blue gum wood wool had a greater capacity to resist impact loads, probably because of the slightly higher density of the boards and stronger strands produced from the hardwood.

In conclusion, the project has identified cement-bonded composites as a potentially appropriate end-product for mallee eucalypt wood wastes and fast-grown blue gum wood. This and other research works in the field of wood-cement composites suggest many avenues by which the mechanical properties of cement-bonded boards made from eucalypt wood wastes could be further improved. However, the only major problem requiring immediate further attention identified in this study is the reduction of flake thickness in the case of the mallee wood.

1. General Introduction

1.1 Mallee eucalypt and melaleuca in agroforestry

Rising water tables in the wheat belt of Western Australia (WA) due to extensive clearing of native vegetation over the last 100 years is transferring salts from ancient marine sediments to the upper soil horizons with devastating effects on agricultural productivity. Almost 10% or 1.8 million ha of wheat belt soils are now affected to some extent by salinity (Government of Western Australia 1996). This is forecast to increase to 50% over the next 50 years unless large-scale revegetation of affected areas is undertaken (Ferdowsian *et al.* 1996). To help rectify the problem an ambitious program to establish large-scale tree plantations has been put in place and it projected that by the year 2020, 800 000 hectares of tree crops (mainly eucalypts) will have been planted on farmland (Shea and Hewett 1997). It is hoped that such plantations will have the dual effect of ameliorating rising water tables and accompanying soil salinity as well as providing income for farmers through the sale of eucalypt leaf oils and wood (Berry 1997, Shea 1998). Around 45 species of eucalypts and acacias are currently being tested for their ability to grow on salt affected land throughout the wheatbelt of WA (Shea 1998). Preliminary results suggest that mallee eucalypts, which are hardy, lignotuberous, multi-stemmed eucalypts adapted to the semi-arid zones of eastern and western Australia are well suited for planting on salt-affected sites and have the potential to generate significant volumes of wood and essential leaf oils (Wildy *et al.* 2000).

Five species in particular, *Eucalyptus polybractea* R.T. Baker, *E. angustissima* F. Muell ssp. *angustissima*, *E. kochii* Maiden and Blakely ssp. *plenissima* (Gardner) Brooker, *E. horistes* Johnson & Hill and *E. loxophleba* (Benth.) show great promise. *E. polybractea* is the premier source of high grade cineole oils (1,8-cineole is the principle active constituent of medicinal oils) in Australia (Boland *et al.* 1991). Leaf oil is the main commercial product derived from mallee eucalypt plantations in Australia, but commerce is currently limited to niche markets in high quality pharmaceutical oils rather than the larger market for general purpose eucalyptus oil, which is supplied at lower cost by China (McKelvie *et al.* 1994). In future Australia could potentially supply very large markets for 'new generation' industrial solvents based on eucalyptus oil (Wildy *et al.* 2000).

There are currently around 10 000 ha of mallee eucalypt plantations in WA, with projections for sharp increases in planting rates (Bartle, J. pers. comm. 1999). The trees coppice prolifically and subsequent harvesting could take place as frequently as every 1 to 2 years (Shea 1998). However, cineole yields from mallee eucalypt leaves are highest in older leaves around 5 years of age (Eastham *et al.* 1993). Later harvest of trees is therefore the preferred option, resulting in the generation of larger quantities of woody biomass left over after stripping the leaves for distillation. Economic analysis indicates that the financial viability of oil production from mallee eucalypt plantations depends on farmers finding a commercial outlet for the woody residues (Bartle *et al.* 1996). Around 3 tonnes/ha/year of clean dry woodchips can be produced at most sites after a 3-5 year rotation (Bartle 2001), so, plantations of oil-mallee eucalypt could potentially generate around 13 million cubic metres of woody biomass annually in WA (Shea 1998). A preferred option for disposing of the woody residue is by chipping, making a ready source of fuel for distillation, electricity generation and carbonisation into activated charcoal products (Evans 1997, Fung 1999), and possibly raw material for the manufacture of wood-based composites (Bartle 2001).

The genus *Melaleuca* (fam. Myrtaceae) comprises an estimated 200 species endemic to Australia, mainly Western Australia, and around 8 from island neighbours to Australia's north (Holliday 1989). Species and provenances span a very wide range of sites from the arid interior to swampy, saline estuarine and coastal sites (Holliday 1989, Doran and Turnbull 1997). Selected species of *Melaleuca* are of considerable economic importance in several developing countries, particularly S.E. Asia, for the production of essential oils such as cineole (Brophy and Doran 1996), as well as flowers and pollen for honeybees, and in Australia as ornamental plants. The wood is also an important source of fuel in some countries (Wang *et al.* 1981, Gardner 1989). Importantly, many *melaleuca* species are adapted to salty, low-lying, water-logged soils, and are among the only large plants which will tolerate such conditions (Holliday 1989). The introduction of *melaleucas* into the agricultural landscape in WA

for 'farm-forestry' is still in the species and provenance testing stage, and there is considerable potential for melaleucas to effectively combat waterlogging and salinity on farmland and to be cultivated by farmers for the commercial production of leaf oils and secondary wood products.

1.2 Wood-cement composites in perspective

This project deals with the potential use of waste wood residues from mallee eucalypt and melaleuca trees planted for salinity mitigation and leaf oils on farmland for the manufacture of wood-cement composites. Cement-bonded wood composite boards have been chosen as they are extremely versatile, with wider application than any other wood composite board product (Dix 1989). Yet they are not widely used in the Australian building industries. The industry is largely unfamiliar with these types of materials, and there are real and perceived problems associated with wood-cement compatibility, strength and weight, and longer production cycles for cement-bonded boards. A summary of wood-cement composite types, characteristics and uses is provided below.

Mineral-bonded wood or other lignocellulosic composites are moulded or compressed blocks and panels containing approximately 30-70% by weight of wood in various forms and 70-30% mineral binder (Simatupang *et al* 1977). Chittenden (1972) divides mineral-bonded wood composites into two distinct groups, (1) composites in which wood is incorporated as an aggregate in the mineral matrix (as fibres, sawdust, shavings or particles) and (2) composites in which the cement (or other mineral binder) acts purely as a binder, such as wood wool cement board or flake board. Wood can serve as a low-cost filler and/or reinforcing material which greatly improves the stiffness, fracture toughness, strength-to-weight ratio, creep deflection, and thermal and acoustic resistance of cement when incorporated into a composite bonded with cement (Goodell *et al.* 1997). The most common types are cement-bonded particleboard (CBP), wood wool cement board (WWCB) and cement bonded fibreboard, commercially known as 'Hardiplank' in Australia. Wood-cement composites have much higher resistance to both decay (i.e. mould, rot, borers and termites) and to combustion than resin bonded boards or solid wood (Pease 1994, Ramirez-Coretti *et al.* 1998, Moslemi 1989, 1993, Goodell *et al.* 1997, Cziesileski 1975, Dix 1989).

Density and flexural properties of a range of different wood-cement composites compared with those of some conventional wood composites are shown in Table 2.2 (Data sourced from Elmondorf 1963, Youngquist 1999, Wolf and Gjinolli 1997, 1999, Cabangon *et al.* 2002, Ma *et al.* 2002). Note that cement-bonded oriented strand board (OSB) can be manufactured with similar mechanical properties to its resin-bonded counterpart.

Table 1-1: Selected mechanical properties of different types of reconstituted wood panels including WWCB, cement-bonded fibre and particleboards

Panel Type	Density (Kg/m ³)	MOR (MPa)	MOE (GPa)	Ref.
WWCB (non-structural)	375-550	1.7 - 5.5	0.6 - 1.3	1
WWCB (Structural)	650-750	7 - 15	1.8 - 2.7	2
WWCB (Oriented)	700-800	17	4.0	2
Resin-bonded particleboard	≈750	11 - 16.5	1.7 - 2.8	3
Plywood	≈750	20 - 48	6.9 - 13.1	3
Orientated Strand Board (OSB)	≈750	47	8.3	3
Cement-bonded OSB	1000-1200	23 - 50	6.5 - 8	4,5
Medium Density Fibreboard	640 - 800	24 - 34.5	2.4 - 3.4	3
Cement-bonded Fibreboard	1200-1300	25	10	6
Cement-bonded Particleboard	1250 - 1450	9 - 15	4.5	3,4

(1) Kollmann 1963b, (2) Cabangon *et al.* 2002, (3) Youngquist 1999, (4) Elmondorf 1963, (5) Ma *et al.* 2002, (6) Wolfe and Gjinolli 1997, 1999.

Wood-cement composites assume considerable importance where the technology and materials for manufacturing conventional resin-bonded wood composites are expensive or unavailable (Kavvouras 1987, Badejo 1988, Alberto *et al.* 2000). They can also be manufactured where available wood or plant waste resources are unsuitable for production for sawn timber or conventional resin-bonded

wood composites (Kelly 1977, Ledhem *et al.* 2000b). More importantly, they are much better suited to high fire, weathering and bio-deterioration risk applications to which solid wood and resin bonded composites are vulnerable (Stillinger and Wentworth 1977, Dinwoodie and Paxton 1991, Chapola 1989). Cement-bonded composites emit no toxic wastes during manufacture (van Elten 2000) and employ an inert binder free from the health risks associated with the use of resin bonded composites (Chen and Hwang 1998).

Wood-cement composites, especially the aggregate types are commonly referred to as being virtually incombustible (Ramirez-Coretti *et al.* 1998, Moslemi 1993, Topf 1989a, b, Deppe 1977, Stillinger and Wentworth 1977). The resistance to fire of aggregate-cement composites such as CBP is attributed to the lower content of organic matter and the crystal water in the binder. Heat evolution and spread in the material, and smoke and flame behaviour are strongly correlated with the wood-cement ratio used (Topf 1989b).

Although often high in density the relatively low strength of wood-cement composite panels limits them largely to non-structural paneling or roofing applications (Karam and Gibson 1994, Oyagade *et al.* 1995, Xiong 1996, Wolf and Gjinolli 1999). Paradoxically, a significant advantage of wood-cement composites to engineering applications appears to lie in their ability to absorb and dissipate mechanical energy (Wolf and Gjinolli 1997, 1999). This, as well as good sound dissipation and absorption properties, has attracted research and development of wood-cement composites as very practical and cost-effective highway sound barriers (Wolf and Gjinolli 1999, Lan and Huang 2000, Boothby *et al.* 2001). Wood-cement composites can also be manufactured to exhibit a range of energy dissipating properties advantageous in areas subject to seismic activity and/or heavy wind loads such as hurricanes (Wolfe and Gjinolli 1997, 1999). For these reasons, cement-bonded wood panels have become a significant component of residential cladding materials in Japan, where building codes place strong emphasis on material resistance to earthquakes and fires, assuming a 41% market share in 1991 (Kuroki *et al.* 1993, 1995).

Despite their higher weight-to-strength ratio, wood-cement composites have become popular, particularly in Europe and Asia, for use as exterior siding, roofing and flooring applications to meet increasingly stringent building design regulations for fire, and failure in service due to deterioration. Some typical external applications well suited to products such as CBP include agricultural buildings, pre-fabricated and mobile buildings, flat roofing, industrial and exterior domestic cladding, tunnel linings, highway sound-barriers, fire-barriers and paving tiles (van Elten 2000). The manufacture and use of CBPs for domestic dwellings is probably furthest advanced in Russia, Western Europe and Japan where surface embossing and painting techniques are used to give stone, brick or solid wood grain finishes to modular exterior cladding (Frick 1989, Kuroki *et al.* 1995, 1997). In recent years, CBP manufacturing and utilisation in housing construction has grown in countries such as Mexico where there is a ready market for mass-produced low-cost, 'fold-out' kit homes (Solorzano 1989, Buys 1989, 1995).

Products such as CBP have been shown to have a long service life, retaining and even increasing its strength after years of exposure to the elements. For example, boards exposed outdoors to temperatures ranging from -55°C to 55°C in the Moscow region over 12 years retained a high average bending strength of 16 MPa (Sergeev *et al.* 1995). The strength properties including stiffness of CBP actually increase markedly with time in a given storage condition (Dinwoodie and Paxton 1989). Boards held for 8 years at 20°C and 65% r.h. increased by almost 12% in strength 4 months after manufacture. A controlled outdoor weathering test of CBPs in Britain over 10 years by Dinwoodie and Paxton (1989) found that strength of CBPs increased by around 45% over the first 3 to 5 years but then declined by about the same amount over the next 5 to 7 years. Enhanced strength and durability of wood-cement composites with aging has been attributed to the 'mineralisation' or 'petrification' of the wood elements by cement minerals (Parameswaran *et al.* 1977, Bentur and Ackers 1989). To place wood-cement composites in perspective with other commercial wood panels, Samek (1978) found that CBP underwent the lowest total and irreversible thickness swelling after exposure to humidity cycling (five cycles) between 27 and 97% compared with a range of commercial UF and PF bonded particleboards, plywoods and hardboard. In a study by Sekino and Suzuki (2002) cement-bonded boards also showed excellent dimensional stability and only slight reduction in mechanical properties after outdoor exposure for 10 years, greatly out-performing other wood-based panels.

Despite their obvious benefits compared with other types of wood panels, there are several factors that have prevented wood-cement composites from becoming more widespread (Moslemi 1989). The most significant of these is the long initial and post-press curing time of the portland cement binder, which leads to reduced production capacity and a requirement for a large inventory of boards during curing (Lipinski 1989, Hsu 1992, Mallari *et al.* 1997). The high weight-to-strength ratio and machine wear of products such as CBP (due to their high cement content) compared with resin bonded particleboards has also reduced their popularity (Lee and Short 1989), despite the higher toughness and durability of cement-bonded boards. A third major obstacle to further successful development of wood-cement composite industries is variation in wood compatibility with cement. There is extreme variation in compatibility among both hardwoods and softwoods with portland cement (Sandermann and Kohler 1964, Hachmi and Campbell 1989) resulting in strong species specificity among potential raw materials for wood-cement composite manufacturing industries. There is no information about the compatibility of many wood species with portland cement or experience in converting and using them for cement bonded boards of different types.

The mechanical properties of composite materials including wood-cement composites are a direct function of the interface bonding between the reinforcing or filler fibre and the matrix and are greatly affected by the type, content, geometry and arrangement of the reinforcement or filler (Brandt 1995, Razi *et al.* 1999). Bond strength in wood cement composites is largely dependent on hydrogen-bonding between the wood or fibre surface and the cement matrix (Coutts 1983, Coutts and Knightly 1984). The wood or fibre surface, modified chemically and physically by method of cutting, extractive enrichment, deposition of foreign materials, and reaction with oxygen and light significantly affects its interaction with most binders (Zavarin 1984). Surface roughness of wood flakes or strands has a positive affect on the bond strength with portland cement (Kayahara *et al.* 1979). The properties of wood-cement composites are significantly influenced by the content, form, arrangement and other characteristics of the wood reinforcement (Kayahara *et al.* 1979, Stahl *et al.* 1997, Badejo 1988).

There have been numerous different strategies for improving the compatibility of wood with cement and other mineral binders, and increasing the strength of wood-cement composites, some of which are employed successfully. Strategies include modifying the wood through extractive removal, pre-treatment with chemicals, and modification of wood content, form and arrangement in the composite. For example, wood in the form of strands imparts greater flexural properties to cement-bonded composite boards than particles and hence permits a much lower cement:wood ratio to be used (Kayahara *et al.* 1979). Modification of binder and its curing include altering the cement type (composition, mineral supplements) and amount, curing conditions (temperature, time, atmosphere), and the use of chemical accelerators and/or fortifying agents.

The compatibility of wood with cement can be strongly influenced by such factors as the season in which it is cut (Weatherwax and Tarkow 1964, Biblis and Lo 1968) and the delay between cutting and use (Shwartz and Simatupang 1984, Sudin *et al.* 1989). The sugars and starches present in wood have been previously identified as the most critical compounds causing incompatibility between wood and cement, especially in softwoods (Sandermann *et al.* 1960, Davis 1966, Bruere 1966, Biblis and Lo 1966). This means that even simple measures like selecting the time of cut (i.e. before spring leaf flush) or log pre-storage can significantly influence wood-cement board quality (Schubert *et al.* 1990).

The cement content strongly influences board properties. The optimum cement content needs to be balanced against the high cost of portland cement relative to wood, and its contribution to board weight (Elmendorf 1963, Moslemi and Pfister 1987). The effect of adjusting wood-cement ratio is different for MOR and MOE (Moslemi and Pfister 1987, Oyagade 1990). The flexural properties of CBPs are strongly correlated with board density, however, for any given board density, its bending strength (MOR) is decreased by further increasing the cement/wood ratio (Oyagade 1990). Bending strength can be increased significantly between the cement:wood ratios of 1.5:1 and 2:1, but decreases at above 2.5:1. Stiffness or Young's modulus (MOE) increases linearly between 1.5:1 and 3:1 (Moslemi and Pfister 1987).

The addition of cement setting accelerators also strongly influences the strength of wood-cement composites. Simple inorganic electrolytes such as CaCl_2 and MgCl_2 are among the most effective

additives in counteracting the inhibitory effects of many woods during composite manufacture (Zoulalian *et al.* 1997, Wei *et al.* 2000, Wei and Tomita 2001). For example, the bending strength (MOR) of CBP containing fir (*Abies grandis*) was increased almost 400% by the addition of 3% CaCl_2 (Ahn and Moslemi 1980). Other commonly used additives include Na_2SiO_3 and $\text{Al}_2(\text{SO}_4)_3$, often in combination to assist with consolidation and strength development over time (Nagadomi *et al.* 1996, Simatupang *et al.* 1977, Kühn and Meir 1990).

1.3 Objectives of this project

Using the some of the knowledge gained from previous research and experience in testing wood compatibility with cement and manufacturing wood-cement composites, the overall aim of this project is to investigate and promote the utilisation of waste wood and bark residues generated from short-rotation mallee eucalypt and melaleuca trees for the manufacture of wood-cement composites. The manufacture of non-toxic, durable cement-bonded composites from the residues could be a viable value-adding option for some of the wastes that would otherwise be dumped, burned or put towards low-value uses such as biomass fuel.

The first objective of this project is to determine and report on the compatibility of mallee eucalypt and melaleuca wood species of interest for salinity control and leaf oil production with portland cement. The effects of different species, ages and growing sites, and the presence/absence of bark in samples on its compatibility with cement are assessed in Part 2 of this report. In the case of the melalucas, the effect of removing inhibitory extractives from the wood is also investigated.

The second objective of the project is to undertake a pilot study to determine whether cement-bonded boards of acceptable quality could be manufactured from mallee eucalypt waste residues that had been converted to particles using a relatively simple and readily available chipper shredder designed to break down small diameter woody wastes. The effect of including bark in the particles on the mechanical properties and water resistance of boards is assessed. It will be necessary to find out what effects the particle geometry produced by chipping might have on the flexural (strength) properties of cement-bonded boards manufactured according to guidelines given by previous workers in the field. Boards made from mallee eucalypt wood are compared with those made from wood flakes of radiata pine, which are normally used to manufacture conventional resin-bonded particleboards. The findings are reported in Part 3 of this report.

The third objective of the project will be to follow on from the experience gained in manufacturing trial boards from chipped mallee eucalypt residues to produce better quality wood-cement composites. The effects of adjusting parameters such as flake size and thickness, wood pre-treatment and board curing temperature on board properties are assessed, with the aim of producing boards that meet or exceed International Standards Organization (ISO) requirements for compressed cement-bonded board products. Boards made from mallee eucalypt were compared with similar boards made from three other timbers grown for commercial wood production in Western Australia; i.e. blue gum (*Eucalyptus bicostata*), maritime pine (*Pinus pinaster*) and radiata pine (*Pinus radiata*). Although mallee eucalypt stems are too small to be converted to wood wool, part of this study also includes an evaluation of the performance of blue gum and pine wood in the manufacture of WWCBs in a factory located in Bendigo, Victoria that produces low-density, non-structural wood wool slabs designed for insulation purposes. Boards made from the Western Australian-grown woods are compared with similar boards manufactured at the factory from radiata pine and sold for internal roof and wall linings. The findings from this work are presented in Part 4 of this report.

The project aims to demonstrate that wood-cement composites can be a viable conversion option for waste lignocellulosic residues left over from the mallee eucalypt leaf oil industry. Wood-cement composites may be one of the few options available for utilising this type of small-diameter waste which likely to contain bark. Because of its small diameter and bark content, it is unsuitable for solid timber or conventional resin-bonded composite panels.

2. The compatibility of mallee eucalypt and melaleuca wood species with portland cement

2.1 Introduction

There is currently no information about the suitability of mallee eucalypt or melaleuca residues for the manufacture of wood-based composites. Part 2 of this report presents information on the compatibility of chipped mallee eucalypt and melaleuca residues with portland cement. This was done by measuring the effect of chipped wood and bark residues on the hydration of portland cement and deriving appropriate wood-cement compatibility indices for each wood type. Wood and bark residues from five species of potentially important oil mallee eucalypt and three species of potentially important melaleuca were measured. Cement hydration tests can be used to measure the effect of lignocellulosic material on the exothermic reaction of portland cement as it hydrates, under controlled conditions (Sandermann and Kohler 1964). Fixed amounts of wood particles, portland cement and water are thoroughly mixed and placed inside an insulated container with a thermometer or thermocouple that measures the increase in temperature generated as the cement hydrates. Temperatures are normally monitored over a period of 24 hours and from these measurements, the maximum temperature reached in the mix, the time taken to reach this and the hydration rate can be easily determined. The wood-cement compatibility indices can then be used to rank different wood samples for their inhibitory effect on cement hydration.

2.2 Aim

To assess using established scientific methods the compatibility with portland cement of chipped wood samples from mallee eucalypt and melaleuca species of current or future commercial importance for salinity mitigation and leaf oil production. Principle objectives include determining the effects of factors such as tree age and growing site, and presence/absence of bark in the mallee residues; and the effect of extractive removal from melaleuca samples by soaking in cold water for 24 h on wood-cement compatibility.

