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Final report

project	**Manufacture of low-cost wood-cement composites in the Philippines using plantation-grown Australian tree species**
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Contents

1 Acknowledgments

During a required update of the ACIAR Forestry Program database in 2013 it became evident that this project 'Manufacture of Low Cost Wood-Cement Composites in the Philippines using Plantation Grown Australian Tree Species' was missing the final report document. A final report is a mandatory requirement for all ACIAR projects to provide an historical record of the scientific and other outputs and outcomes of the project. Consequently, this final project report was compiled by an ACIAR staff member in 2013 by collating and summarising key information from relevant project documentation including project proposal, annual reports, project review report and an adoption study implemented in 2011. Due to the limitations of this retrospective process and missing project documentation there are a number of gaps in the information presented in relation to project outputs and outcomes. These gaps include:

Results from the following objectives

Sub-project 1 - Compatibility of Eucalypts and Acacias with Portland Cement

1.2 Compare cement inhibition indices obtained using chemical and physical criteria.

1.3 Determine the relationship, if any, between wood properties (growth rate, heartwood percentage, and wood density) and cement inhibition.

Sub-project 2 - The Effect of Post Harvest Storage on the Suitability of *A. Mangium* Wood for the Manufacture of WWCBs

2.2 Examine the effect of debarking billets, prior to storage, on the extractive content of the wood and their suitability for the manufacture of WWCBs.

2.3 Determine the levels of bark or decayed wood that can be incorporated in WWCBs without significantly reducing board properties.

Sub-project 3 - The Effect of Processing Parameters on the Properties of WWCBs Manufactured from Eucalypts and Acacias

3.2 Manufacture WWCBs from such species and compare their properties with those of boards manufactured from indigenous wood species including, *G. arborea*, *P. falcataria,* and *L.leucocephala*.

3.3 Compare the properties of boards manufactured from eucalypts and acacias with those of commercially manufactured boards.

3.4 Subject to findings from sub-project 1 determine whether it is possible to substitute cement in WWCBs with rice hull ash. Determine the maximum level of substitution, consistent with maintaining board properties.

3.5 Examine the effect of incorporating rice hull ash on the properties of WWCBs.

The contributions of the following project members are acknowledged.

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2 Executive summary

In the Philippines wood-wool-cement board (WWCB) is made in both small and large factories by mixing wood-wool (shavings) from low-quality wood, additives and Portland cement. The result is a highly suitable building material that resists water, fungi, termites and fire, and is easy to work with. This high-value product uses thin logs unsuitable for sawing. It also provides employment for small communities. WWCBs have the potential to provide an economic building material that could help to alleviate the serious shortage of low cost housing in the Philippines.

Re-forestation of degraded land in the Philippines using Australian species of eucalypts and acacias has led to the availability of these species as source materials for WWCBs. This project aimed to improve the suitability of Australian eucalypts and acacias for wood-wool cement boards. The first sub-project aimed to overcome constraints to do with incompatibility with Portland cement by screening Acacia and Eucalyptus species, provenances and families to identify those with the lowest content of extractives that cause incompatibility. The second sub-project determined the effect of post harvest storage on the suitability of A Mangium wood for the manufacture of WWCBs. The third sub-project investigated methods to optimise processing conditions to produce WWCBs from eucalypts and acacias.

This project which was implemented between 01/1997 and 12/2001 screened 36 species and provenances of acacias and 39 species of eucalypts which were tested for their compatibility with cement. Almost all the acacias sampled were classed as incompatible with cement, with only *A. elata* classed as moderately compatible. In contrast to the acacias, several temperate eucalypts of commercial importance in Australia, including *E. regnans* and *E. obliqua* showed relatively high natural compatibility with Portland cement, with potentially little or no requirement for removal of inhibitory extractives.

Trials of the manufacture of WWCBs from *Acacia mangium*, which is known to be unsuitable for the manufacture of wood-cement composites without removal of inhibitory heartwood extractives, have yielded promising results. The methods to improve the compatibility of acacias with cement include wood wool pretreatments or additives which accelerate curing. Either process adds to the cost of production. The results of this research suggest that the same results may be obtained by the selection of appropriate timbers.

The research on the optimisation of the basic board manufacturing process, including correct wood/cement ratios, billet pre-storage to reduce soaking time, and mat quality, has been successfully transferred to WWCB plants. This project laid the foundation knowledge necessary for the development and growth of the WWCB industry in the Philippines to help meet the need for low-cost, locally produced building materials. It has demonstrated that low-density plantation-grown wood, which is unsuitable for applications requiring the use of solid sawn wood, can be used to manufacture WWCBs at relatively low cost and with natural durability in tropical conditions.

Training has formed an important aspect of this research. Filipino scientists from the FPRDI were trained in Australia at CSIRO and in the ANU. These training programmes and others offered to FPRDI staff on the statistical design and analysis of multivariate experiments will have a lasting impact on the rigour with much of the work undertaken at the FPRDI.