2.3 Materials and Methods

2.3.1 Wood sample collection and conversion

The mallee eucalypt trees available for sampling were multi-stemmed, shrub-like, and less than 3m in height. Stem diameter ranged from approximately 10 to 40 mm, necessitating the removal of all stems present at between 0.3 and 1.3m in height. Species sampled were *Eucalyptus polybractea* R.T. Baker, *E. angustissima* F. Muell ssp. *angustissima*, *E. kochii* Maiden and Blakely ssp. *plenissima* (Gardner) Brooker, *E. horistes* Johnson & Hill and *E. loxophleba* ssp. *lissophloia* (Benth.). Wood was sampled from the mallee eucalypt field trials in April/May 1999 from two of the blocks at each site, one containing the 2.5 year old coppice and the other containing 6-year-old seedling trees. Due to cyclone damage at Canna in 1998, insufficient material was available for sampling at this site, so five sites with varying rainfall, Kalannie, Trayning, Beverly, Newdegate and Esperance are represented in this study. One site (Newdegate) had only 2.5-year-old coppice available for sampling. Two trees were cut at random from each block.

The melaleuca trees were available only from native populations growing along riparian strips that are subject to periodic waterlogging. Wood samples were collected from native populations of three species of potential commercial interest; *Melaleuca lateriflora* Benth, *Melaleuca acuminata* F. Muell. and *Melaleuca uncinata* R. Br. Three small diameter (<10 cm) trees from each species were destructively sampled. For comparison, wood residues from a ubiquitous crop fodder tree, tagasaste or tree lucern (*Chamaecytisus proliferus* var. *palmensis* (Christ) Hansen & Sunding), were also sampled.

The trees were multi-stemmed, reaching around 2 m in height. Stems from three trees of each species were sampled using a chainsaw in a similar manner to that described above for the mallee eucalypts. The locations of the sampling sites for mallee eucalypt and melaleuca trees are shown in Figure 2.1

Due to the youth and small diameter of the sampled mallee eucalypt and melaleuca trees, the wood represented was all sapwood. Once the stems were cut, the leaves were removed and the stems separated into two portions, one of which was stripped of bark. The wood was then air dried for two weeks, and the barked and de-barked portions of each tree were chipped separately in a MTD Chipper-Shredder. The residues were bagged and sent to Canberra where they were separated by sieving into four size classes (<3.86 mm, 2.4 to 3.86 mm, 1.68 to 2.4 mm and <1.68 mm). The 1.68 to 2.4 mm fraction from each tree (with and without bark) was retrieved and kept in a conditioning room maintained at $20 \pm 1^\circ \text{C}$ and $65 \pm 5\%$ r.h. for three weeks. This size class was used to examine the effect of mallee eucalypt or melaleuca wood on the hydration of cement. Two 5 g samples (one with bark and one without) from each tree were placed in open-topped plastic tubes. Samples were returned to the conditioning room until use. Two samples of commercial radiata pine sapwood particleboard flakes were also prepared and tested in the same manner for their compatibility with cement.



Figure 2-1: Sampling locations for mallee and melaleuca trees in Western Australia. Rainfall: Kalannie, Trayning 300 mm; Canna, Newdegate 350 mm; Beverley 500 mm; and Esperance 600 mm per annum.

2.3.2 Removal of extractives

One of the most common methods of preparing wood for the manufacture of wood-cement composites is to pre-soak it in water at ambient temperature to remove inhibitory water-soluble extractives (mainly polysaccharides and/or heartwood tannins). It was therefore relevant to determine what effect this simple pre-treatment might have on the compatibility of melaleuca and tagasaste wood with cement. From each prepared and conditioned wood sample, 7 g of material was removed and soaked in water at ambient temperature (20°C) for 24 h to remove inhibitory extractives. Each sample was placed in a 600 mL plastic container into which 500 ml of distilled water at 23°C was added and stirred to submerge the wood. The water was decanted and replaced with fresh 500 mL aliquots after 6 and 12 h. Pre-soaking was undertaken in a controlled temperature room set at $20 \pm 1^\circ\text{C}$ to eliminate any effects of diurnal and day-to-day temperature fluctuation. After 24 h the samples were removed. Wood samples were strained through 0.5 mm mesh. Strained samples were air dried for 7 days and re-conditioned at 20°C and $65 \pm 5\%$ r.h. to 12% for approx. 3 weeks prior to testing for wood-cement compatibility.



(a)



(b)



(c)

Plate 2-1:(a) mallee eucalypt hedgerows, (b) hedgerow ready for harvest, and (c) Stem wood material to be utilised for composites after chipping

2.3.3 Measurement of wood-cement compatibility

To prepare each cement hydration sample 100 g of fresh, dry portland cement (Blue Circle Southern Cement batch no. 041MA01) was thoroughly mixed with 43.5 mL of distilled water in a sealable 'Dalgrip' polythene bag for 2 minutes. The wood wool or flour sample was then added and massaged through the cement slurry until evenly mixed. The tip of a temperature thermocouple (Type J) was then taped to the outside of the sample bag and enclosed within the body of the cement or wood–cement mix by folding the bag and contents around it. The folded bag was then secured with adhesive tape, placed in a 4 mm thick polystyrene cup and sealed inside a 1 L capacity thermos flask. This process was carried out for six samples in turn. A cement hydration temperature logging apparatus (illustrated in Plate 2.2), similar to that used by Irle and Simpson (1993), was used to measure the heat of hydration of six wood–cement samples over 23 hours. The temperature in each sample was recorded at 15 minute intervals. A cement hydration temperature curve for each sample was plotted using the progressive average of each three successive readings. All experiments were done in a controlled temperature room maintained at $20 \pm 1^\circ\text{C}$. This is because ambient temperature at the time of mixing and setting affects cement hydration and strength (Lea 1971, Dodson and Rajagopalan 1979, Taylor 1997), and day-to-day temperature variation has been shown to significantly affect the results of wood-cement compatibility tests (Miller and Moslemi 1991a).

From each plot of hydration temperature v time, four wood-cement compatibility indices were derived. These were (i) maximum heat of hydration temperature (T_{max}); (ii) time taken to reach T_{max} (t); (iii) hydration rate (R) = temperature rise/t; and (iv) the C_A -factor of Hachmi *et al.* (1990), which is the area beneath the hydration curve for a wood-cement sample divided by that of pure cement, expressed as a percentage.



Plate 2-2: Apparatus used to measure cement hydration temperature.

2.3.4 Experimental design and statistical analysis

Wood samples from the mallee eucalypts and melaleucas were collected, prepared and tested for compatibility with cement in two different experiments. Therefore results were analysed separately and are presented separately here. However, a general comparison between the results can be made since the tests were undertaken using the exactly the same experimental conditions. The experimental designs for the testing of wood-cement compatibility of mallee eucalypt and melaleucas both used factorial principles. The effects of three fixed factors on wood-cement compatibility were analysed, i.e. species, the presence/absence of bark, and extractive removal, and also various random effects, such as those associated with replicates obtained from different trees.

The design of the experiment that examined the effect of mallee eucalypt wood and bark residues on the hydration of cement reflected the nesting of species/age class plots within sites (locations) and the availability of wood from 2 trees (replicates) per species and plot. At each location, there were three plots, each containing trees of a different age-class. Therefore it was not possible to replicate each age-class at the site level as the two trees from each species/age class plot were taken from within the same plot due to restrictions on tree removal. During assessment of the effect of wood and bark residues on cement hydration, each daily run of 6 cement hydration samples contained 3 species/age class combinations and samples 'with' and 'without' bark. Every 16 successive hydration samples contained all species/age class combinations randomised for one tree and site. All site, species, age class and

bark combinations were assayed for the first tree followed by all of those for the second. A total of 180 mallee eucalypt samples were tested over a period of 45 days.

The smaller experiment designed to test the compatibility of three melaleuca species with cement contained 12 species/bark/soaking combinations; each of which contained two hydration samples for each of three trees per species. A total of 72 melaleuca and 4 tagasaste samples were tested over a period of 15 days. Species/bark/soak combinations were fully randomised for each tree over the duration of the experiment. Within each daily 6-sample run, three tree/bark content combinations were tested, incorporating the unextracted and extracted sample for each. Four cement-control runs (containing no wood sample) were randomly interspersed throughout the experiment.

The main effects of, and interactions between, each of the three factors on $T_{\max}$, t , R , and C_A -factor were tested for significance using an appropriate multi-factorial ANOVA model at the 5% significance level. Before the final analysis, diagnostic checks on the normality and variance of the data were undertaken. The factorial design of the experiments allowed data to be averaged across non-significant ($p > 0.05$) effects thereby giving the experiments greater precision. Significant results are plotted graphically and bars representing the least significant difference ($p \leq 0.05$) are included on graphs to facilitate comparison of means.

2.4 Results and Discussion

The hydration of portland cement was significantly ($p < 0.001$) affected by species of mallee eucalypt, and the presence of bark in the wood residue (Table 2.1). Compatibility indices for the mallee eucalypt wood and bark residues and radiata pine (RP) are shown in Table 2.2. The effects of selected mallee eucalypt wood and bark residue samples on the exothermic hydration of portland cement are also illustrated in Figure 2.2. The maximum rate of increase in temperature during the heat evolution stage for neat cement and water was 3.4°C/h ($C_A = 100\%$). Note that a sample of higher compatibility (illustrated by *E. polybractea*) reduced the maximum temperature attained by about 8°C , resulting in a decreased hydration rate (from 3.4°C/h to 1.6°C/h), but did not greatly increase the time taken for the cement to set. Such samples could be classed as 'moderately compatible' with cement (R between 1.5 and 2°C/h). For samples of lower compatibility (as illustrated by *E. angustissima* and *E. loxophleba* with bark), both $T_{\max}$ and t were significantly altered. Note from Table 2.1 that the age of the residues and where they came from (site class) did not significantly influence wood compatibility with cement, however there was a detectable effect on hydration ($T_{\max}$, R and C_A -factor) arising from an interaction between age and bark content (Table 2.1).

Table 2-1:F-probabilities (p-values) for main effects and interactions between factors on cement hydration reaction indices.

	Tmax	Time	Rate	CA-factor
Site	n.s.	n.s.	n.s.	n.s.
Age	n.s.	n.s.	n.s.	n.s.
Species	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Age x Species	n.s.	n.s.	n.s.	n.s.
Bark	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Age x Bark	$p = 0.041$	n.s.	$p = 0.017$	$p = 0.041$
Species x Bark	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Age x Species x Bark	n.s.	n.s.	n.s.	n.s.

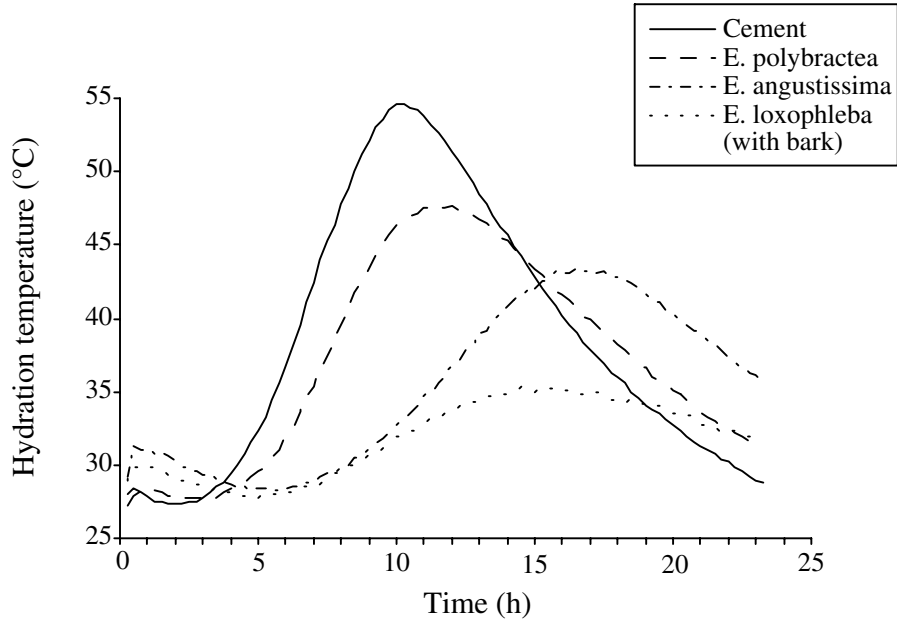


Figure 2-2: Typical exothermic reactions (temperature v time) for pure cement and cement containing mallee eucalypt wood residue of selected species. All results shown are for 2.5 y.o. residues from Beverley site.

2.4.1 Mallee eucalypt species differences and the effect of bark

Table 2.2 and Figure 2.3 illustrate the effects of different mallee eucalypt species (with and without bark) on the hydration rate of portland cement. In the absence of bark, all species inhibited cement hydration to a similar degree and could be ranked as moderate in compatibility with cement. *E. horistes* had the highest average compatibility ($R = 1.78$ °C/h, $C_A = 70.8\%$), while *E. angustissima* had the lowest ($R = 1.52$ °C/h, $C_A = 59.9\%$). The hydration rate for radiata pine flakes was 1.88 °C/h ($C_A = 78\%$), not significantly higher than mallee eucalypt residue without bark.

Table 2-2: Cement compatibility indices of mallee eucalypt wood species (with and without bark) and radiata pine (RP).

	E. angustissima		E. horistes		E. lox. liss.		E. plenissima		E. polybractea		RP
	n.bark	bark	n.bark	bark	n.bark	bark	n.bark	bark	n.bark	bark	n.bark
Tmax	42.6	39.9	45.5	43.9	44.0	32.4	44.7	44.7	43.5	41.7	46.1
Time	14.3	16.5	13.2	14.9	12.3	15.8	13.7	13.9	12.7	13.9	13.2
H rate	1.5	1.2	1.8	1.5	1.7	0.5	1.7	1.7	1.6	1.4	1.8
CA	59.9	50.7	70.8	66.7	64.8	25.5	68.5	68.7	62.5	58.6	73.0

N.B. Indices for cement control were 55.7°C , 9.6 h, 3.4°C/h and 100% .

As can be seen in Figure 2.3, the presence of bark in most of the mallee eucalypt residue samples had no significant effect their compatibility with cement, except in the case of *E. loxophleba* where the bark strongly inhibited cement hydration. Bark in the wood samples of *E. angustissima* also inhibited cement hydration, but not to the same extent as for *E. loxophleba*. Wood samples of *E. horistes*, *E. kochii* ssp *plenissima* and *E. polybractea* all retained their moderate compatibility ($R = 1.5, 1.7$ and 1.6 °C/h respectively) with cement even when bark was present, suggesting that the complete removal of bark from these species may not be necessary in order to manufacture well-consolidated cement-bonded composites. The chemical composition of bark varies greatly among wood species (Jensen *et al.* 1963), and the results here for *E. loxophleba* compared to the other mallee eucalypt species suggests that this may be the case even among relatively closely related eucalypt species such as mallee eucalypts.

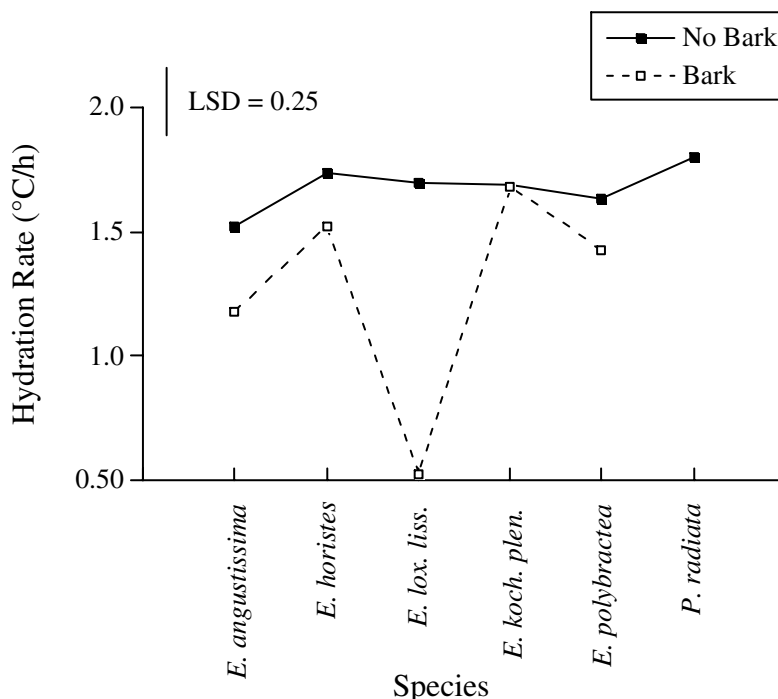


Figure 2-3: Effect of species and of bark content in residue on wood-cement compatibility (hydration rate) of mallee eucalypt, averaged across site and age class.

Note from Table 2.2 that the compatibility indices of many of the mallee eucalypt species, particularly *E. horistes*, *E. plenissima* and *E. polybractea* were similar (not statistically different) to those of radiata pine. Radiata pine is considered suitable for wood-cement composites and used in Australia for the commercial manufacture of wood wool cement boards (Woolley, J. pers. comm. 1998). This suggests that from the point of view of wood-cement compatibility, these species (with or without bark) may also be suitable for wood-cement composites, notwithstanding possible confounding effects of wood flake geometry on board mechanical properties, which will be examined in Parts 3 and 4 of this report.

2.4.2 Site and age effects on mallee eucalypt compatibility

Despite the variation in average annual rainfall among the five different trial sites throughout the wheat belt zone of WA from which material was sampled, the location at which the mallee eucalypt trees were grown exerted no significant influence on wood-cement compatibility (Table 2.1). This is a positive finding which is in contrast to others; for example, variation among trees of *Eucalyptus deglupta* grown at different sites in Indonesia (at different altitudes) has a highly significant effect on the compatibility of the wood with cement (Paribotro and Suwandi-Kliwon, 1977). Site also had a significant effect on the compatibility of selected temperate eucalypt species grown in Eastern

Australia with portland cement (Semple *et al.* 2000b), which was related to differences in the proportions of heartwood and sapwood in the trees of each species grown at the two sites.

Note that there was a small influence ($p = 0.04$) on $T_{\max}$, R and C_A -factor arising from an interaction between age and bark (Table 2.1). This may have occurred because there was a greater proportion of bark present in the chipped residues from the younger, smaller-diameter coppice trees, which led to a greater inhibitory effect on cement hydration.

2.4.3 Compatibility of melaleuca wood and bark with cement

Unadulterated samples from the melaleuca species and the tagasaste were very low in compatibility with cement or 'incompatible' compared with the wood from mallee eucalypts. The results of the ANOVA for the effects of species, bark content, extractive removal and interactions between factors are shown in Table 2.3. Differences between melaleuca species did not significantly affect $T_{\max}$ or R but they did significantly influence setting time and, by extension the C_A -factor (Table 2.3). Water-soluble carbohydrates in sapwood (which act as set retarders) can greatly delay the setting time of portland cement. The chipped residues from melaleuca were less compatible with cement than the majority of the mallee eucalypt residues, reducing the normal hydration rate of portland cement from 3.4 °C/h to an average of 1.15 °C/h ($C_A = 61\%$). This compares with the 'moderate' compatibility of mallee eucalypt wood from *E. polybractea* and *E. horistes* ($R = 1.75^\circ\text{C/h}$). The addition of unextracted residues from tagasaste resulted in the complete inhibition of cement hydration and the mixes did not set within 24 h. In the absence of compatibility indices for this species, it was omitted from the ANOVA model.

Table 2-3: F-probabilities (p-values) for effects of main factors species, extraction and bark content and interactions between factors on compatibility indices of melaleuca species.

	Temperature	Hydration rate	Time to $T_{\max}$	C_A -factor
Species (s)	N.S.	N.S.	<0.001	0.001
Extraction (e)	<0.001	<0.001	<0.001	<0.001
Bark (b)	N.S.	N.S.	0.028	N.S.
s x b	N.S.	N.S.	<0.001	0.019
s x e	N.S.	N.S.	<0.001	0.028
b x s	0.012	N.S.	0.002	0.017
s x b x e	0.008	N.S.	<0.001	0.007

*Level of significance $p \leq 0.05$.

The presence of bark and the interactions between species and bark also influenced setting time and C_A -factor (Table 2.3). These effects are illustrated in Figure 2.4 for (a) time to $T_{\max}$ and (b) C_A -factor. There was a significant interaction between species and bark content on time to $T_{\max}$ ($p < 0.001$), as illustrated in Fig 2.4 (a). Wood (without bark) from *M. uncinata* was significantly ($p < 0.001$) less compatible than the other species, with a delayed setting time of 22 h ($C_A = 32\%$), however when bark was present, its compatibility was greatly increased, reducing set time = 17 h ($C_A = 66\%$). Bark also increased the compatibility of *M. lateriflora*, but to a lesser extent. In this case set time was reduced from 17 h to 14.5 h. In contrast, the presence of bark in the residue made *M. alternifolia* slightly less compatible (denoted by increased set time from 15 to 17 h). C_A -factor was also reduced but this was not significant at the 5% level. For reference, set time for portland cement on its own is approx. 9 h.

The most significant effect on wood-cement compatibility was that of extractive removal ($p < 0.001$), which can be clearly seen in Figure 2.4(a) and (b). As a result of aqueous extractive removal, the average hydration rate for cement containing residues was increased to 2.5 °C/h (i.e. 'compatible') and the time taken to set was reduced from an average of 16.7 h to 9.9 h. This indicates that most of the inhibitory constituents of the melaleuca wood are readily soluble in water and effectively removed by cold-water-soaking. With appropriate tree size and availability, correct wood conversion and pre-soaking, melaleuca wood is likely to be well suited for the manufacture of wood-cement composites. Other simple methods of reducing the effects of water- and alkali-soluble inhibitory carbohydrates in sapwood include pre-storage of wood and the addition of simple salts such as CaCl_2 .

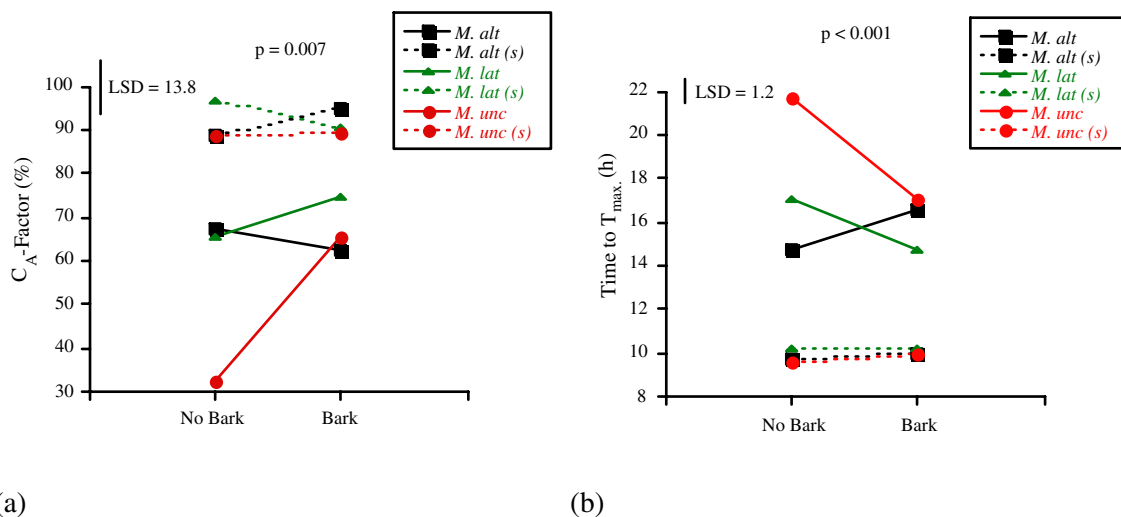


Figure 2-4: The effects of species, bark content and extractive removal on (a) time taken to set cement and (b) CA-factor. (s) denotes pre-soaked samples

Another interesting aspect of the results of testing the compatibility of melaleuca wood with cement was that the bark of two of the three tested species appeared to be as or more compatible with cement than the wood itself. In these cases the partial supplementation of wood with bark may improve the compatibility of residues with cement. Melaleuca has a thick, spongy multi-layered bark that comprises 15 to 20 % of total stem volume (Chiang and Wang 1984). Because the bark is of much lower density than the wood, the samples containing bark had up to 50% less wood (w/w) than samples that contained no bark. This made a significant difference to the hydration of cement containing residue of *M. uncinata*, whose wood was less compatible than its bark and the wood of the other species. The suitability of melaleuca species for the manufacture of cement-bonded composites may be considerably improved if it is not completely necessary all the bark from the wood.

The finding that the presence of bark improved wood-cement compatibility runs counter to the general observation that bark of many tree species contains much higher levels of water, and particularly alkali-soluble constituents than the wood. Extractives in bark often constitute between 40 and 60% w/w of material, and include polysaccharides and pectins, phenolic compounds such as tannins and resin acids, and suberins (Wenzl 1970, Sjostrom 1981). Bark structure and chemical composition also varies greatly among species (Jensen *et al.* 1963), and the high tannin-containing bark of woods such as pines has been shown to have highly inhibitory effects on the setting of portland cement (Yoshimoto and Minami 1976). The solubility of reactive bark polyphenols is highest in alkaline solutions (Yazaki 1985, Yazaki and Collins 1994), such as that found in hydrating cement paste. Melaleuca bark (from the species *M. quinquenervia* (Cav.) Blake) has also been shown to contain very high levels of phenolic extractives, as suggested by its high methanol soluble fraction (22.5%) compared to that of sapwood (2.7%) (Wang and Huffman 1982). Melaleuca bark also contains many layers of suberised cells (Chiang and Wang 1984). Suberin in bark cells is a natural water-repellent barrier to pathogens to which melaleucas are susceptible in their often water-logged growing conditions (Laks 1991). Another interesting characteristic of melaleuca bark is its high content ($\approx 16\%$) of fatty substances (lipids), giving it the highest known calorific content of any tree material (Wang and Huffman 1982, Wang *et al.* 1982). Non-polar fats and terpenes have been shown by Miller and Moslemi (1991a) to have little adverse effect on cement setting. These physical and chemical characteristics may have influenced the compatibility of the bark with cement, for example high levels of fats and suberin may have reduced the solubility and mobility of the phenolic extractives in the bark that inhibit cement setting reactions.

2.5 Conclusions

The wood from 5 leaf-oil producing species of mallee eucalypt had moderate to good compatibility with portland cement. The presence of bark made the wood residues from *E. loxophleba*, and to a lesser extent *E. angustissima*, less compatible with cement and therefore less suitable for use in wood-cement composites. In contrast to findings from other eucalypts, geographic location of trees and their age exerted little influence on the compatibility of wood of mallee eucalypt with cement. The higher proportion of bark in the younger (2.5-year-old) trees reduced their compatibility with cement to a small extent. Average compatibility indices for debarked residues from mallee eucalypt species (1.5 °C/h and 65% hydration rate and C_A -factor, respectively) were similar to those for radiata pine particleboard flakes, making them potentially well suited for the manufacture of wood-cement composites

In contrast, wood from the three sampled melaleuca and tagasaste species was classed as 'incompatible' with cement, making the fresh wood unsuitable for wood-cement composites. The wood of *M. uncinata* was significantly lower in compatibility than the other melaleuca species, however the compatibility of the residue was significantly increased by the partial substitution of the wood by its bark. Substitution of wood for bark had little effect however on the compatibility of *M. acuminata* or *M. lateriflora* wood with cement. The most critical factor affecting compatibility of melaleuca residues with cement was the removal of inhibitory carbohydrates by pre-soaking in water. Such a simple pre-treatment would likely make melaleuca wood well suited for use in cement-bonded composites, provided there is sufficient source material. Although insufficient material was available from melaleucas to enable the trial manufacture of wood-cement composites, as described in Parts 3 and 4 of this report, it would be worthwhile testing pre-soaked melaleuca wood in a further study to confirm its suitability for wood-cement composite manufacture.

3. The manufacture of cement-bonded particleboards (CBPs) from field-chipped mallee eucalypt residues

3.1 Introduction

In Part 2 it was shown that mallee wood is of similar compatibility to radiata pine, a species commonly used to manufacture wood-cement composites. Laboratory cement hydration tests provide a useful general guide to the potential capacity of woods to inhibit setting of portland cement, but on their own are insufficient to fully assess whether a wood species is suitable for the manufacture of cement-bonded composites. This is because the hydration test necessarily has a much higher cement:wood ratio than most wood-cement composites and does not account for the effects of factors such as wood element size and geometry, and post curing time and conditions on the final strength and mechanical properties of cement-bonded composite boards. Therefore cement-bonded particleboards (CBPs) were manufactured in the laboratory from chipped residues of the sampled mallee eucalypt species and tested for their strength and physical properties. Due to insufficient source material, the same could not be done for the melaleuca at this time.

3.2 Aim

The aim of this study was to determine whether cement-bonded boards of acceptable quality could be manufactured from waste residues of mallee eucalypt that have been chipped using a readily available chipper shredder. The effects of species and of included bark on the flexural properties and water resistance of boards was assessed. Results were compared with those obtained from testing CBPs manufactured from radiata pine (*Pinus radiata* D. Don) particleboard flakes, a species that is suitable for the manufacture of wood-cement composites (Semple and Evans 2000a).

3.3 Materials and Methods

3.3.1 Manufacture of CBPs in the laboratory

Cement-bonded particleboards were manufactured from chipped and screened mallee eucalypt residues. Due to restrictions on tree removal from the growth trials, there was insufficient material to allow the manufacture of boards from individual trees representing each species, site and tree age class. Therefore, for each species, the 2.4 to 3.8 mm (large) and the 1.7 to 2.4 mm (small) size fractions were combined in the proportions 65 % and 35 % across site and age class respectively to produce bulk samples each weighing approximately 700 g, sufficient for the manufacture of two boards (replicates). This was done separately for residues with and without bark. The small size (<10-50 mm diameter) of mallee eucalypt stems may potentially restrict the options for converting the wood into engineered wood particles designed to maximise the strength of particleboards (Maloney 1977). Hence, it was important to compare the mechanical properties of CBPs made from chipped mallee eucalypt residues with those of boards made from commercially produced radiata pine particleboard flakes.

The manufacture of CBPs followed the methodology of Yasin and Quereshi (1990) and Sudin and Ibrahim (1990). Boards contained 325 g of wood (oven dry basis), 650 g of portland cement (a wood:cement ratio of 1:2), 250 g of water and 13 g of CaCl_2 (2% w/w cement). The wood residue for each board was first sprayed evenly with the dilute aqueous solution of CaCl_2 and cement was sprinkled through the dampened wood particles. The cement and wood was mixed by hand to evenly coat all particles with cement. The mix was then immediately transferred to a steel mould measuring 240 x 300 mm placed on a rectangular sheet of plywood measuring 340 x 420 x 17 mm. The mat was evenly spread and flattened using a wooden block, the mould removed and another piece of plywood placed on top of the mat. Two wooden spacing rods measuring 12 x 12 x 300 mm were placed at either end of the two plywood sheets to ensure that pressed board thickness was 12 mm. The resulting

assemblage was pre-pressed to reduce its height while the mat for the next board was mixed. This process was repeated to produce a sandwich of 3 mats. This stack of mats was placed between two steel plates measuring 340 x 470 x 15 mm and pressed to approximately 60 kN using a PHI 101.6 mm RAM hydraulic operated press. The pressed mats were kept under constant pressure for 24 h by bolting the two steel plates together using four 8 mm thick bolts. After 24 h the boards were de-clamped, stacked vertically and conditioned for 28 days at 20 ± 1 °C and $65 \pm 5\%$ r.h. to allow the cement to cure and gain strength.

In addition to the 20 boards made from mallee eucalypt residue, 2 boards were manufactured in exactly the same manner from commercial radiata pine particleboard flakes obtained from CSR Timber Products in Tumut, NSW. During the manufacture of mallee eucalypt boards, replicate 1 of all species and bark content combinations were manufactured in random order over the first 5 days, followed by replicate 2 over the next 5 days.

3.3.2 Determination of board mechanical properties

Conditioned boards measuring 240 x 300 x 12 mm were sawn into 4 test samples measuring 230 x 50 mm. Samples 1 and 3 were tested for modulus of rupture (MOR, MPa) and modulus of elasticity (Young's modulus-MOE, MPa) in the dry condition. Samples 2 and 4 were tested for MOR and MOE in the wet condition, after they had been soaked in water at ambient temperature (20°C) for 24 h. Before soaking, the samples were weighed and their thickness measured at three points along their length using a Mitutoyo digital caliper. After soaking, the samples were drained on paper towels for 15 min to remove excess water. The sample thickness and weight of samples was re-measured and the absorption of water (WA %) and thickness swelling (TS %) of samples was calculated (expressed as percent of original weight and thickness, respectively). 3-point flexural (bending) tests (Plate 3.1) was carried out using an Instron 4505 Universal Testing Machine, with a span of 180 mm, cross-head and bearer diameter of 25 mm and loading speed of 5 mm/min.



Plate 3-1: Three-point bending test for board samples.

3.3.3 Experimental design and statistical analysis

The experimental design for the manufacture of cement-bonded particleboards from mallee eucalypt wood and bark residues was constructed to examine the effects of three factors on board properties i.e. species, the presence of bark, and the effect of exposing board samples to water for 24 h. Due to lack of material, 'Species' is represented by pooled material from all trees, sites and age classes. Two boards (replicates) for each combination was manufactured, 20 boards in total. All species/bark combinations were manufactured in randomised order for board 1 followed by board 2. The analysis of variance models for Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) used

transformed data (log e) to make statistical inferences, however the actual values are also presented and discussed. Again, significant results are plotted graphically and bars representing the least significant difference (LSD) are included on graphs to facilitate comparison of means.

3.4 Results and discussion

3.4.1 Board mechanical properties

Cement-bonded particleboards manufactured from mallee eucalypt residues and an accelerator (CaCl_2) were generally well consolidated, however their mechanical properties (MOR and MOE) were significantly ($p = 0.005$) affected by species and whether board samples were tested in the dry or wet condition (Table 3.1). These effects are illustrated for transformed ($\log_e$) MOR and MOE in Figure 3.1 (a) and (b), respectively. The average strength properties of boards made from mallee eucalypt and pine particles are given in Table 3.2. Although the presence of bark in boards slightly reduced their mechanical properties, its effect was not significant ($p > 0.05$). *E. horistes*, *E. kochii* ssp. *plenissima* and *E. polybractea* produced the strongest boards (Average dry MOR = 1.29, 1.44, and 1.48 MPa, respectively), in accord with the higher compatibility of these species with cement.

In comparison, boards containing radiata pine flakes averaged 5.72 MPa in bending, even though they were of similar compatibility with cement to the mallee eucalypt particles. The strength properties, particularly MOR, of boards made from radiata pine were also not significantly affected by immersion of samples in water for 24 hours prior to testing (Figure 3.1a). In contrast, boards made from *E. loxopleba* and *E. angustissima* had the lowest strength (Average dry MOR = 0.69 and 0.96 MPa, respectively) and were most affected by exposure to water. These species were clearly less suitable for the manufacture of wood-cement composites than the other mallee species.

Table 3-1: F-probabilities (p-values) for main effects and interactions between factors influencing mechanical properties of CBPs made from mallee eucalypt and radiata pine wood species.

	lnMOR	lnMOE	Thickness Swell	Water Abs.
Species	0.005	0.006	0.075	0.199
Bark	0.080	0.111	0.050	0.013
Sp. x Ba.	0.660	0.674	0.504	0.974
Test Condition	<0.001	<0.001	N.A	N.A
Test x Sp.	0.087	0.01	N.A	N.A
Test x Bark	0.173	0.286	N.A	N.A
Test x Sp. x Ba.	0.112	0.07	N.A	N.A

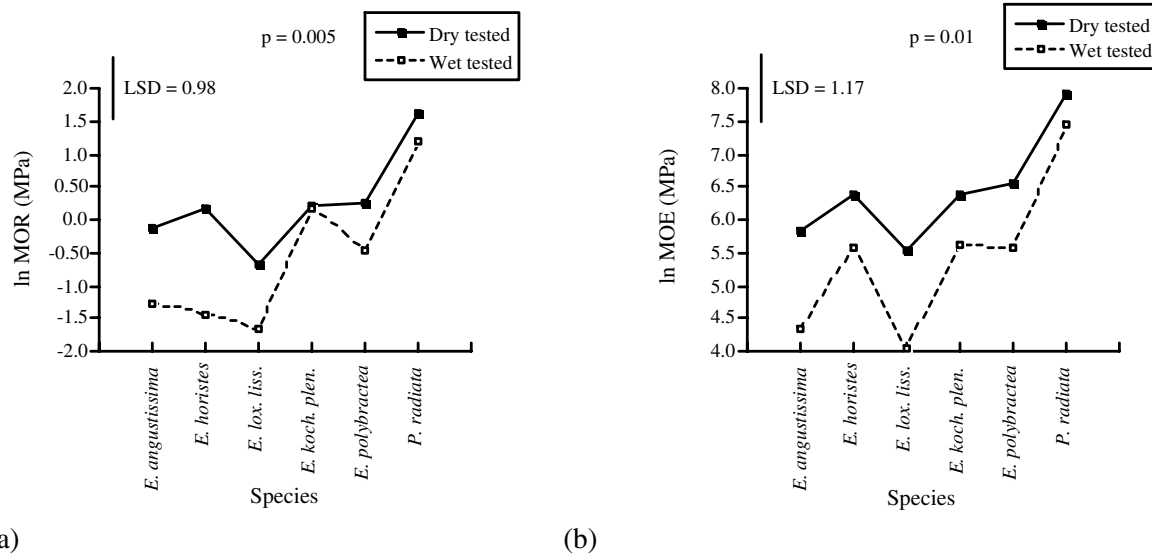


Figure 3-1: Flexural properties (a) lnMOR and (b) lnMOE of CBPs manufactured from mallee eucalypt residues as affected by testing condition (wet or dry), results averaged across site, age class and bark content.

Table 3-2: Average strength and mechanical properties for CBPs made from mallee eucalypt with and without bark and radiata pine particles without bark.

	Bark	MOR (MPa)	MOE (MPa)	TS (%)	WA (%)
E. angus	N	1.08	455.3	5.2	29.6
	Y	0.83	302.1	10.0	35.3
E. horistes	N	1.66	825.6	4.5	23.7
	Y	0.92	446.5	6.7	29.2
E. lox. liss.	N	0.93	525.4	6.2	26.8
	Y	0.46	250.9	6.4	32.9
E. kochii	N	1.57	675.1	4.3	26.1
	Y	1.30	644.2	5.4	29.4
E. poly.	N	1.53	870.6	4.5	24.1
	Y	1.42	720.1	5.5	28.0
P. radiata	N	5.72	2848.2	1.8	22.2

As Figures 3.2(a) and (b) show, the thickness swelling and water absorption of boards were not significantly affected by species, however when bark was present in the residue, water absorption of boards increased from an average of 26.1% to 31.0% and thickness swelling from 4.7% to 6.5%. Note in Table 3.2 that boards containing *E. angustissima* with bark had the highest TS (10%) and WA (35%). The bark from this species constituted up to 40% of the total volume of residue used to manufacture boards and was much more fibrous than the bark of the other mallee eucalypt species. Note also that CBPs made using residues from species of relatively low compatibility (i.e. *E. loxopleba* and *E. angustissima*) were also more susceptible to deterioration of flexural properties after exposure to water, as can be clearly seen in Figures 3.1(a) and (b). This was probably because the cement binder was poorly consolidated and more easily penetrated by water and disrupted by the swelling of wood particles.

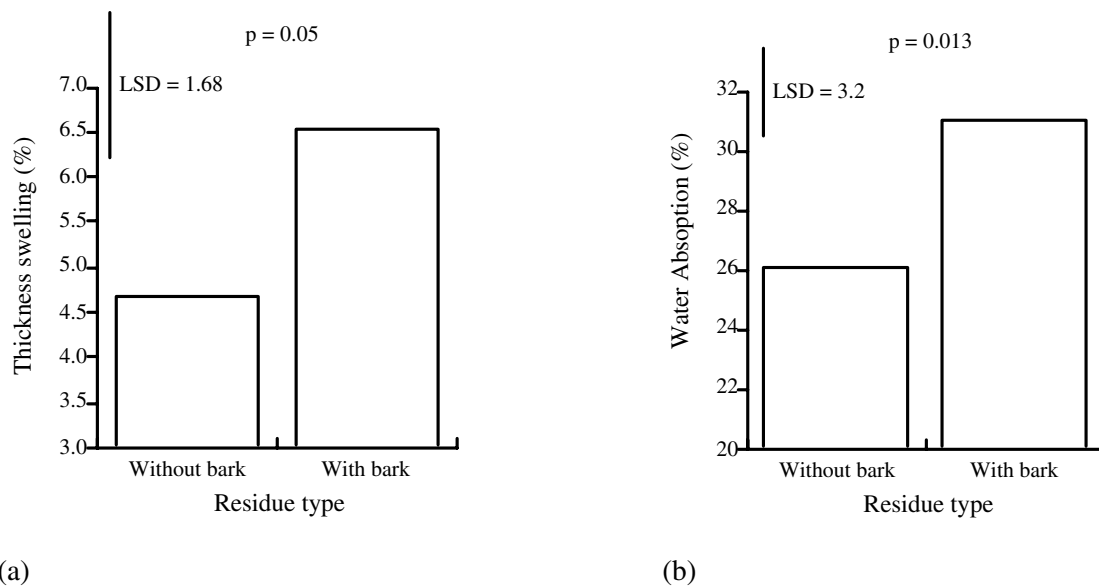


Figure 3-2: Effect of bark in residue on average (a) water absorption and (b) thickness swelling of CBPs manufactured from mallee eucalypt residues, results averaged across species, site and age class.

The international standard for cement-bonded particulate composite panels (ISO 8335) specifies a maximum TS for boards of 2%. The CBPs manufactured failed to meet this standard despite the addition of CaCl_2 . This may have been due to a combination of factors including; their relatively low cement content for particulate-cement composites, the use of wood of only 'moderate' compatibility with cement, and the exacerbating effects of bark in the residue. Although the presence of bark did not significantly affect the wood-cement compatibility of three of the five mallee eucalypt species, nor significantly reduce the flexural properties of CPBs, its adverse effect on the water resistance of boards detracts significantly from the potential utility of residues that contain bark. This effect is likely to have arisen from the fibrous, spongy nature of the bark leading to greatly increased water absorption compared with the wood on its own. Aggregates (such as bark) that contain high levels of water-soluble constituents significantly reduce the dimensional stability of cement-bonded composites (Ledhem 2000a and b). As a result, these types of aggregates require pre-treatment either to remove water-soluble constituents or the addition of stabilising agents such as silicone compounds or polyethyleneglycol to improve the dimensional stability and water resistance of cement-bonded composites (Broker 1973, Broker and Simatupang 1974b, Mougél *et al.* 1995, Gamage 1996, Ledhem 2000a and b).

3.4.2 Effect of particle geometry on board flexural properties

It is clear that the flexural properties of CBPs made from the chipped mallee eucalypt residues were very low (1 to 1.5 MPa in MOR and 250 to 900 MPa in MOE) compared with those of boards made from commercially produced radiata pine wood flakes (MOR = 5.72 MPa, MOE = 2850 MPa), and of commercially produced CBPs whose flexural properties range from 8 to 15 MPa in bending and 4000-6000 MPa in elastic modulus (Dinwoodie 1978, Moslemi 1989, Wolf and Gjinnolli 1997). This is despite the fact that the radiata pine and mallee eucalypt wood samples were of similar compatibility with cement. The CBPs manufactured in this study did not conform to the minimum strength properties set out in ISO 8335 that covers particulate cement-bonded boards of this type, despite the addition of CaCl_2 to boards during manufacture. Minimum MOR and MOE required by this standard are 9 and 3000 MPa, respectively, and minimum MOR after 24 hours exposure to water of 5.5 MPa.

The observation that mallee eucalypt wood residues (particularly those of *E. polybractea* and *E. kochii* ssp. *plenissima*) were of similar compatibility with cement to radiata pine but produced boards of significantly lower strength suggests a strong confounding effect of particle geometry. The chipped

mallee eucalypt residues consisted of small but bulky particles, with a much lower slenderness or aspect ratio than the radiata pine particleboard flakes. This can be clearly seen by viewing a typical cross-section of CBP manufactured from chipped mallee eucalypt (in this case *E. polybractea* without bark) residue compared with that of a board made from radiata pine flakes (Plates 3.2(a) and (b)). From Plate 3.2(b) it appears as though the geometry of the mallee eucalypt particles did not permit adequate horizontal alignment throughout the board cross-section nor adequate compression to eliminate voids. The size, geometry and arrangement of wood elements in particleboards strongly influences their packing behaviour during pressing, contact and bonding between particles and the horizontal density distribution in the composites (Kelly 1977, Wang and Lam 1998).



(a)



(b)

Plate 3-2: Sanded cross-sections of cement bonded boards made from (a) radiata pine particleboard flake, and (b) chipped residues from *E. polybractea*.

The poor packing and contact between the mallee eucalypt particles is likely to have contributed to the lower strength properties of the mallee eucalypt boards since there is a strong correlation between the slenderness ratio (the length of a particle divided by its thickness) of wood flakes used in particleboards and the mechanical properties of the boards (Fisher 1972, Maloney 1977). Some previous attempts to utilise eucalypt wood in cement-bonded composites have also been hampered by difficulties in converting the wood to particles with the correct geometry. For example, Tachi *et al.* (1988) found that poor strength properties of CBP made from *Eucalyptus deglupta* compared with other hardwood species (*Paraserianthes falcataria*, *Acacia mangium* and *Gmelina arborea*) was caused by unfavourable particle geometry, rather than lower wood-cement compatibility. The radiata pine particleboard flakes were of similar thickness to the mallee eucalypt particles however they were generally longer and wider or more 'plate-like' (as can be seen in Plate 3.3 which shows particles from pine and mallee eucalypt), enabling greater capacity to stack and compact in a horizontal arrangement throughout the mat.



Plate 3-3: Chipped mallee eucalypt particles and radiata pine particleboard flakes.

The conversion of small diameter mallee eucalypt residue into particles or flakes with a greater slenderness ratio would be desirable, although smaller particles from mallee eucalypt residue may, however, be suitable as a surface material for particleboards whose central layer contains larger sized material from different wood species. Improvements in the size and distribution of particles and flakes in wood-cement composites is examined and discussed in greater detail in Part 4 of this report.

Alternatively, small mallee eucalypt stems may be suited to conversion into composites composed of longitudinally split strands such as those used in 'Scrimber' (Hutchings and Leicester 1988), produced by crushing and splitting stems through a series of rollers. Composites based on sliced strands such as SST (Miyatake and Fujii 1997), which uses sharp roller shredders to convert green small-diameter stems into strands measuring 2-4 mm in thickness may also be suitable. In the absence of such purpose-designed equipment, other alternative methods of converting mallee eucalypt stems using conventional equipment should be explored. Part 4 investigates the manufacture of cement-bonded boards from flakes and particles prepared using a knife flaker.

3.5 Conclusions

The flexural properties of CBPs made from mallee eucalypt residues were significantly influenced by species, but not the presence of bark. Water absorption and swelling of boards, on the other hand, was not significantly influenced by species but was significantly increased by the presence of bark in the boards. Although well consolidated boards could be manufactured from the residues of most mallee eucalypt species, the boards had very low flexural properties compared to commercially produced CBPs or those made from radiata pine particles. The small particle size and slenderness ratio of the chipped mallee residues is believed to have been the primary cause of low mechanical strength of boards. From the results of this pilot study, two challenges were identified in order to improve board quality. There were firstly to find alternative methods of preparing residues for the manufacture of cement-bonded composite panels, and secondly to reduce the quantity and effects of incorporated bark on board water resistance. These are investigated in Part 4, which deals with the manufacture of wood-cement flake and particleboards not only from mallee eucalypt waste wood and bark residues but also from commercial species of pine and eucalypt grown in Western Australia which are normally used for solid timber and pulp.

4. The manufacture of cement-bonded flake, particle and wood wool boards from mallee eucalypt, blue gum and commercial pine species grown in Western Australia

4.1 Introduction

The findings presented in Part 2 indicated that the wood and bark residues of selected commercially interesting mallee eucalypt species were of 'moderate' compatibility with portland cement, not significantly less so than wood of radiata pine, a species that is currently used for the manufacture of wood-cement composites in Australia. The outstanding exception to this was *E. loxophleba* ssp. *lissophloia*, which was incompatible when the wood residues contained bark. In contrast to the mallee eucalypts, the compatibility of untreated wood and bark residues from three species of melaleuca was low unless it was first soaked in water. The very high bark content and limited availability of melaleucas, however, make them a less suitable raw material for wood-cement composites than the mallee eucalypts. Therefore test composites were not manufactured from melaleucas and the work reported here focuses on mallee eucalypts and commercially important plantation species grown in Western Australia.

The manufacture of cement-bonded boards from chipped wood and bark residues of mallee eucalypts indicated that in-field chipping of the residues did not result in particles with the size and geometry that optimises the strength properties of wood-cement composites. The pilot study found, however, that the presence of bark (with the exception of *E. loxophleba*) did not significantly affect the strength properties of boards but resulted in unacceptably high water absorption and swelling of boards when they were exposed to water. Mallee eucalypt stems are very small in diameter (<10 cm), often crooked and with a high proportion of bark (up to 50%) that is difficult to remove using conventional log debarking machinery.

To try to overcome these problems and manufacture better quality cement-bonded composites, the mallee eucalypt stems, including bark, were converted into flakes of different sizes, using a knife-flaker that is used to prepare wood for particleboard manufacture. The properties of wood-cement boards manufactured from mallee eucalypts (*E. polybractea* and *E. horistes*) are examined. The properties of the composites are compared with those of similar boards manufactured from commercial plantation timbers grown in Western Australia, Tasmanian blue gum (*Eucalyptus bicostata*), radiata pine (*Pinus radiata*) and maritime pine (*Pinus pinaster*). While mallee eucalypt residues were not suitable for conversion to wood wool because of their small diameter, crookedness and difficulty in removing bark, blue gum and pine logs were suitable. Therefore a commercial trial was undertaken to manufacture non-structural wood wool cement boards from these species. This was undertaken in a factory located in Bendigo, Victoria, Australia that produces this product from radiata pine.

This is the first report on the utilisation of the commercially important blue gum timber for wood-cement composite boards such as CBP and WWCB. A feature of blue gum and other fast grown plantation eucalypts is that they generate marketable volumes of timber after just a few years which contains a high proportion of juvenile wood that is often unsuitable for the manufacture of solid wood products because of its poor sawing and drying characteristics (Hillis 1978, Waugh 1980). The suitability of eucalypt wood for conventional resin-bonded composite panels is also adversely affected by high levels of water- and alcohol-soluble phenolic heartwood extractives that affect gluing (Hillis 1978, Yazaki *et al.* 1993). Young plantation grown blue gum wood is a light yellow brown in colour, open textured with commonly interlocked grain and is therefore suitable for the manufacture of paper

and rayon pulps (Hall *et al.* 1970, Turnbull and Pryor 1978). Unbleached blue gum kraft fiber (grown in Spain) was used as part of a study by Lhoneux *et al.* (1991) that examined the effects of autoclaving in lime-water on the tensile properties of a range of reinforcing fibers for use in cement-bonded fiberboard. Otherwise, as mentioned above, the suitability of blue gum wood for particulate, flake or wood wool cement composites is unknown.

4.2 Aims

To follow on from the findings of Part 3, this research had the overall objective of producing better quality wood-cement composite boards from mallee eucalypt wood wastes and commercially important plantation timber species grown in Western Australia i.e. blue gum, radiata pine and maritime pine. The research included three major experiments with the following specific aims:

- To determine which commercially important WA species, including mallee eucalypt, are best suited for the manufacture of wood-cement flake and/or particleboards.
- To optimise the strength properties of flake boards for each species by manipulating wood element size, wood pre-treatment and curing temperature. The properties of mallee eucalypt composites were compared with those of composites manufactured from the commercial WA plantation species.
- Determine the suitability of Western Australian-grown blue gum, radiata pine and maritime pine for the commercial-scale manufacture of insulating WWCB slabs. Tests were undertaken to compare the properties of factory-made boards of these species with those of commercial products manufactured from radiata pine.

4.3 Materials and Methods

4.3.1 Log harvesting

Mallee eucalypt (*E. polybractea* and *E. horistes*), Tasmanian blue gum (*E. bicostata*), radiata pine (*P. radiata*) and Maritime pine (*P. pinaster*) logs were obtained from trees growing on different sites in the south west of Western Australia in June/July 2001. Details of the plantations are given in Table 1. For all species, wood from 10 individual trees was obtained and pooled to ensure a representative mix of parent material. The mallee eucalypt wood was sourced from seedlings grown from seed collected from native stands. Trees were sampled from hedgerows spaced 40 to 50 m apart on pasture land. Being multi stemmed, one large stem (measuring between 1 and 2 m and 7-10 cm in diameter) was harvested at ground level from each of the ten trees for the two mallee eucalypt species. The stems were cut to a length of 1 m for transporting to Canberra. Blue gum and the two pine species were sampled from plantations during commercial harvesting operations. One log, measuring 1.2 m in length, was cut from a different height in each tree to ensure a mixed sample of wood representing different trees and positions in trees. Blue gum trees at the Eckersley plantation were of two different DBHOB as a result of harvesting of dominant (30-45 cm, Blue gum A) and suppressed (7-15 cm, Blue gum B) trees from the stand (Table 4.1). The soil type was fairly consistent across the sites from which the trees were sampled, however tree age among the species varied considerably at the time of harvest.

Table 4-1: Summary of species, planting dates and sites for wood species used to manufacture flakeboards.

Species	Site	Soil	Planting date	Tree Height
<i>E. polybractea</i>	Narrogin	Gravel/loam	1995	5-6 m
<i>E. horistes</i>	Narrogin	Gravel/loam	1995	2.5 m
<i>E. bicostata</i> (A)	Eckersley	Gravel/loam	1988	≈25 m
<i>E. bicostata</i> (B)	Eckersley	Gravel/loam	1988	≈15 m
<i>P. radiata</i>	Stirling Dam	Gravel/loam	1988	≈25 m
<i>P. pinaster</i>	Harvey Weir	Gravel/loam	1981	30-35 m

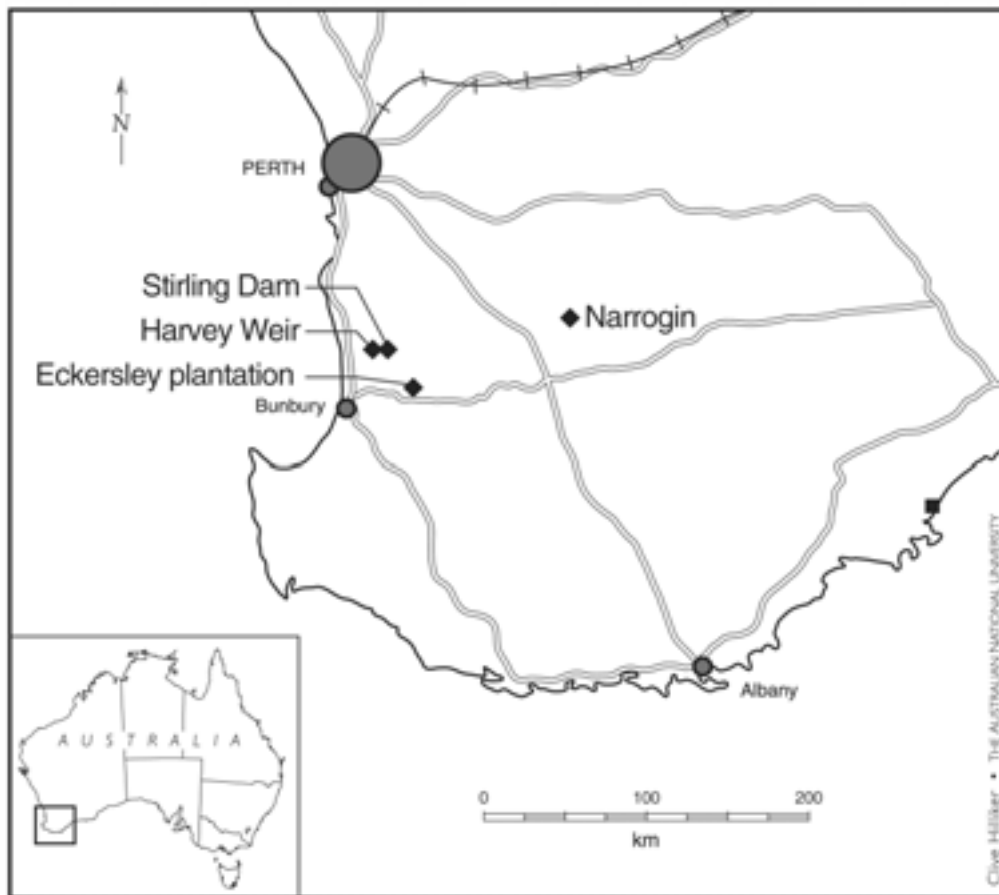


Figure 4-1: Locations of mallee eucalypt, blue gum and pine trees sampled in the South West of Western Australia.

4.3.2 Preparation of wood flakes, particles and wood wool

Log samples were converted into flakes and particles using a pilot-scale disk flaker (Bezner No. 6577) located at the Carter-Holt Harvey particleboard factory in Oberon, NSW, Australia. The blue gum and pine logs were first debarked by hand using an axe and then cross-cut using a chainsaw into rounds measuring 200 mm in length. These were then further reduced to pieces measuring approx. 200 x 50 x 100 mm using a block splitter. It was difficult to debark the mallee eucalypt stems, therefore they were cut into 200 mm long rounds which were flaked with the bark on. The disk flaker (Plate 4.1) was 80 cm in diameter and contained 8 separate knife blades set at a 45° angle to cut flakes along the grain measuring approximately 60 x 45 mm and 0.4 mm in thickness. The flakes were collected in 1 m³-capacity Nylon wool-bales and subsequently dried in a large oven at 50°C for approx. 48 h to reduce their moisture content to approximately 10%. The flakes were stored undercover for 4 months and then screened through two sieves (Plates 4.2): 10 mm to retain those flakes over about 10 x 50 mm, and a 7 mm sieve to retain those particles smaller than about 7 x 30 mm. The larger sized flakes ranged from approx. 0.3 to 2 mm in thickness, depending on species, and small flakes measured 0.2 to 0.5 mm in thickness. Although the larger flakes were cut to a nominal thickness of 0.4 mm, there was noticeable variation between species in the appearance and thickness of flakes, as shown in Plates 4.3, which show close-up images of flakes from maritime pine, blue gum and mallee. To quantify this variation and how it might impact on the mechanical properties of cement-bonded flakeboards, an assessment of variation in flake thickness from each species was made as part of this study. Fortunately much of the bark from the mallee eucalypt rounds formed smaller flakes that were

separated from the large flake fraction during sieving. However, this meant that the quantity of bark in the small flake fraction used to make CBPs was around 40-50 % by volume.

To produce wood wool ten logs each measuring 1.2 m from blue gum 1, radiata pine and maritime pine, from the same trees that were sampled for the flakeboard experiment were sent to WoodTex Pty Ltd, in Bendigo, Victoria in July 2001. The logs were debarked, cut into 360 mm billets and converted in the green condition to 'coarse' wood wool measuring 3 x 0.5 mm. After shredding the wood wool was fed through a rotating drum sieve that separated and removed the short wood wool pieces from the long strands that were used to manufacture boards. The wood wool from each species was kept separate, and it was then loosely packed into large (1 m³ capacity) aerated plastic bags and stored undercover for nine months prior to manufacture of WWCBS.



Plate 4-1: Disk flaker used to produce flakes and particles from log samples.



(a)

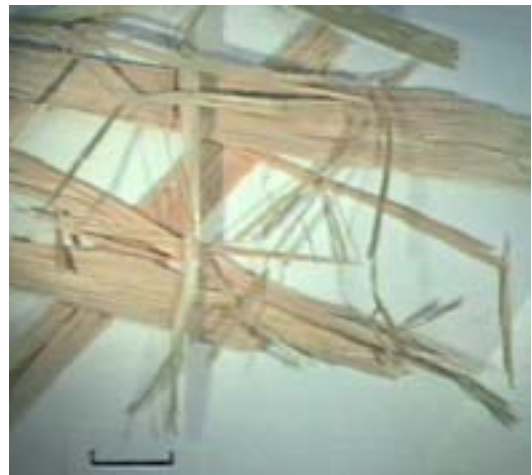


(b)

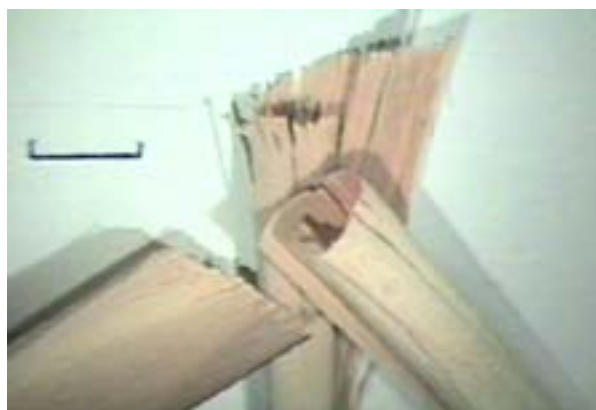
Plate 4-2: Sieving flaked mallee eucalypt wood to separate (a) large flakes and (b) small flakes.



(a)



(b)



(c)

Plate 4-3: Appearance of (a) maritime pine, (b) blue gum 1, and (c) blue gum 2 and mallee flakes. Scale bar represents 10 mm.

4.3.3 Manufacture and testing of flakeboards, particle boards and WWCBs

Experiment 1: species and flake pre-treatment

Cement-bonded flakeboards were manufactured to test the effects of two factors on the properties of boards, i.e:

- species (mallee eucalypt, low and high density blue gum, radiata pine and maritime pine),
- flake pre-treatment (none, cold water soak for 24 h, hot water soak for 8 h, addition of CaCl_2 or MgCl_2 at 2% w/w cement).

A total of 55 flakeboards were manufactured over a period of approximately 25 days. Boards measured 380 x 300 x 15 mm and used a wood:cement ratio of 1:3, and a water:cement ratio of 0.5. 450 g of air-dry wood flakes were placed in the rotating drum of a cement mixer while water was sprayed onto the flakes. Approximately 500 mL of water was added at first and the flakes were mixed for 2-3 min to facilitate wetting of flakes. Cement powder (1350 g) was then slowly added by hand to the tumbling flakes and the remaining water (175 mL) was sprayed onto the wood-cement mix to moisten the cement powder and to ensure even coating of flakes with cement. The cement-coated flakes were tumbled for a further 5 min and they were then removed and distributed as evenly as possible by hand into a formply mould measuring 300 x 380 mm, which was placed on a rectangular sheet of formply measuring 340 x 420 x 17 mm. Cement-coated flakes were added to the mould to evenly build up the mat. The mat was smoothed and flattened using a small 3-pronged gardening fork. The mould was then removed and another piece of formply was placed on top of the mat. Two wooden spacing rods measuring 15 x 15 x 300 mm were placed at either end between the two formply sheets to allow for a pressed final board thickness of 15 mm. The resulting assemblage was pre-pressed while the mat for the next board was mixed, and the process repeated to produce a sandwich of 2 mats between 3 sheets of formply. The stack of mats was placed between two steel plates measuring 340 x 470 x 15 mm and pressed at ambient temperature at approximately 60 kN using a PHI hydraulic operated press. The pressed mats were kept under pressure for 24 h by bolting the two steel plates together using four 8-mm-thick bolts. After 24 h the boards were de-clamped, stacked and conditioned for approx. 10 weeks at 20 ± 1 °C and 65 ± 5 % r.h. to allow the boards to cure and increase in strength.

After curing the flakeboards were cut into 5 samples each measuring 50 x 230 x 12 mm. Due to the high cement content of the boards they had to be cut up using a diamond edged saw. This type of saw is water lubricated, and to minimize the wetting of boards their surfaces were first sprayed with petroleum ether to disperse the water from the surface. Excess moisture was removed from the samples immediately after cutting using a sponge and samples were further dried using compressed air. Any remaining moisture was removed by air-drying samples in the sun for approx. 2 hours. The laboratory-scale manufacturing process for cement-bonded boards is illustrated in Plates 4.4(a) to (f).

Samples were kept in a conditioning room at 20 ± 1 °C and 65 ± 5 % r.h. for 14 days prior to the testing of physical and mechanical properties. Properties assessed were density, bending strength (MOR), stiffness or Young's modulus (MOE) and the resistance of boards to water (water absorption and thickness swelling) after immersion in water for 24 h. Board flexural properties were tested using the Instron 4505 Universal Testing Machine, as described in Part 3.

Experiment 2: Flake size and curing temperature (flake and particle boards)

This experiment was designed to examine the effects of two further variables; particle size and board curing temperature, on the strength and water resistance of cement-bonded boards. The species used were radiata pine, blue gum and mallee eucalypt, except in this experiment only the low-density blue gum 1 wood was used. The flaking equipment available could not produce particleboard flakes and therefore in the case of radiata pine commercial particleboard flakes were obtained from Carter-Holt Harvey, Oberon, and were used in the experiment. Small flakes and splinters that were produced during the flaking of the eucalypt woods were separated from larger residues by sieving and used for the manufacture of eucalypt CBPs.

The boards were manufactured using the same procedures described above (for Experiment 1). Coating of particles in the cement mixer took longer because the fines tended to stick to the sides and bottom of the mixer and had to be scraped away periodically during mixing. Fines also tended to clump together the longer the mix was tumbled. To cure boards at 65°C, the mats were clamped between two bolted steel plates as described above and the clamped stack was placed in a large bread-baking oven for 16 h. After 24 h they were de-clamped, stacked and conditioned for approx. 10 weeks at 20 ± 1 °C and 65 ± 5 % r.h. The CBPs were manufactured using the same wood-cement and water ratio as for the flake-boards. The equation normally used to determine the quantity of water that is required to hydrate cement during the manufacture of CBPs (Simatupang 1979) would have required the addition of 571 mL of water to the wood-cement mix. This figure is considerably lower than that used to manufacture flakeboards, and in trials it was found to be insufficient for boards made using the commercial radiata pine particleboard flake and the equipment that was available. This discrepancy was probably caused by the loss of water to the inside surface of the cement mixer and evaporation of the fine spray used to wet the particles. When 571 mL of water was added to the wood particles and fines it was rapidly absorbed by the wood and a very dry mix and friable boards resulted. It was therefore decided to increase the water content to a level similar to that used in the manufacture of the flakeboards, i.e. 700 ml. Board mechanical properties were determined as described for Experiment 1.



(a) cement mixer



(b) mat and forming mould



(c) PHI press and mat clamps



(d) a sample CBP (L) and flakeboard (R)



(e) sample cutting saw



(f) selected mechanical test samples

Plate 4-4: (a) to (f) Manufacturing and testing process for cement-bonded flakeboards.

Experiment 3: Commercial WWCBS

Low-density WWCBS measuring 270 x 160 x 25 cm were manufactured from the wood wool of each species using the same manufacturing conditions used at WoodTex, Bendigo to manufacture commercial insulating WWCBS from radiata pine. The wood:cement:water ratio was 1:2:1 using air-dried ($\approx 10\%$ MC) wood wool. The wood wool was first manually fed from the bags onto a conveyor that passed it in small batches under a toothed rotating drum through a bath of cold water. Excess water was removed from each batch of wood wool by passing it through a wringer. As a result of this, each batch of wood wool contained a consistent quantity of water. Batches of wet wood wool were then fed up into a rotating spiked drum that evenly mixed the wood wool and cement. Cement-coated wood wool was then dropped onto a load cell where it was collected into batches of uniform weight (approx. 2 kg) before being dispensed into moulds measuring 270 x 160 x 25 cm. An end-to-end train of moulds passed under the wood wool mat dispenser forming a continuous mat that was then cross cut using an automated chain saw bar to separate each mat. Each mat was then passed into a stacker capable of stacking up to 30 mats. As each mat passed on to the stacker, any large clumps were in the mat were redistributed by hand and any large solid wood pieces from the shredding process were removed.

Radiata pine was run through the board manufacturing process first, followed by maritime pine and finally blue gum. One stack of mats for each species was produced, with the available wood allowing the production of 26 boards from radiata pine, 19 boards from maritime pine and 11 boards from blue gum. About 50% less wood wool was produced from the blue gum logs for two reasons. Firstly some of the billets could not be shredded due to excessive defects such as large knots and secondly the wood was denser ($\approx 500\text{--}600 \text{ kg/m}^3$) resulting in higher losses due to the occurrence of numerous short pieces and chips during shredding.

Each stack of mats was pre-pressed by the stacker for around 5 min before being removed using a forklift to an undercover curing bay. A concrete block measuring 270 x 170 x 20 cm and weighing 1.1 tonne was placed on top of each of two stacks of mats using a forklift and the stacks were left to cure for 7 days undercover at ambient temperature. The mats were then de-moulded and stacked vertically outdoors in a steel rack to dry for a further three weeks, followed by undercover storage at ambient temperature for 4 weeks. Each panel was then trimmed to 1200 x 600 mm. The manufacturing process for the WWCBS in this study is illustrated in Plates 4.5(a) to (g).

From each trimmed panel, four adjacent samples measuring 600 x 75 x 25 mm were cross-cut using a circular saw and conditioned for around two weeks at 20°C and 65% relative humidity. The dimensions of each piece were accurately determined using Mitutoyo digital calipers, and its conditioned weight recorded. From its weight and volume, piece density was determined, and basic

density determined from assayed moisture content. Pieces 1 and 4 were then tested for flexural properties (MOR and MOE) using a three point static bending test, adhering as closely as possible to ASTM D 1037 (1999) for panels 25 mm in thickness. Samples were tested using the Instron 4505 Universal Testing Machine according to the following specifications: span = 470 mm, nom. depth = 25 mm, nom. breadth = 75 mm, loading speed = 10 mm/min, bearer diam. = 50 mm, loading nose diam. = 40 mm, as shown in Plate 4.6(a).

The remaining portion of each panel, measuring 600 x 900 mm, was destructively tested for impact strength as per the requirement of British Standard 1105. The standard specifies that boards > 50 mm in thickness are able to withstand a 45-kg mass dropped from 1.2 m in height and a static load of 1.32 kN. The test was modified to suit the thinner, weaker panels used here, and is shown in Plate 4.6(b). The panel was fixed to two saw-horses using four G-clamps and two strips of 21-mm-thick medium density fibreboard beneath a suspended weight. The span was 750 mm. The weights were made from sand and nylon sacking. The capacity of the board to withstand breakage by dropping a 5-kg mass through 50 and 100 mm was recorded. If the board did not break under the 5-kg weight, the 8-kg weight was tested, first from 50 mm then from 1 m. If breakage still did not occur then the 8-kg drop from 100 mm was repeated until failure.



(a) wringer



(b) drum mixer



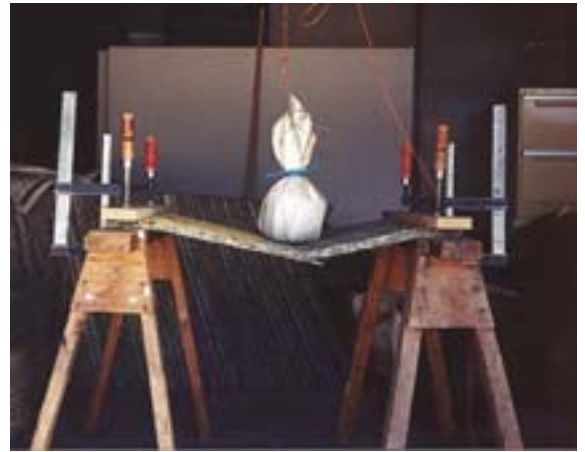
(c) mat distribution



(d) mat roller



(e) mat pressing



(f) weighted curing stacks

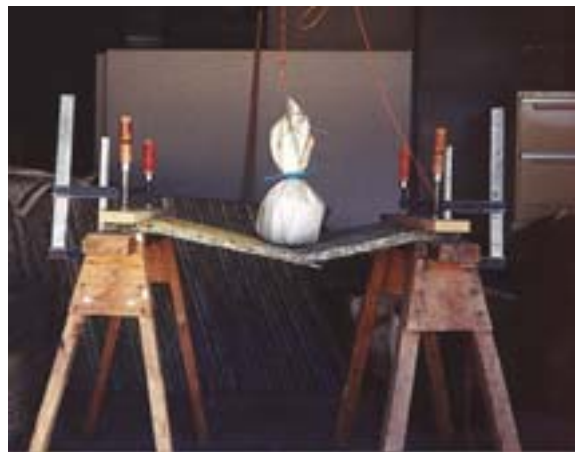


(g) air-drying of boards

Plate 4-5: (a) to (g) Commercial WWCB manufacturing process at WoodTex Pty Ltd, Bendigo.



(a)



(b)

Plate 4-6: (a) 470 mm span 3-point bending test jig for WoodTex panel samples and (b) impact test rig for 600 x 900 mm panels showing the 5 kg load.

4.3.4 Experimental designs and statistical analyses

Experiment 1 used a balanced factorial design to examine the effects of species and wood pre-treatment on the properties of flakeboards cured at ambient temperature only. For Experiment 1 two boards (replicates) for each treatment were manufactured in blocks of species in random order, with all permutations for board 1 manufactured followed by all those for board 2. Some treatment combinations involved the manufacture of an extra one or two boards if there was any inconsistency caused during manufacture. Experiment 1 also contained an assessment of the effect of species (maritime pine, radiata pine, blue gum 1 and 2, and mallee eucalypt) on the average thickness of randomly sampled large screened flakes. For the analysis of variance model, flake thickness was transformed ($\log_e$); however the true averages are shown in Table 7.7.

Experiment 2 used a balanced factorial design to examine the effects of species (pine, blue gum 1 and mallee eucalypt) and pre-treatment (none, hot water or accelerator) on the properties of flake and particle boards cured at either ambient (20°C) or elevated temperature (65°C). For Experiment 2, three boards for each treatment combination were manufactured, blocked into groups of two size (flake or particle)/wood pre-treatment combinations that were randomly assigned within each species/curing temperature combination.

Experiment 3 (Commercial WWCBs) was restricted to an investigation of species (maritime pine, radiata pine and blue gum 1) on the density, thickness and mechanical properties of low density WWCBs, and therefore involved a simple design, i.e. manufacturing runs blocked by species, with a variable number of boards manufactured according to the quantity of wood wool produced from each species.

The statistical analyses of board mechanical properties of all three experiments involved the use of mixed linear models and REML variance components analyses. This approach is best suited to the analysis of unbalanced data sets from experiments that contain both fixed and random effects, and hence was highly suitable for the analysis of data here. A chi-square distribution was used to obtain significance levels (shown in Table 4.2 for Experiment 1, Table 4.8 for Experiment 2 and Table 4.12 for Experiment 3) for fixed effects and interactions between factors determined from Wald tests for variance component estimates. In Experiment 1, the effects of the broader categories, 'wood type' (pine or eucalypt) and 'treatment type' (none, soaking or accelerator), were incorporated into the analysis of variance. A separate analysis of variance was also conducted to assess the effects of board condition (dry or after immersion in water for 24 h) on mechanical properties, and whether there were interactive effects between species and wood pre-treatment. Significant results are plotted graphically and bars representing the least significant difference ($p \leq 0.05$) are included on graphs to facilitate comparison of means.

4.4 Results and Discussion

4.4.1 Experiment 1: Species and flake pre-treatment

Mechanical properties

The results from the Analysis of Variance of the effects of species and flake pre-treatment on mechanical properties of boards are shown in Table 4.2. Species, wood pre-treatment and interaction between these two factors had highly significant ($p < 0.001$) effects on all physical properties, except for thickness swelling. Wood type (pine or eucalypt) did not significantly influence board density or thickness swelling, but did significantly affect board strength properties and water absorption. In contrast, treatment type (none, soaking or accelerator addition) had highly significant effects on all board properties including strength and water resistance. Since there was no treatment type $\times$ individual treatment interaction, the effects of treatment type on the strength of flakeboards (MOR) for different species are combined and illustrated graphically in Figure 4.2. Averages for MOR and other board properties, as influenced by species and wood pre-treatments, are shown in Tables 4.3 and 4.5 to 4.9.

Table 4-2: Chi-square probabilities for the significance of effects of species, flake pre-treatment and interactions; N.S. = not significant at the 5% probability level.

	Density	MOR	MOE	TS	WA	WMOR	WMOE
species (S)	<0.001	<0.001	<0.001	N.S.	<0.001	<0.001	<0.001
treatment(T)	<0.001	<0.001	<0.001	N.S.	<0.001	<0.001	<0.001
S x T	0.009	0.003	<0.001	0.042	<0.001	<0.001	0.007
wood type (WT)	N.S.	<0.001	<0.001	N.S.	<0.001	<0.001	<0.001
treat. type (TT)	<0.001	<0.001	<0.001	0.015	<0.001	<0.001	<0.001
WT x S	<0.001	<0.001	<0.001	N.S.	<0.001	<0.001	<0.001
WT x TT	0.022	0.033	<0.001	N.S.	0.002	<0.001	0.003
TT x T	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
WT x S x TT	N.S.	<0.001	0.003	N.S.	0.005	N.S.	N.S.
WT x TT x T	N.S.	N.S.	N.S.	N.S.	0.011	N.S.	N.S.
WT x S x TT x T	0.004	N.S.	N.S.	0.005	<0.001	0.015	0.007

All flakeboards manufactured in Experiment 1 exceeded the minimum density of 1000 kg/m³ stipulated by ISO 8335 for cement-bonded boards, ranging in density between 1080 and 1300 kg/m³. The average basic density of flakeboards as affected by species and wood pre-treatment is shown in Table 4.3. Despite the relatively low range in board density overall, species, pre-treatment and interaction between these factors significantly influenced board density. For example addition of accelerator significantly increased the density blue gum and mallee eucalypt boards, but not maritime pine boards, as shown in Table 4.3.

The average strength properties (MOR and MOE) of boards as affected by species, flake treatment and test condition are shown in Table 4.4. There were no significant first- or second-order interactive effects between test condition (wet or dry) and the other factors, species and treatment, indicating that no particular species or flake treatment affected the strength losses of boards after 24 h exposure to water.

Table 4-3: Average basic density (Kg/m3) of flakeboards as influenced by species and flake treatment.

	No Treatment	Cold Water	Hot Water	CaCl ₂	MgCl ₂
maritime	1137	1142	1126	1143	1164
radiata	1156	1143	1150	1206	1214
blue gum 1	1095	1098	1154	1218	1114
blue gum 2	1154	1205	1187	1220	1270
mallee eucalypt	1104	1152	1161	1201	1259

Least Significant Difference = 62

As can be seen from Table 4.3, the differences between treatment types (soaking or accelerator) were not significant within each species. Therefore the performance of the different species and the average effects of pre-soaking or addition of accelerator on MOR are summarised in Figure 4.2. Pre-treatment did not significantly affect the strength of boards made from pine wood, however the use of accelerator (CaCl₂ and MgCl₂) significantly increased the strength of boards made from blue gum 1 and mallee eucalypt wood. However, boards made from blue gum 2 did not respond to the addition of accelerator. The highest average board strength was achieved using the lower density wood from blue gum and adding an accelerator, suggesting that lower density blue gum as well as the pine wood is well suited for the manufacture of cement-bonded flakeboard.

Table 4-4: Chi-square probabilities (p-values) for effects of species, wood pre-treatment and test condition (wet or dry) on strength properties MOR and MOE of flakeboards.

	MOR	MOE
Species (S)	< 0.001	< 0.001
Treatment (T)	< 0.001	< 0.001
Test condition (TC)	< 0.001	< 0.001
S x T	< 0.001	< 0.001
S x TC	0.089	0.095
T x TC	0.169	0.180
S x T x TC	0.155	0.070

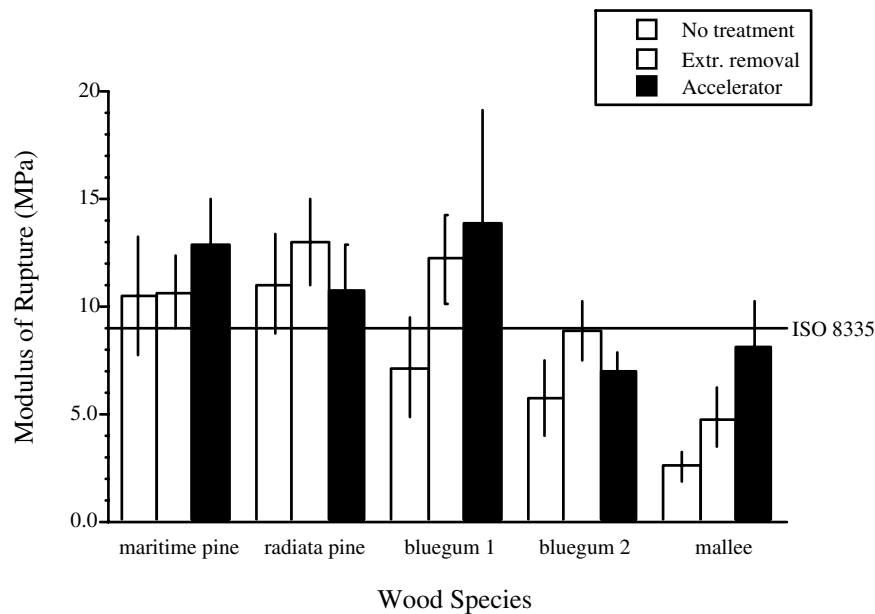


Figure 4-2: Average MOR of flakeboards made from different species with no treatment, extractive removal or addition of accelerator. (Bars = Stdev., ISO standard of 9 MPa indicated by line).

The average dry MOR and MOE, and wet MOR of boards, as influenced by species and pre-treatment, are shown in Tables 4.5 to 4.7. The shading denotes samples that did not meet the standard strength properties of 9 MPa in MOR (dry samples), 5.5 MPa in MOR (after exposure to water for 24 h) and 3000 MPa in MOE for cement-bonded boards (ISO 8335).

Boards made from untreated flakes of maritime and radiata pine exceeded the ISO standard and no marked increase in MOR resulted from pre-soaking the flakes or adding cement setting accelerators (Table 4.5 and Figure 4.2). In contrast, there was a 20% increase in MOE of maritime pine boards as a result of adding $MgCl_2$ (Table 4.6). Overall, the best flake pre-treatment for maritime pine was the addition of $CaCl_2$ whereas the best pre-treatment for radiata pine was extractive removal by hot water. The latter may result from the deleterious effect of untreated heartwood on the mechanical properties of cement composites made from radiata pine (Semple and Evans 2000a), since the flakes used contained both heartwood and sapwood.

Table 4-5: Average MOR (MPa) of flakeboards influenced by species and flake treatment.

	No Treatment	Cold Water	Hot Water	CaCl ₂	MgCl ₂
maritime	10.5	9.9	11.2	13.8	12.1
radiata	11.1	12.9	13.1	11.9	9.6
blue gum 1	7.2	11.0	13.0	12.2	15.5
blue gum 2	5.8	8.7	9.0	7.2	7.0
mallee	2.6	4.4	5.3	7.8	8.4
eucalypt					

Least Significant Difference = 3.2

Table 4-6: Average MOE (MPa) of flakeboards influenced by species and flake treatment.

	No Treatment	Cold Water	Hot Water	CaCl ₂	MgCl ₂
maritime	4112	4175	4307	4870	4902
radiata	4493	4764	4792	4990	3879
blue gum 1	1987	3487	4310	4595	3809
blue gum 2	2068	2888	3062	2634	3880
mallee	592	1651	2330	3359	3939
eucalypt					

Least Significant Difference = 1038

While boards made from untreated low-density blue gum flakes did not meet the ISO minimum of 9 MPa in bending, pre-soaking and addition of accelerator significantly ($p < 0.001$) improved the mechanical properties of boards. Average MOR increased from 7.2 MPa to between 11 and 15.5 MPa as a result of flake pre-treatment. In the case of the higher density blue gum (blue gum 2) and the mallee eucalypt, neither cold water soaking or the addition of accelerators was sufficient to produce boards exceeding 9 MPa in bending (Table 4.5 and Figure 4.2). However, variation in MOR (shown by standard deviation) indicates that some mallee eucalypt boards containing CaCl₂ and MgCl₂ met the standard, suggesting that an increase in the quantity of accelerator used might allow boards of acceptable quality to be manufactured from the mallee eucalypt flakes. Other reasons for reduced strength of boards containing mallee eucalypt and higher density blue gum flakes are discussed later. It is apparent from Table 4.6 that the MOE of mallee eucalypt boards containing cement setting accelerators were above the ISO standard of 3000 MPa.

In accordance with the objective of this study the strength properties of flakeboards made from mallee eucalypt were markedly higher than those of boards manufactured from chipped mallee eucalypt wood (Part 3), particularly after addition of accelerator. This suggests that flakes rather than particles should be used for the manufacture of cement-bonded boards where the aim is to produce boards of high strength. The good performance of blue gum (especially the lower density wood) in cement-bonded flakeboards is also significant, since it represents a considerable improvement on previously cited examples of poor performance of eucalypt wood in cement-bonded composites (e.g. Tachi *et al.* 1988, Yasin and Quereschi 1990). The potential of blue gum is supported by another study on the use of eucalypt wood for the manufacture of cement-bonded boards (Warden *et al.* (2002). In their study, eight temperate eucalypt species, including blue gum (of similar density to that used here) were tested in the manufacture of wood-cement flake boards and wood-cement particleboards. The wood:cement ratio was 1:3 and water content 0.38, considerably lower than that used here (0.5), and CaCl₂ was added at 2% w/w cement to some boards. Boards were between 1200 and 1400 kg/m³ after curing. Only boards made from blue gum were above 8 MPa in bending strength, averaging 10.8 MPa. Greatly reduced board strength among other species was attributed to poor flake geometry (low aspect ratio) and a high quantity of fines in the boards.

Board dimensional stability and resistance to water

The average bending strength of boards after soaking in water for 24 h are shown in Table 4.7. All boards made from pine or low-density blue gum exceeded the minimum wet MOR of 5.5 MPa specified in ISO 8335, however, no boards made from mallee eucalypt met the standard, possibly because of their low initial strength. Pre-soaking of higher density blue gum flakes or the addition of accelerator (CaCl_2) was necessary to prevent a reduction in bending strength to below 5.5 MPa after exposure of boards to water. The wet MOR values of boards made from mallee eucalypt were generally significantly lower than those of other species, except when accelerator was used.

Table 4-7: Average wet MOR (MPa) of flakeboards influenced by species and flake treatment.

	No Treatment	Cold Water	Hot Water	CaCl_2	MgCl_2
maritime	8.4	8.8	5.9	8.7	7.7
radiata	7.6	7.1	9.9	8.7	7.7
blue gum 1	6.0	7.4	7.2	8.6	10.8
blue gum 2	2.8	6.0	5.9	6.3	5.3
mallee	1.4	2.7	2.4	4.9	5.0
eucalypt					

Least Significant Difference = 2.3

Thickness swelling of boards was not significantly ($p > 0.05$) affected by species or pre-treatment (Table 4.3), but the interaction between species and pre-treatment was significant ($p = 0.042$). Thickness swelling and associated water absorption by boards made from the different species and subject to the various flake pre-treatments is shown in Table 4.8. ISO 8335 has a requirement for maximum thickness swelling of cement-bonded particleboards boards after soaking in water at ambient temperature for 24 h of 2%. Most boards manufactured here exceeded this value, but usually not by a wide margin (Table 4.8). Hot water soaking, CaCl_2 and MgCl_2 treatments were effective in many boards at reducing thickness swelling of boards to within standard limits. ISO 8335, however, has no maximum specified water absorption. There were highly significant differences and interactions between species and flake pre-treatment that influenced water absorption. Water absorption by boards containing pine wood was not significantly altered by flake pre-treatments and ranged from about 10 and 13%. Boards made from eucalypt wood were highly variable in water absorption; in some boards water absorption exceeded 20% but was generally between 12 and 14% when a cement setting accelerator was incorporated into boards.

Table 4-8: Average thickness swelling (%) of flakeboards influenced by species and flake treatment. (water absorption, %, in parentheses.)

	No Treatment	Cold Water	Hot Water	CaCl_2	MgCl_2
maritime	2.2 (11.8)	2.3 (10.9)	2.2 (12.1)	2.2 (10.6)	2.0 (10.0)
radiata	2.1 (12.3)	2.6 (12.5)	2.0 (12.9)	1.7 (9.4)	1.8 (9.9)
blue gum 1	2.9 (20.1)	2.7 (26.2)	1.6 (16.3)	1.5 (13.3)	2.6 (18.1)
blue gum 2	2.9 (16.5)	2.1 (13.6)	2.0 (15.4)	1.6 (12.8)	1.9 (12.1)
mallee	2.9 (23.3)	3.0 (17.2)	3.3 (16.7)	2.2 (13.9)	2.0 (12.7)
eucalypt					

TS Least Significant Difference = 0.98, WA Least Significant Difference= 3.01

Warden *et al.* (2002) found that the size and shape of wood elements strongly influenced thickness swelling of wood-cement flakeboards. Thickness swelling increased significantly with increasing flake thickness (from 0.3 to 0.9 mm), and decreasing flake length. The use of thicker flakes resulted in greater heterogeneity throughout the board cross-section and a more irregular 'open' board surface that was more easily penetrated by water, similar to the features of boards made from blue gum 2 and mallee eucalypt in this study.

The effect of wood density, flake parameters and mat structure

The size and thickness of the flakes, the small size of the mould and the manual mat forming technique used made it difficult to evenly distribute flakes in the boards manufactured here. Boards with greater heterogeneity and surface roughness (produced from mallee eucalypt and blue gum 2) were weaker, and failure tended to occur within less compacted zones. The relationship between MOR and MOE for all boards is shown in Figure 4.3. There was significant variation in MOE among boards exceeding about 7 MPa in bending. Localised variation in mat distribution and density arising from hand forming of mats and the variation in flake thickness may account for this. Some examples of variation in board structure and vertical density profile can be seen in the sanded board cross-sections shown in Plates 4.7 (a) to (d).

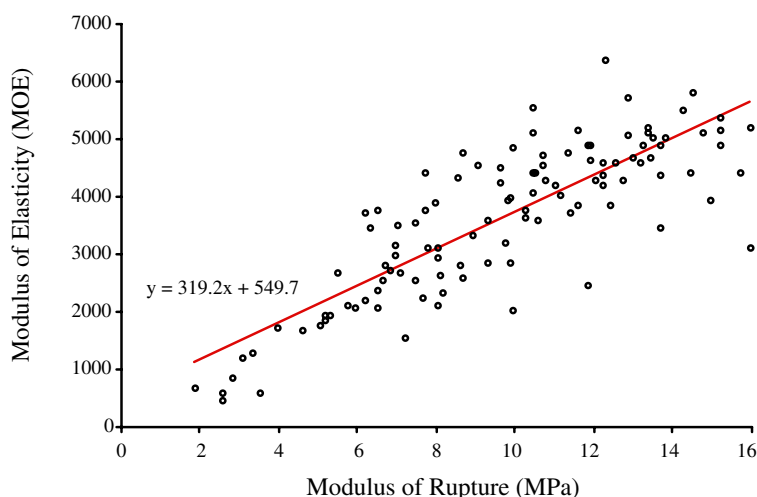


Figure 4-3: MOR vs MOE for cement-bonded wood flakeboards manufactured from pine and eucalypt wood.

Better control of flake thickness and automatic mat forming equipment could overcome this problem, leading to enhanced board flexural properties. Warden *et al.* (2002) also observed significant variation in the mechanical properties of cement-bonded flakeboards, which they attributed to manual mat formation and to the relatively large wood element size used to make boards. Flake length and thickness significantly affect the mechanical properties of resin-bonded OSB (Youngquist 1999, Barnes 2000, 2001); but according to Warden *et al.* (2002), these parameters do not appear to greatly influence the same properties of cement-bonded flakeboards. While there is no recommended minimum flake length (especially in the panel sub-surface) for use in flakeboards, the slenderness ratio (i.e. high length-to-thickness ratio) is critical to achieving good strength properties (Barnes 2000). The lower strength of boards made from mallee eucalypt and high density blue gum (even after extractive removal) is likely to have been strongly influenced by their high average, and highly variable, flake thickness (as shown in Table 4.7), geometry and reduced mat compressibility. The density of the wood that goes into compressed cement-bonded and other panel products can significantly affect bending strength through its effect on mat compression ratio, with less dense woods resulting in higher mat compression during pressing and enhanced panel strength (Geimer and Price 1978, Roffael and Dix 1994).

The thickness of flakes produced from the different species is shown in Figure 4.4. The average thickness of blue gum 2 and mallee eucalypt flakes were significantly higher than those produced from blue gum 1 or pine wood. Average flake thickness of blue gum 1 was significantly lower than that of the pines. Flaking of mallee eucalypt and high density blue gum 2 produced flakes of variable thickness; ranging from less than 0.15 mm to over 3 mm, as shown in Table 4.9. The thicker flakes had a tendency to scroll up during drying (see Plate 4.3(c)). This adversely affected flake slenderness ratio, mat homogeneity, compression, and evenness of board surfaces. In contrast pine and low density

blue gum flakes were significantly ($p < 0.001$) thinner (averaging 0.3 to 0.36 mm). They were less variable in thickness and remained flat during drying. The thin flakes from blue gum 1 tended to separate longitudinally into a more fibrous form that did not seem to have adversely affected board strength. Therefore, both pine and low density blue gum flakes produced a more compact mat structure. Eucalypt wood has been suggested as having good potential for flake-based wood composites, provided flaker-knife settings are set to produce flakes that are 10 to 15% thinner than flakes from lower density woods such as pine or aspen that are currently used in the manufacture of flake and waferboards (Klemmerewski *et al.* 2000). This suggestion accords well with our findings and highlights the need for adjustment of flaker-knife parameters to better suit dense woods and produce more even flakes with a higher slenderness ratio as a means of improving the mechanical properties of flakeboards.

The effects of high variation in flake thickness on mat consolidation and board microstructure can be seen in images of sanded board cross sections shown in Plates 4.7(a) to (d). The greater degree of uniformity and consolidation in boards made from pine and blue gum 1 can be seen in Plates 4.7 (a) and (b), compared with the reduced uniformity and greater void space in boards made from flakes of blue gum 2 or mallee eucalypt, as shown in Plates 4.7 (c) and (d).

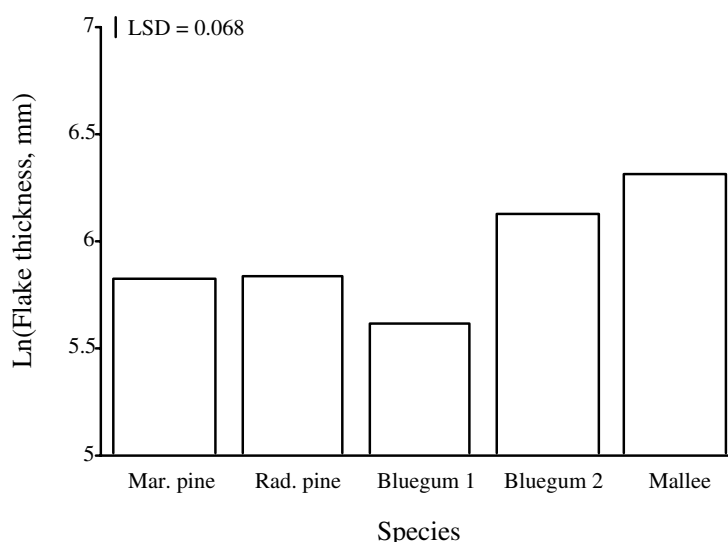


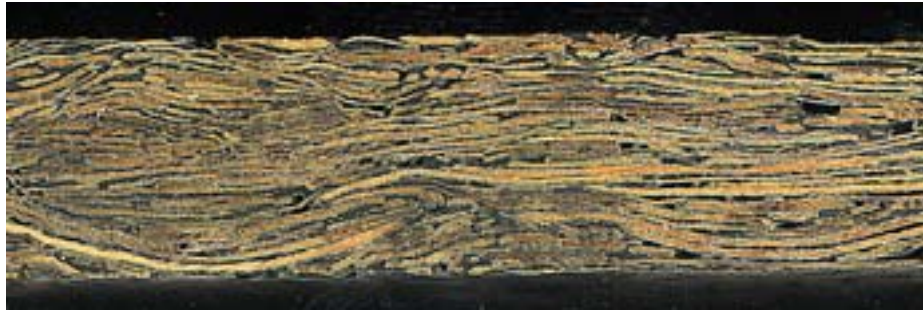
Figure 4-4: Variation in average thickness of large flakes produced from different species.

Table 4-9: Average wood density and flake thickness as affected by species.

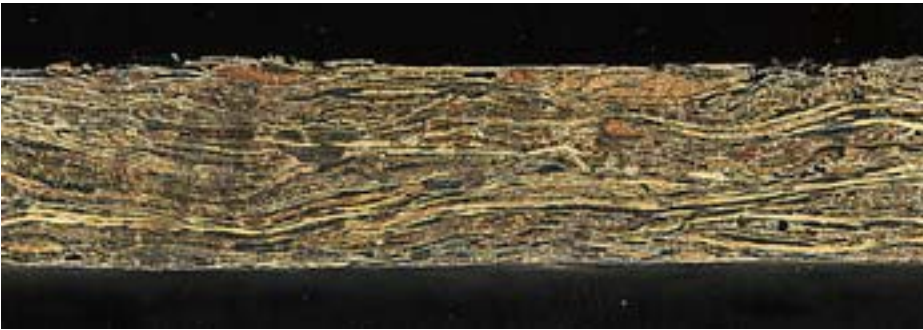
	Basic Density (Kg/m ³)*	Average Flake Thickness (mm)**	Std. Dev.	Range (mm)
maritime pine	470	0.36	0.12	0.11-0.85
radiata pine	395	0.36	0.11	0.12-0.79
blue gum 1	500	0.30	0.13	0.07-1.15
blue gum 2	900-950	0.54	0.44	0.12-3.58
mallee eucalypt	850	0.60	0.32	0.18-2.72

*Forest Products Commission data

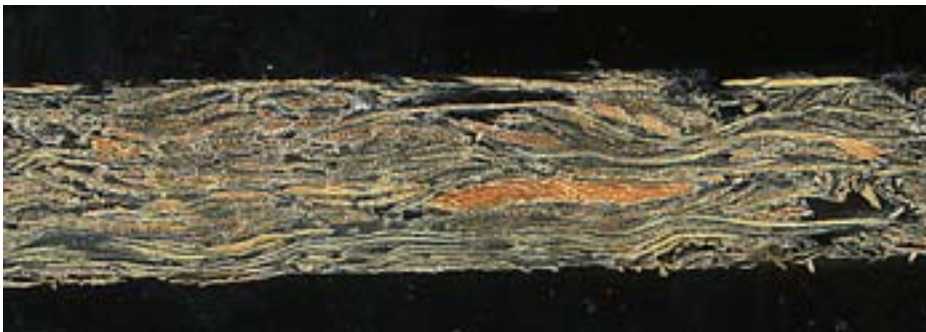
**Average of 300 flakes/wood type.



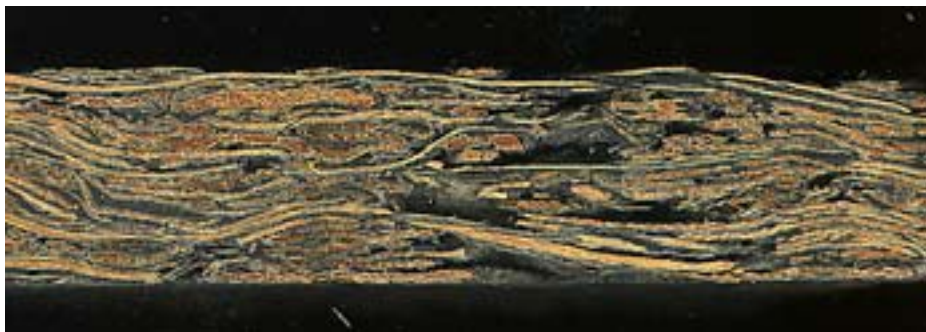
(a)



(b)



(c)



(d)

Plate 4-7: Cross sections of flakeboards made from (a) pine, (b) blue gum 1, (c) blue gum 2, (d) mallee eucalypt.

4.4.2 Experiment 2: flake size and curing temperature

Mechanical properties

The chi-square probabilities for the effects of the main factors, species, flake size, pre-treatment, curing temperature and interactions between factors are shown for each mechanical property in Table 4.10. Results are shown graphically for MOR only and averages for other properties of flakeboards and CBPs examined in this experiment are shown in Tables 4.11 and 4.12.

Table 4-10: Chi-square probabilities (p-values) for effects of species, flake size, flake pre-treatment, curing temperature and interactions on board properties. N.S. not significant at the 5% probability level.

	Dens	MOR	MOE	WMOR	WMOE	TS	WA
Species (S)	< 0.001	< 0.001	N.S.	< 0.001	0.008	< 0.001	< 0.001
Flake Size (F)	N.S.	< 0.001	N.S.	< 0.001	< 0.001	< 0.001	< 0.001
Pre-treatment (T)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Curing Temperature (C)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
S x F	< 0.001	< 0.001	< 0.001	< 0.001	0.002	0.002	< 0.001
S x T	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
F x T	N.S.	N.S.	< 0.001	0.025	N.S.	0.025	N.S.
S x C	< 0.001	0.006	0.003	< 0.001	< 0.001	< 0.001	0.005
F x C	N.S.	N.S.	N.S.	N.S.	0.011	N.S.	0.030
T x C	< 0.001	< 0.001	< 0.001	0.025	0.003	< 0.001	< 0.001
S x F x T	< 0.001	0.006	< 0.001	0.011	0.004	< 0.001	0.010
S x F x C	< 0.001	0.037	0.015	< 0.001	0.003	< 0.001	< 0.001
S x T x C	N.S.	N.S.	< 0.001	0.006	0.002	0.017	0.001
F x T x C	N.S.	0.002	0.003	N.S.	N.S.	N.S.	N.S.
S x F x T x C	0.009	0.043	0.014	N.S.	0.023	0.001	0.008

All board properties except for MOE were significantly affected by species and flake size (flakes or particles). As might be expected, board density was not influenced by flake size, since the weights of cement, wood and water used to manufacture boards remained the same regardless of flake size. All board properties were strongly influenced by flake pre-treatment (none, hot water or accelerator), and initial curing temperature (20 or 65°C). The interactions of species x flake size, species x pre-treatment, species x curing temperature, and pre-treatment x curing temperature had highly significant effects on all board properties. The effects of flake pre-treatment and curing temperature on the MOR of flake and particleboards are illustrated in Figure 4.5.

Although both flake and particleboards responded in a similar manner to wood pre-treatments and curing, the CBPs were significantly ($p = 0.002$) lower in strength. When cured at ambient temperature, flakeboards generally did not require pre-soaking or accelerator to significantly increase board strength, whereas in the case of the CBPs, strength was significantly increased by hot water extraction of particles and by the addition of accelerator. Contrary to expectations, the strength of both flake and particleboards was greatly reduced by curing at 65°C, especially when the wood was not pre-treated with hot water or an accelerator added. The curing at 65°C of boards that did not contain an accelerator resulted in localised zones of powdery, unconsolidated cement. This was particularly apparent in boards made from unextracted wood flakes and particles of both pine and eucalypt. This effect may have arisen from localised de-watering of cement paste caused by over heating before the cement had a chance to set. Another study (Manzanares *et al.* 1989) that compared heat curing (75°C for 8 h) with curing at ambient temperature for wood-cement aggregate blocks found that composite strength was higher for blocks cured at ambient temperature. Research by Oblivin (1992), Schwarz and Simatupang (1984b) and Lange and Simatupang (1985) indicates that accelerated heat curing of CBPs, particularly at temperatures over 50°C, results in reduction of final composite strength. Therefore heating should only be used to maintain ambient temperature of the hydrating composite at, or just above, the maximum hydration temperature generated by the cement during initial curing

(around 40 to 50°C). The composites should not also be cooled too quickly. It would certainly be worthwhile testing the addition of deliquescent and/or heavily hydrated accelerators such as $\text{Al}_2(\text{SO}_4)_3 \cdot 9\text{H}_2\text{O}$ with accelerated curing using heat, so that extra water can be provided to compensate for the rapid drying that apparently takes place.

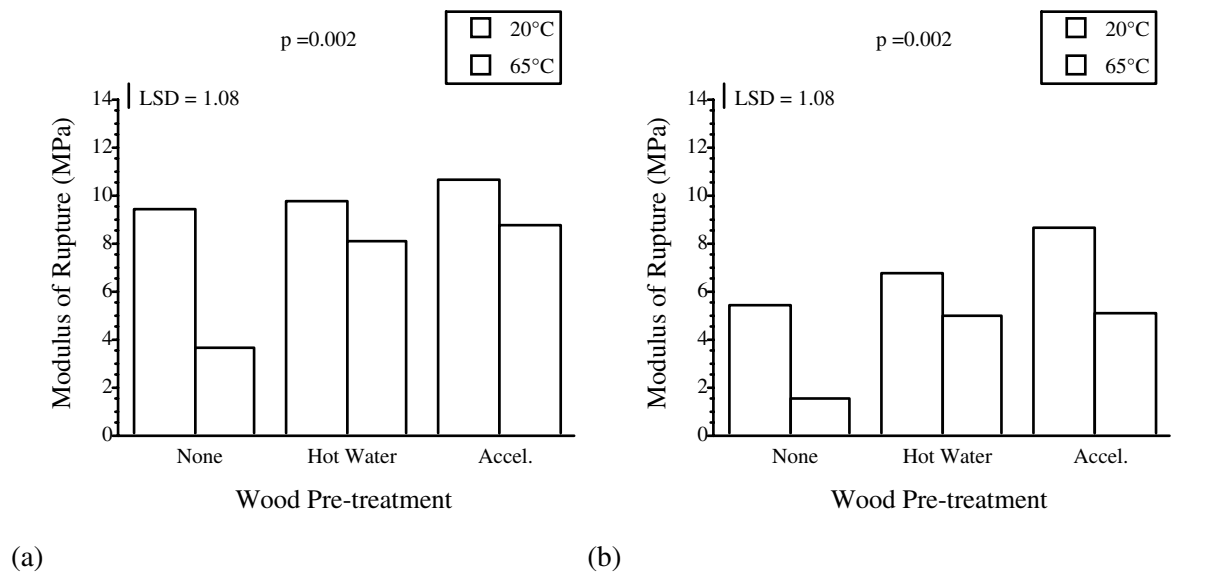


Figure 4-5: The average effects of wood pre-treatment and curing temperature on MOR of (a) flakeboards and (b) particleboards manufactured from eucalypt (blue gum and mallee eucalypt) and pine (radiata) wood.

The interactive effects of wood pre-treatment and flake size on the MOR of boards made from each of the three wood types (pine, mallee eucalypt and blue gum) are shown in Figures 4.6. In contrast to the flakeboards (even without wood pre-treatment), no CBPs met the ISO standard of 9 MPa in bending, except for those made from blue gum 1 containing particles cured at 20°C and an accelerator (MgCl_2). In this case, average MOR was 9.8 MPa. Similar boards made from mallee eucalypt had the second highest average bending strength (8.4 MPa) suggesting that further addition of accelerator may bring these boards up to standard. These findings suggest that wood in the form of particles (particularly those designed for resin-bonded particleboard) is far less satisfactory than flakes (at least under the experimental conditions used here) for the manufacture of cement-bonded boards. The average strength of the CBPs produced in this study may also have been reduced by their lower mat compression ratio, since the mats had a lower volume than the flakeboards, but were pressed to the same thickness.

Wolf and Gjinolli (1997) also found that laboratory-made CBPs that used the same wood-cement ratios as commercial products had poor properties in bending (between 0 and 3 MPa). Although the effects of particle size and geometry on mechanical properties are claimed to be the same for resin- and cement-bonded particleboards (Pease 1994), the findings here and other work on CBP suggests otherwise and indicates that cement-bonded boards may require a much larger particle size than resin-bonded panels. Research by Badejo (1988) showed that MOR and MOE of CBPs manufactured from pre-treated mixed tropical hardwood flakes showed a significant linear increase with increasing flake length (12.5-37.5 mm) and board density (1050-1200 kg/m^3), and a significant linear decrease with increasing flake thickness (0.25-0.5 mm). Maximum MOR and MOE of 11.2 MPa and 4800 MPa, respectively, were attained by using 37.5 x 0.25 mm flakes, with a board density of 1200 kg/m^3 . These results suggest that particle slenderness ratio greatly impacts on the flexural properties of CBP.

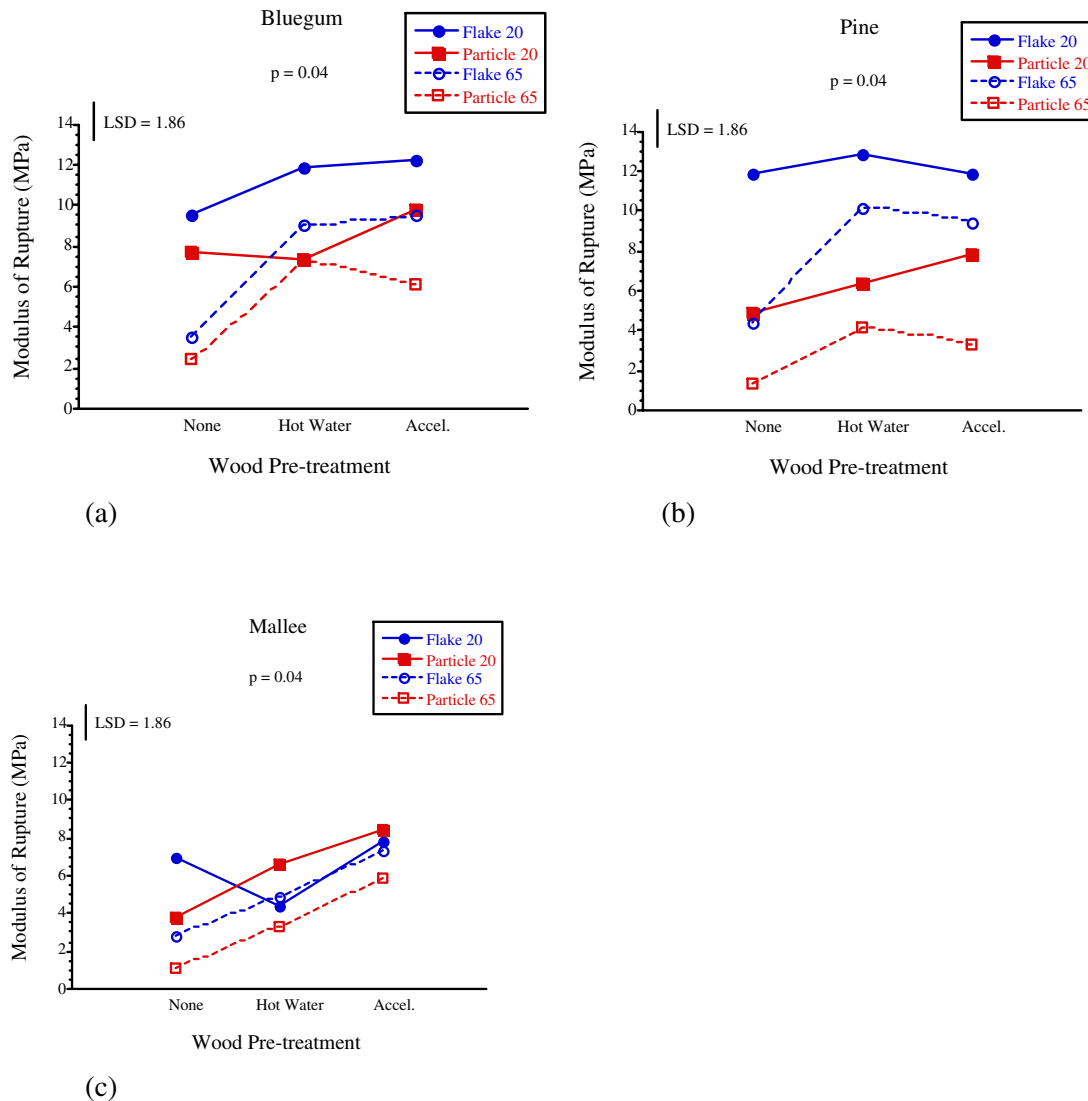


Figure 4-6: Interactions between wood pre-treatment and 'treatment type' (size and curing temp.) on MOR for (a) pine, (b) blue gum, and (c) mallee eucalypt boards.

An important difference between the 'fines' generated from flaking the eucalypt wood and the factory-produced particles of radiata pine was their geometry. The length of the pine particles from the particleboard factory varied from 5 to 15 mm, and ranged in thickness from 0.2 to 1.5 mm. The small 'flakes' of eucalypt wood were longer (between 5 and 30 mm), wider (up to 10 mm) and much thinner than the pine particles. The nature of the particle alignment in cross-sections of the CBPs made from pine and eucalypt are shown in Plates 4.8 (a) to (c). In the case of CBPs made from radiata pine particles, there was minimal interlaying and contact between wood elements, rather the particles appeared more like an aggregate filler rather than fibrous reinforcement. This may have been why CBPs made from the pine particles did not meet the ISO standard of 9 MPa in bending even when cement setting accelerators were used. In the case of resin-bonded particleboard, fines are used in the surface layers to produce a smooth finish that requires minimal sanding, and does not adversely affect panel strength. However, fine particles in the surface layers of cement-bonded boards detract from their bending strength (Fuwape and Fuwape 1994). In addition more recent research (Kuroki *et al.* 2002) shows that, contrary to the conventions governing particle size distribution in resin-bonded particleboards, the distribution of longer strands in the surface layers and smaller strands in the core layer enhances the flexural properties of cement-bonded wood composite boards.



(a)



(b)



(c)

Plate 4-8: Cross-sectional profiles of CBPs made from (a) factory-produced particles of radiata pine, and screened small-sized elements of (b) blue gum and (c) mallee eucalypt.

The effects of species, particle pre-treatment and board curing temperature on the MOE of flake and particleboards are shown in Table 4.11. Despite the propensity of CBPs to break under relatively low loading, their ability to resist deflection under a given load (expressed as MOE) was often higher than that of the flakeboards, especially in the case of boards made from eucalypt wood and subjected to pre-treatment, as shown in Table 4.11. This may be why MOE was not significantly affected by flake size, unlike MOR (Table 4.10). In most CBPs (particularly after hot water or accelerator treatment), the average MOE for a given species and treatment exceeded the 3000 MPa required by ISO 8335.

This trend is also clearly illustrated by comparing the relationship between MOR and MOE among the flakeboards (Figure 4.3) and the particleboards (Figure 4.7 above), where the slope of the regression line for particleboards was higher than that of the flakeboards. The most likely reason for this observation is that the finer wood elements in particleboards produced a much more compact mat structure upon pressing which resulted in reduced void space and irregularities. However, this better compaction of mats was offset by negative effects on cement setting caused by the much larger surface area-to-volume ratio of the wood in the form of small particles.

Table 4-11: Average MOE of flakeboards and CBPs made from pine, blue gum and mallee eucalypt according to wood pre-treatment and board curing temperature. Shading denotes boards that did not meet ISO 8335.

Flakeboards	No Treatment		Hot Water		Accelerator	
	20°C	65°C	20°C	65°C	20°C	65°C
Radiata pine	4755	1464	4764	4200	4990	3356
Blue gum 1	3878	1318	3630	3330	4595	3290
Mallee eucalypt	3880	1391	1651	2322	3359	4406
CBPs						
Radiata pine	2662	1010	4298	3191	4461	2143
Blue gum 1	4008	1382	3139	3459	4469	3289
Mallee eucalypt	2601	883	4713	2256	5438	5294

LSD = 948

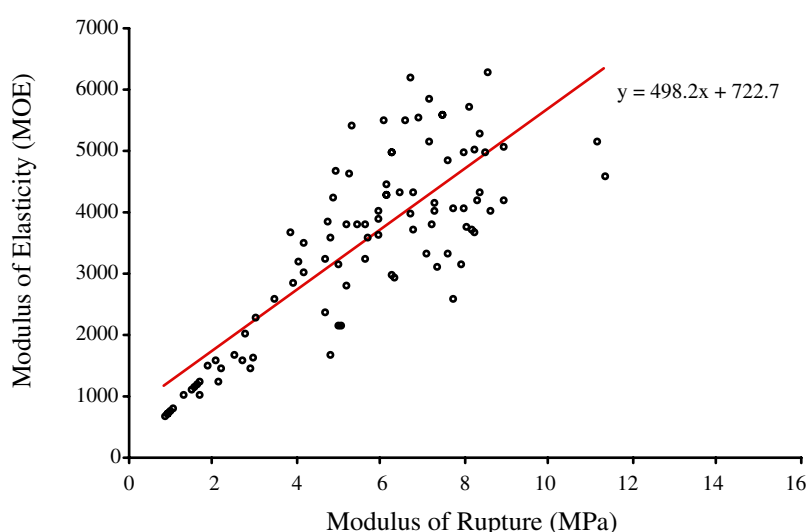


Figure 4-7: MOR vs MOE for cement-bonded wood particleboards manufactured from pine and eucalypt wood.

Dimensional stability and resistance to water

The average MOR values of flake and particleboards after soaking in water for 24 h are given in Table 4.12. Because of their higher initial strength, more flakeboards remained above 5.5 MPa in bending than did particleboards. Flakeboards cured at 65°C, however, were especially susceptible to strength loss after soaking, particularly if they did not contain an accelerator. No CBPs were above 5.5 MPa in wet MOR, except for one case. In keeping with the trend for dry samples, only boards made from low-density blue gum particles using $MgCl_2$ and cured at ambient temperature exceeded 5.5 MPa in MOR as required by ISO 8335. Boards cured at 65°C were significantly lower in bending strength after exposure to water, particularly those made from radiata pine and mallee eucalypt particles which were not subject to pre-treatment. There is no specified minimum MOE of boards after 24 h exposure to water stipulated by ISO 8335. Average wet MOE ranged from 392 MPa for boards made from untreated radiata pine cured at 65°C to 3850 MPa for boards made from mallee eucalypt particles containing accelerator and cured at 20°C.

Table 4-12: Average wet MOR of flakeboards and CBPs made from pine, blue gum and mallee eucalypt according to wood pre-treatment and board curing temperature. Shading denotes boards that did not meet ISO 8335.

Flakeboards	No Treatment		Hot Water		Accelerator	
	20°C	65°C	20°C	65°C	20°C	65°C
Radiata pine	7.5	2.9	9.5	5.7	8.1	4.9
Blue gum 1	6.1	1.8	7.1	5.4	10.7	6.2
Mallee eucalypt	1.4	1.5	2.4	2.6	4.9	5.9
CBPs						
Radiata pine	3.7	0.6	5.0	2.7	4.7	2.9
Blue gum 1	4.7	1.9	4.2	4.1	6.5	3.5
Mallee eucalypt	2.5	0.5	4.0	2.2	4.9	3.8

LSD = 1.1

Table 4.13 shows the average thickness swelling of flake and particleboards made from pine, blue gum and mallee eucalypt. The thickness swelling of CBPs was generally lower than that of the flakeboards, with most CBPs falling within the 2% limit specified in ISO 8335. Exceptions to this were the poorly consolidated boards made from untreated particles from all species cured at 65°C.

Table 4-13: Average thickness swelling of flakeboards and CBPs made from pine, blue gum and mallee eucalypt according to wood pre-treatment and board curing temperature. Shading denotes boards that did not meet ISO 8335.

Flakeboards	No Treatment		Hot Water		Accelerator	
	20°C	65°C	20°C	65°C	20°C	65°C
Radiata pine	2.1	4.5	2.0	2.6	1.8	2.4
Blue gum 1	2.9	6.1	1.6	2.2	2.6	2.3
Mallee eucalypt	2.9	3.0	3.3	2.4	1.9	1.4
CBPs						
Radiata pine	0.5	3.1	0.8	0.6	0.9	1.4
Blue gum 1	1.0	2.3	1.2	1.1	1.2	1.2
Mallee eucalypt	1.9	3.1	0.8	1.5	0.8	0.4

LSD = 0.66

The lower thickness swelling of particleboards accords well with the findings of Warden *et al.* (2002) who also found that flakeboards swelled more than cement-bonded particleboards on exposure to water, due to their rough surface and greater internal void-space in the boards. Fuwape and Fuwape (1994) attempted to rectify this problem in cement-bonded flake-boards made from spruce (*Picea sitchensis*) by using sawdust in the top and bottom layers. Such an approach improved dimensional stability, but significantly reduced board bending strength and stiffness. This finding accords with the results of other work on CBP, which support the notion that increased flake length improves the flexural properties of cement-bonded boards, particularly when they are located in the surface layers.

4.4.3 Experiment 3: Manufacture of WWCBs

Physical properties and static bending tests

Chi-square probabilities were calculated for effects of the factor 'species' on all WWCB properties i.e. basic density, board thickness, breaking load, deflection, MOR and MOE. Of all board properties, only density was significantly ($p = 0.025$) affected by species of wood wool from which boards were made.

The average density and strength properties of WWCBs made from Western Australian blue gum, maritime and radiata pine are shown in Table 4.14. Results can be compared with those of commercial 'Woodtex' manufactured to the same specification (using local radiata pine wood). In the absence of an Australian standard for this type of panel product, the board properties have been compared with the British and Japanese standards for insulating wood wool slabs.

Table 4-14: Average density, thickness and flexural properties for factory-made WWCBs of blue gum, maritime pine, radiata pine and commercial 'Woodtex' boards (standard deviation in parentheses).

	Basic Density	Breaking Load (N)	Deflection (mm)	MOR (MPa)	MOE (MPa)	Thickness (mm)
Blue gum	366.6 (44.4)	83.0 (27.0)	6.8 (1.4)	1.21 (0.47)	438.0 (246.3)	18.4 to 29.6
Maritime pine	351.3 (32.1)	91.6 (49.2)	6.2 (1.6)	1.23 (0.43)	457.7 (219.7)	21.6 to 29.1
Radiata Pine	337.4 (33.0)	89.1 (38.1)	6.1 (1.1)	1.29 (0.46)	475.9 (177.9)	22.3 to 26.6
Commercial prod.	356.5 (31.0)	86.3 (30.4)	5.9 (1.2)	1.23 (0.41)	454.2 (122.7)	23.2 to 26.7

Contrary to expectations the average bending strength and variation among WWCBs made from pine and eucalypt wood were very similar to each other, and to the commercial product, despite the significant variation in board density. Average MOR for WWCBs was between 1.21 and 1.29 MPa (Table 4.14). All of the total 160 board samples tested except for seven were below 2 MPa in MOR specified in BS 1105 (1980) for low-density insulating WWCB slabs. None of the samples from the commercial batch of 'Woodtex' met this standard. No minimum MOE is specified in BS 1105, however as Figure 4.8 shows, MOE was very closely correlated with MOR in the lower range of MOR but, like the flakeboards examined earlier, became more variable as bending strength of boards increased. From Figure 4.8, it might be reasonable to expect that a corresponding minimum MOE for boards 2 or more MPa in MOR should not be below about 800 to 1000 MPa. The Japanese standard for insulating wood wool board, JIS-A 5404 (1979), does not specify minimum bending or stiffness values for boards (at various nominal thicknesses), but instead states a breaking load of not less than 490 N and deflection of not more than 8 mm for boards 25 mm in thickness. Although the boards here were well below this minimum breaking load (Table 4.14), average deflection prior to breaking was below 8 mm.

Surprisingly, the wood wool boards manufactured in this study displayed wide variation in thickness, particularly those made from blue gum and maritime pine. Thickness tolerance specified in JIS-A 5404 is +1 and -2 mm above and below a nominal thickness of 25 mm. Commercial and experimental boards made from radiata pine were within the lower limit, but slightly above the upper limit, whereas some of those made from blue gum and maritime pine were outside the upper and lower limits. Variation in board thickness may have arisen from imprecise edge heights of the moulds and/or from variation in the distribution of wood wool in the mats, possibly influenced by the parent wood.

Average board density did not vary greatly between species, ranging from an average of 351 kg/m³ for maritime pine to 367 kg/m³ for blue gum. The average density of blue gum boards was slightly (but significantly- $p = 0.004$) higher than that of boards made from maritime pine. There was wide variation in sample density, particularly in the cases of blue gum where board density ranged from 284 to 552 kg/m³ and maritime pine (280 to 501 kg/m³). In contrast, density variation among the commercial 'WoodTex' panels was less (302 to 415 kg/m³). This suggests greater heterogeneity in the distribution of cement-coated wood wool from blue gum and maritime pine and highlights a need for 'fine-tuning' of the manufacturing process to better suit these wood species.

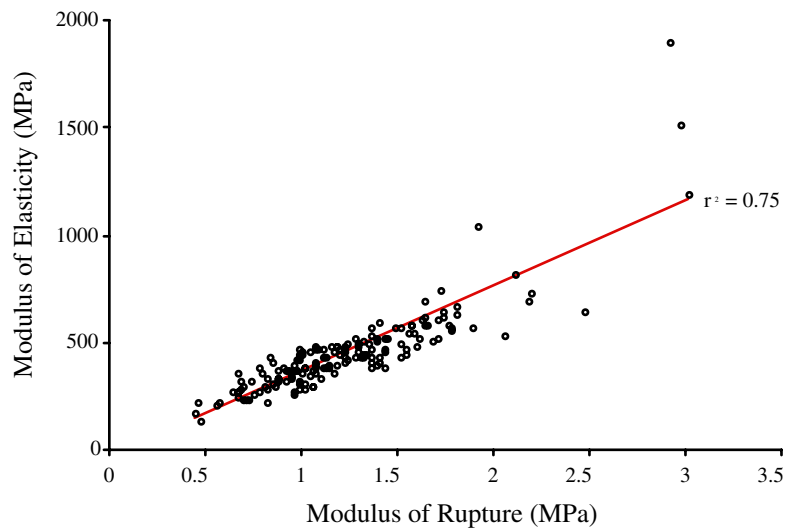


Figure 4-8: MOR vs MOE for all WWCBs manufactured in the commercial plant.

The minimum mass per square meter of 25-mm-thick WWCB required by BS 1105 is 18 kg/m². Equivalent average mass of the boards manufactured in this study ranged from 9.7 kg/m² for boards made from radiata pine to 10.8 kg/m² for boards made from blue gum. These values are only 53 to 60% of the minimum density of WWCB required by BS 1105 and may explain why the boards were below the minimum 2 MPa in MOR. Increasing the amount of cement-coated wood wool distributed into each mould and increasing average board density would probably increase average bending strength and stiffness of boards regardless of wood species used. The relationship between board density and MOR is shown below in Figure 4.9.

Figure 4.9 suggests that while there is a positive relationship between board strength and density, board density alone does not explain all the variation in MOR. During sample testing, there were noticeable differences in the distribution and packing of wood wool along the sample length, i.e. through the board cross section. Although samples were loaded at mid-point along their length, they tended to fracture within a lower density region. This suggests that improvements to the mat distribution process to prevent the occurrence of such low density zones would increase board strength.

A third possible source of variation in strength within and among boards is poor mixing of wood wool of different compatibility with portland cement. This has been shown to reduce the strength WWCBs made from radiata pine (Semple and Evans 2000a) and could have affected the properties of boards here.

Given that the manufacturing process was kept constant for all wood batches, the most important factor that was thought to have influenced mat quality at the time of board manufacture was variation between species in wood wool bulk density and quality (length and thickness variation and wood wool content). In the case of blue gum mat height was about 5 cm compared with 10 cm in the case of pine wood wool, which was likely caused by a smaller volume of blue gum wood wool being deposited into each mould. Mats of blue gum wood wool appeared to be somewhat less continuous and less interlocked, possibly due to a greater frequency of shorter, heavier strands and of solid chips produced by the shredding process. There may also have been a smaller volume of cement-coated blue gum wood wool per batch weighed by the load cell (which was a fixed weight designed for pine wood wool). Both of these factors could have influenced mat quality and board structure. Although these observed differences in mat characteristics at the time of board manufacture were expected to translate into reduced board strength in the case of blue gum, this does not appear to have been the case when the properties of blue gum boards are compared with those of the commercial product

manufactured from radiata pine. On the contrary, certain strength properties were increased in boards made from blue gum.

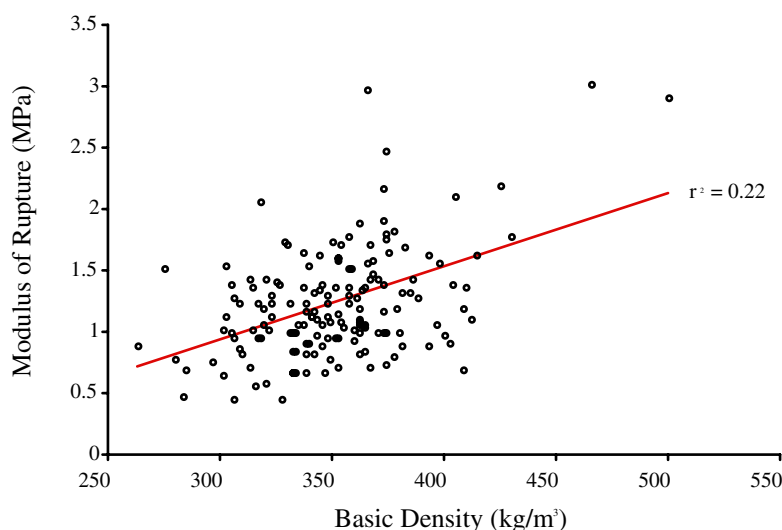


Figure 4-9: MOR vs basic density of WWCBs manufactured at Woodtex Pty Ltd.

Impact Resistance of WWCBs

The percentage of each type of WWCB that broke under each weight and drop height are shown in Table 4.15 below. Shaded cells denote the majority response of boards made from each species. The majority of boards (95%) made from blue gum survived the 5-kg drops followed by the 8-kg weight dropped from a height of 50 cm, and 35% of the boards survived one or more drops of the 8-kg weight from a height of 1 m. Impact resistance was lower among boards made from pine wood, especially among the low density panels. Around 50% of all boards made from pine wood survived the 5-kg weight dropped from 1 m but broke when the 8-kg load was dropped from 50 cm. Breakage was often clean through the middle of the panel and at the clamping points. Less than 20% of the boards made from pine wood survived the 8-kg load dropped from 1 m. The strongest boards of all species were the thicker and higher density boards with a more compacted mat structure. The stronger blue gum wood wool strands may also have contributed to the higher impact resistance of boards made from blue gum. Plate 4.5 shows a typical impact test sample of WWCB (made from radiata pine) after dropping the 8-kg load.

Table 4-15: Percentage of wood wool boards that failed after dropping different weights from different heights.

	5 kg		8 kg		
	50 cm	100 cm	50 cm	100 cm	multiple drops
Blue gum	0	0	5	60	35
Maritime	6	30	47	16	--
Radiata	0	30	50	15	5
Woodtex	10	40	50	10	--

Possible reasons for the reduced impact strength of boards made from pine wood include the above-mentioned problem of low heartwood compatibility with cement. Zones of friable, less well consolidated wood-cement bonding were noticed in many of the weakest boards made from pine wood. In contrast, the heartwood of blue gum does not adversely affect its compatibility with portland

cement. Another possible factor contributing to the higher impact strength of boards made from blue gum is the reduced volume of wood wool in the mats resulting in a higher wood/cement ratio. This is likely to have improved the bonding and consolidation of boards and enabling greater load distribution across board surfaces, thus increasing impact resistance.

4.4.4 Current interest and further potential for wood-cement flakeboards

Despite their relative ease of manufacture and favourable properties, there are still relatively few studies on the manufacture and utilisation of wood-cement flakeboards of the type investigated here. Despite the increased thickness swelling of boards composed of flakes compared to boards containing particles, the use of larger-sized flakes has a number of advantages. This study has shown that boards with acceptable mechanical properties can be manufactured using relatively simple processing technology, with minimal need for wood pre-treatment or accelerators, especially if the wood is naturally compatible with cement, such as the pine wood used here. The use of large flakes is also a very effective way of reducing carbonation-induced shrinkage in wood-cement composites (Sandermann 1973, Broker and Simatupang 1974).

Cement-bonded wood flakeboards were first developed as a building material by Elmondorf (1963, 1964). However, relatively little subsequent research and commercialisation of this type of wood-cement composite has taken place until quite recently. There is increasing interest in, and use of, wood-cement flakeboards or 'waferboards' in China and Korea for their combination of favourable properties including: strength, resistance to moisture, biodeterioration and fire, low manufacturing cost and energy efficiency (Kim and Lee 1987, Zhou 1992, Tu 1995), but there are few published reports in English on this subject. The wood-cement flakeboards referred to by Zhou (1992) and Xiong (1996) are made from either portland cement, blast furnace slag or a mix of both, and a wood-cement ratio of ≈ 0.3 , water-cement ratio of 0.6-0.7 and accelerators (CaCl_2 , Na_2SiO_3 , $\text{Al}_2(\text{SO}_4)_3$ + $\text{Ca}(\text{OH})_2$) at between 3 and 8% w/w cement. Wood flakes from sawmill wastes and branches are reported to be 18-25 mm in length, 4-6 mm wide and 0.2-0.5 mm in thickness. Mats are compressed at between 1 and 3 MPa and cured by autoclaving for 6-8 h, followed by curing at ambient temperature for 14 days. Superior board properties are reported to arise from higher cement content, higher compression, and lower water:cement ratio. MOR and MOE for such boards are ≈ 7 and 5570 MPa, respectively, and are within the range of strength values found for cement-bonded flakeboards manufactured in this study.

Large flakes also provide much greater scope for flake or strand orientation to impart higher flexural properties to boards. The most recent research on wood-cement flakeboards have re-visited the idea of flake alignment (Kim and Lee 1987, Bach and Kolker 1995, Mat *et al.* 2002, Kuroki *et al.* 2002), with significant beneficial effects on board strength properties. Wood is an anisotropic material with significantly higher mechanical strength and dimensional stability in its longitudinal direction (Panshin and DeZeeuw 1970, Kajita and Mukudai 1993). Modern oriented strand composites attain their high strength properties through a combination of high slenderness ratios and close to parallel flake orientation in the surface layers (McNatt *et al.* 1992, Barnes 2000). The idea of manufacturing oriented and layered wood-cement flakeboards was first developed and patented by Elmondorf (1963, 1966) to produce a high strength panel product (termed Embedded Fiber Board) at a fraction of the cost of producing plywood, and before resin-bonded OSB was developed. This is the earliest published example of wood-cement flakeboard being produced as a viable commercial product, so it is discussed in depth here. A pilot plant at Palo Alto, California produced 12-mm-thick boards containing flakes measuring 2.5 and 5 cm in length, a wood-cement-water ratio of 1:2.5:1, and were pressed at up to 200 psi to a target density of between 1000 and 1200 kg/m³. The cement:wood ratio could be varied to between 2 and 5 parts cement to balance durability, weather resistance and strength against cost and ease of machining and handling on building sites. Two board types were manufactured; Type A composed of a single mat containing randomly oriented flakes; and Type B composed of a three-layered mat much like that of OSB. In the top and bottom layers the flakes were aligned with each other whereas in the middle layer the flakes were either randomly oriented or aligned perpendicular to the orientation of flakes in the top and bottom layers. The flexural properties of type A boards were 14.8 MPa in bending (MOR) and 2071 MPa in elastic modulus or stiffness (MOE), whereas those for type B boards were 22.7 MPa and 6560 MPa for MOR and MOE

respectively. The increase in bending strength after strand orientation was 53%. Flake orientation was also investigated and applied in the USSR to improve the strength properties of 'Arbolit' cement-bonded boards (Klar and Vankov 1975), whereby flexural properties were increased by 2 to 3 times those of random flake distribution.

A recent study (Ma *et al.* 2002) used the same production technique (i.e. aligned surface flakes and randomly oriented core flakes) to greatly improve the strength properties of cement flakeboards made from sugi, a species normally considered unsuitable for wood-cement composites. Strength properties were maximised by adding 3.75% CaCl₂, and using a surface-to-core (or 'shelling') ratio of 1 to 4. The average bending strength of the resulting boards was almost 50 MPa and average elastic modulus was 8 GPa. The gain in strength from using surface orientation of flakes in this instance was 250%. These values are the highest cited in the literature for wood-cement composites, and compare with average strength values of resin-bonded orientated strand board (OSB) of 47 MPa in MOR and 8300 MPa in MOE (Youngquist 1999). Cement-bonded boards that employ conventional OSB manufacturing technology and combine the high production rate and flexural properties of OSB with high fire resistance are also attracting renewed interest in the North American construction market (Bach and Kolker 1995). Here a combination of rapid setting magnesite cement, a highly reactive MDI (isocyanate) resin and hot pressing are used to achieve the production rate of OSB. Experimental cement bonded OSB made by Kuroki *et al.* (2002) employed spruce (*Picea jezoensis*) and used a wood-cement ratio of 1:2.5 with a water content of 40% and 10% silica fume (fly ash). Injected CO₂ gas was used to accelerate curing during pressing and boards were hardened for 24 h at 50°C. Flexural properties of boards were between 25 and 30 MPa in MOR and between 3500 and 4500 MPa in MOE.

The early work of Elmendorf (1963) demonstrated that mechanical strand orientation can be readily applied during the manufacture of cement-bonded flakeboards; however, the moisture present in and on the strands is critical to the success of the process. There must be just enough to bind the cement powder to the strands during mat formation or 'air-felting' but not enough to enable the flakes to clump together. Particles or flakes can be oriented either mechanically or electrostatically depending on the size of the wood elements used. Mechanical strand orienters are designed for long, thin and slender flakes whereas electrostatic alignment of the wood elements in the mat is more suitable for small particles (Kajita *et al.* 1982, Kajita and Mukudai 1993). Mechanical orientation involves dropping cement-coated flakes down through a regularly spaced series of parallel reciprocating plates, disks or vanes usually aligning flakes parallel with mat length (Kajita and Mukudai 1993). The degree of strand alignment is controlled by adjusting the free-fall distance from the bottom of the grille to the mat surface as it travels beneath the dispenser (Kajita *et al.* 1982, Kajita and Mukudai 1993). A simple mat forming box containing regularly spaced plates was used by Kuroki *et al.* (2002) to orient the layers of surface and core flakes perpendicular to each other.

The other relatively simple technique for improving cement-bonded flakeboard properties, including dimensional stability (without resorting to siliceous cement supplements, autoclaving, CO₂ and/or hot pressing), is flake pre-treatment with inorganic and/or organic additives. The results here showed that the addition of cement setting accelerators was the only effective method of increasing the strength of the wood-cement flakeboards, particularly in the case of boards made from high-density eucalypt wood where flake thickness was sub-optimal. Novel methods exist for preparing wood flakes for use in wood-cement composites by pre-mixing them with relatively inexpensive minerals. A patent by Walter and Walter-Gurzeler (1991) describes a process of pre-mineralising small wood flakes using a 13-15% solution of Al₂(SO₄)₃ followed by a water-based suspension of finely ground kaolin (Al₂O₃·2SiO₂) to significantly improve the performance of wood-cement composites. An Australian patent lodged by Gamage (1997) involving the pre-treatment of sawdust with sodium meta-silicate powder, MgCO₃, MgSO₄, polyethyleneglycol and lime claims to achieve a similar effect. Relatively simple pre-mineralisation methods such as these deserve to be tested on mallee eucalypt wood and bark residues with the aim of improving board strength and resistance to water.

4.5 Conclusions

This study investigated the utilisation of eucalypt wood (both small-diameter waste stems from oil mallee eucalypt species and commercial plantation blue gum timber) for cement-bonded composite boards. Boards made from pine (radiata and maritime pines) as controls. Flakeboards manufactured from pine and low density blue gum at wood-cement ratio of 1:3 were of good quality. The addition of accelerators (CaCl_2 or MgCl_2) further improved the properties of boards made from blue gum. The average MOR of boards made from commercial blue gum and containing MgCl_2 was 15 MPa, indicating that this eucalypt species has good potential for the manufacture of cement-bonded flakeboards. Thickness swelling of boards made from untreated wood flakes of all species was above 2% the maximum level permitted by ISO 8335, however hot water-extraction of flakes or the addition of accelerators reduced thickness swelling in most cases.

The effects on board properties of using smaller particles and elevated curing temperature (as is employed during the commercial manufacture of CBP) were also examined. The results showed that the use of large flakes resulted in composites with significantly higher bending strength (MOR) than those composed of small particleboard flakes. This was probably due to improved strand contact and interlocking and the higher mat compression ratio of flakeboards compared to particleboards. Board stiffness (MOE) was not significantly affected by small flake size, but the dimensional stability of boards was generally improved by the use of particles. The elevated temperature curing regime recommended for the manufacture of CBP reduced board properties under the heating regime used here. Similar trends have been found in other studies, indicating that the heating regime has to be carefully controlled during the manufacture of cement-bonded boards.

The flexural properties of flakeboards were greatly reduced in the cases where boards were made from flakes of higher density wood species (blue gum 2 and mallee eucalypt). Addition of accelerators at 2% w/w cement significantly improved the strength of boards made from mallee eucalypt flakes, but these were not sufficient to enable boards to meet the minimum properties specified for cement-bonded boards in ISO 8335. Adjustment of flake thickness, geometry and alignment, and the use of simple cement-setting accelerators would be recommended to improve the properties of boards so that they meet the standard.

In contrast to initial expectations based on observation during the manufacture of WWCBs, eucalypt wood turned out to be well suited to the manufacture of WWCBs even without the use of cement setting accelerators. The mechanical properties of factory-produced WWCBs made from lower density blue gum wood were very similar to those of boards made from the commercially used radiata pine wood, however the impact resistance of blue gum boards was higher. The factory-made boards did not meet standard requirements for strength, however this was probably due to their below-standard density rather than any inherent unsuitability of the test species used in this study for the manufacture of wood-cement composites.

The improved board properties arising from the use of larger flakes in cement-bonded composites, and the ability to orient flakes to further improve strength properties, has not gone unnoticed by other researchers and there is renewed interest in developing oriented cement-bonded flakeboards. The results from this study help show that fast-grown plantation eucalypt wood may be well suited to the manufacture of wood-cement flakeboards, provided the wood is flaked to the correct length and thickness and other manufacturing variables are optimised.

5. Implications of Project

The results from this study indicated that mallee eucalypt wood and bark residues were of moderate compatibility with portland cement, and unlike many other hardwoods, would be quite well suited to the manufacture of wood-cement composites without any need for pre-soaking. Mallee eucalypt wood residues (with or without bark) were similar in compatibility to wood particles of radiata pine, a species that is currently used in the manufacture of wood-cement composite panels in Australia. This means that, provided an improved method for flaking the small stems can be found, it will require minimal pre-treatment (such as soaking) in order to produce wood-cement composite panels of acceptable quality.

Wood from melaleuca would also be very suitable for wood-cement composites provided the content of inhibitory sugars is reduced first. This can be very simply achieved by pre-soaking the wood. The results showed that the highly inhibitory constituents of melaleuca wood were readily removed in water at ambient temperature, making the pre-soaked wood highly compatible with portland cement.

A pilot study on the manufacture of cement-bonded boards from mallee eucalypt residues that had been chipped using readily available, general purpose equipment highlighted the importance of converting the stems to flakes or large particles with a more appropriate geometry (slenderness ratio) that maximise wood-cement composite flexural properties. There is evidence from the literature on wood-cement particleboard and flakeboard that the conventions with regard to particle size and distribution in the mat which maximise the properties of resin-bonded boards may not apply to cement-bonded composites. Instead, larger and longer wood particles or 'flakes' have been suggested to be better, especially in the surface layers of the boards.

A follow-up study that examined the effects of particle size and geometry, wood pre-treatment and curing conditions indicated that large flakes (50 to 100 mm in length) rather than small particles would be a far more appropriate conversion option for mallee eucalypt, pine or other eucalypt wood residue under the relatively simple experimental conditions used here. Wood flakes from all species were simply pre-stored in dry conditions for several months prior to manufacture. Pine wood in the form of flakes produced cement-bonded boards of acceptable properties without pre-soaking or additives. However, eucalypt wood flakes required the addition of a small quantity (2%) of simple cement set accelerators (CaCl_2 or MgCl_2) to produce boards of adequate strength and water resistance.

An important finding was that low-density blue gum timber from fast grown plantation trees produced high quality boards with the aid of only a small quantity of cement setting accelerator. Fast-grown blue gum timber poses considerable challenges to other more conventional conversion options, such as dried and dressed solid timber (Waugh 1980), or resin bonded composites (Hillis 1978, Yazaki *et al.* 1993). Its high content of juvenile wood and commonly interlocked grain also hampers conversion to particles for particleboard manufacture, and is therefore most commonly used for paper and rayon pulps (Hall *et al.* 1970, Turnbull and Pryor 1978). These features do not appear, however, to have adversely affected its conversion to wood flakes and its performance in wood-cement flakeboard. This makes cement-bonded flakeboard stand out as a highly suitable conversion option for some of the large quantity of fast-grown blue gum wood produced in Western Australia and some Eastern states.

The strength properties of boards made from mallee eucalypt and small diameter, higher-density blue gum wood in this study were compromised by the production of flakes that were of high average thickness with high variation in thickness. This was because the knife flaker was designed for the conversion of softwoods rather than higher density eucalypt timber. It was felt that if flakes produced from the mallee eucalypt and higher density blue gum wood were thinner (0.1 to 0.4 mm in thickness) then cement-bonded boards of acceptable quality could similarly be manufactured with no more complicated treatment other than pre-storage and the aid of a small quantity of cement-setting accelerator.

If a factory producing cement-bonded flakeboard panels were to be established at a location where large quantities of mallee eucalypt are grown, harvested and used for oil distillation, then the wood waste would cost as much as it takes to collect and transport it from the field to the mill. The location of a factory would also need to take into account other factors such as the procurement and transport of cement, and the distance to markets for the finished products. An market and economic feasibility study would be a necessary pre-cursor to any development of cement-bonded composite board industries in Western Australia.

6. Recommendations

This part of the report examines some options for further improving the properties of cement-bonded flakeboards manufactured from small diameter tree crop wastes such as mallee eucalypt. The discussion combines findings from this project and recent findings of other researchers in the expanding field of wood-cement composites which would be worthwhile investigating with a view to improving potential production efficiency and properties of wood-cement composites made from mallee and other tree crop wastes.

To produce cement-bonded flakeboards a purpose-designed disk flaker is necessary. Flakes need to be screened for size, which could be done using a relatively simple mechanical sieving apparatus. Further work will be necessary to determine the most appropriate design and setting of disk flaker parameters (including knife protrusion and angle) to produce thinner, more uniform flakes from higher density eucalypt woods. An important finding from the study was that although small diameter mallee eucalypt stems were difficult to debark practically, if they were flaked after the bark had dried out then the bark was converted to small flakes and dust, most of which was easily removed with the fines during sieving. Of all the material flaked, approximately a third to a half of this would be removed as fines. These could be further sieved to remove a second size fraction of smaller, thinner flakes that could be used, for example, for inner portions of thicker boards. Recent research by Adefisan and Olorunisola (2001) and Kuroki *et al.* (2002) that smaller particles increase the surface area of adhesion between the substrate and the binder, leading to enhanced strength properties of boards; however, this needs to be balanced against the lower compatibility with cement of finer particles. The use of particle size and density gradients designed to tailor the strength properties of resin-bonded particleboards is common, and so similar cement-bonded products certainly warrant further research since there is very little information about the properties of multi-layered cement-bonded composites containing different sized particles.

The dust and fines from sieving the flakes be used as biomass fuel to run a heat plant to generate heat and/or CO₂ for accelerated pressing and curing. There are numerous strategies currently under investigation in the field of inorganic-bonded fibre composite materials that involve the use of heat, CO₂, additives and cement supplements aimed at reducing pressing and curing times and improving composite quality. Some of these deserve consideration in relation to the potential utilisation of mallee eucalypt and other tree crop wastes in cement-bonded composite boards.

The results from the curing of boards at elevated temperature highlighted the need to further develop correct curing schedules that balance accelerated curing with final board strength. It was learned that the curing temperature used in this study (65°C) was too high for the boards made under the laboratory-based experimental conditions used here. For the purposes of speeding up the production of cement-bonded boards, elevated temperature curing (possibly during the pressing stage) requires further investigation, coupled with the correct type of cement-setting accelerators. Sodium silicate and aluminum sulphate are less corrosive than chloride-based additives, and are commonly used in accelerated pressing of CBP. These compounds also enhance the long-term strength of boards. These and possibly other additives deserve investigation as part of a manufacturing strategy for cement-bonded boards from mallee eucalypt or other eucalypt wood that hastens production without compromising board properties. However, previous research discussed in Part 4 of this report indicates that accelerated curing using heat inevitably results in some loss of final board strength properties.

Other recommendations for further improving the properties of cement-bonded boards made from mallee eucalypt residues include simple approaches such as adjusting the wood-cement ratio, fine-tuning the water content and accelerator type, and adjusting the amounts of ingredients (i.e. wood and cement) per unit area to optimise the compression ratio for mats pressed to different target thickness. The use of large flakes rather than particles also opens up the opportunity to further significantly improve the flexural properties of cement-bonded boards through strand orientation. Findings from several old and new research works in this field illustrate these effects very clearly, as discussed in detail in this report. Mechanical flake orientation technology may be readily transferable from the

production line used to manufacture resin-bonded OSB. It is recommended that such a technique be tested in the manufacture of flakeboards from mallee eucalypt as a strategy for further enhancing board properties that does not require extra cement or additives.

There are other important properties of cement-bonded flakeboards that need to be determined, but were beyond the scope of this project. These include gathering technical data on the resistance of such boards to bio-deterioration, including mould, rot, borers and termites using standard testing methods. The same applies to the fire behaviour of boards, including combustibility, flame spread and smoke generation. The findings then need to be placed into context with the properties other types of wood-based panels available in the Australian building materials market. Furthermore, data on the mechanical properties of cement-bonded flakeboards need to be determined using full sized panels to complement the strength values obtained from small specimens such as those used in this study. Cement-bonded composite panels such as WWCB and pulp sludge-cement panels are used to build model houses in the Philippines where their condition is monitored over time (Soriano *et al.* 2002, Fernandez *et al.* 2002). A similar strategy should be employed for structures such as low-cost dwellings or agricultural structures made from cement-bonded flakeboards in Australian environments (including tropical, arid and semi-arid regions) for both demonstration and monitoring of their performance in realistic service conditions.

A feasibility study of the establishment of a wood-cement particleboard plant for the province of Alberta, Canada by Ligna Technologies (1987) indicated that this panel type certainly has a place in exterior siding applications where deterioration (i.e. mould, rot, freeze/thaw and fire) are problematic. The study found that there was sufficient market interest throughout the United States and Canada in CBP siding for such a plant to become fully operational with a return on investment within two to five years. It is recommended that a similar study be undertaken in the Australian context. A cement-bonded board manufacturing plant requires around one third of the capital expenditure required to establish a resin bonded panel manufacturing facility (van Elten 2000). A positive image of such panels is apparent from the fact that the constituents of cement-bonded boards are non-toxic, totally inert during service, release no fumes during processing and are relatively inexpensive. They also have a natural durability and resistance to fire that resin-bonded composites do not have unless they are specially treated with (often toxic) biocides or fire retardants, which further adds to their cost. On the other hand, cement-bonded boards cannot be produced as fast as resin-bonded boards at present and this reduces the 'economy of scale' for such products, resulting in higher cost per unit relative to conventional resin-bonded panels (Moslemi 1993, Pease 1994). It would be highly pertinent to undertake a cost/benefit analysis of the production of cement-bonded flakeboard from mallee eucalypt residue at a plant/s located close to where large quantities of residues are generated. As the report of Ligna Technologies (1987) suggests, the likely place in the building materials market such boards might occupy needs to be thoroughly researched first, and a customer/distributor awareness campaign of the properties and uses of such products needs to be created. A logical first step would be to create awareness among representatives from Australian panel manufacturing industries and from the building industry about cement-bonded panels, their properties and uses, and the results from product development research such as this project.

7. References

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8. Appendices

Please note that the Appendices are not included in this report and are available as a hard copy only. Please contact RIRDC for more information (02 6272 4819 or 6272 3736).