Good relationships established between ACIAR and the various participants in this project contributed much to its success. The degree of collaboration appeared to be excellent on both a personal and a scientific basis. Much of this stemmed from a genuine interest from the project leaders in all locations to utilise the project results as part of the solution for a major social problem in the Philippines**.**

3 Background

Plantations of Australian eucalypts and acacias are of major economic, environmental and social importance throughout Asia. Wood from the plantations established at the community (village) level is mainly consumed as fuel, but it would be desirable if some of it was used to manufacture higher value products. This would increase household incomes in rural regions and encourage reforestation. Unfortunately many wood manufacturing industries are difficult to integrate at the community level because of their large size and requirements for capital and other resources. Other industries, for example small scale sawmilling, which may operate locally have difficulty in utilising the lower quality, small sized, wood that young eucalypt and acacia plantations yield. One industry that is not subject to these constraints is the wood-wool-cement board (WWCB) industry which can operate on a small scale using lower quality wood to manufacture building panels with excellent properties, including ease of machining and resistance to water, fungi, termites and fire.

WWCBs are mainly used for building construction and are increasing in importance around the world. WWCBs have the potential to provide an economic building material that could help to alleviate the serious shortage of low cost housing in Asia. Currently in the Philippines there is a chronic shortage of housing; annual housing needs in the Philippines are 633, 726 units with a shortfall of 3, 203, 010 units (Anon 1993). Therefore one of the key thrusts of Government Policy in the Philippines for the period 1993-98 was the implementation of a National Shelter Program to make inroads into this problem.

This project was inspired by the acute shortage of low-cost housing in the Philippines and a need to develop a local, low-cost building-panel system suited to the tropical climate. Imported materials and engineered composite panels familiar to building systems in Western countries are not only costly, but in many cases will not tolerate tropical climatic conditions, which makes them unsuitable for low-cost housing projects in the Philippines. WWCBs are better suited for this purpose since they contain simple and relatively cheap constituents (pulp-quality wood, Portland cement, water and small quantities of cement set accelerator), and can also be produced in small-scale, low-tech production plants, unlike conventional engineered wood composites. Cement-bonded composites also have much higher resistance to biodeterioration, including termites and decay, than solid wood and conventional composites. Furthermore WWCBs can be used for a wide variety of building applications including exterior weatherboards and cladding, ceilings, partitions and roofing tiles. WWCBs in combination with other locally available materials can be used to construct low cost housing and anecdotal evidence (Comendador 1995) suggests that houses built from WWCBs are resistant to the destructive effects of typhoons.

Re-forestation of degraded land using Australian based species of eucalypts and acacias has led to the development of plantations of these species. It would be of great benefit if some of the wood from the acacia and eucalypt plantations established throughout Asia could be processed on a small scale, thereby providing employment and income for local communities. In the case of *A. mangium*, which is one of the most important plantation species in SE Asia, its use for WWCBs is being constrained by its poor compatibility with cement. This occurs because it contains certain low molecular weight carbohydrates and extractives that interfere with cement hydration which result in WWCBs of inferior strength. This problem is particularly pronounced with *A.mangium* because it contains small quantities of teracacidin which strongly inhibits cement hydration even in the presence of cement-hardening accelerators (Tachi *et al.* 1988, 1989). The unwanted effects of soluble wood components in *A. mangium* on cement are overcome in WWCB plants by soaking the wood wool in water prior to board manufacture and by adding compounds that accelerate cement hydration reactions. While these measures reduce some of the negative interactions between the wood and cement they create additional problems or costs. For example, differences in soaking times can vary from 4 hours for a species which is compatible with cement to 12 hours for a species such as *A. mangium* which is less compatible. Increased water consumption and the use of cement accelerators can significantly increase production costs.

The development of localised wood using industries also provides an important economic incentive for reforestation in developing countries which local demand for fuelwood does not. Thus Turnbull (1991) writes 'numerous surveys have found that fuelwood scarcity rarely provides sufficient incentives for people to plant trees'. WWCB plants, as mentioned above, are suitable for the value added processing of wood at the local level and their establishment provides a stimulus for economic development and reforestation in rural areas. Another significant advantage of the WWCB Industry is the use of local labour that does not require high-level skills.

The research problem

Wood wool cement boards are a low cost building material that can be manufactured on a small scale by mixing wood strands with Portland cement and additives. Prior to this project there were 15 small scale plants manufacturing WWCBs in the Philippines and the industry has grown to this size from a base of only one plant in 1993 (Bello *et al.* 1995). There were plans for a further 24 plants in the Philippines and further rapid expansion of the industry in the Philippines and elsewhere in SE Asia was anticipated in the future (Bello *et al.* 1995). The Cement Bonded Board Manufacturers Association of the Philippines (CBBMAP) indicated that lack of research and development and technical assistance were significant factors constraining the development of the industry and associated tree planting cooperatives. In a report prepared for the then President Fidel Ramos Bello *et al.* (1995) identified the following as constraining the development of the WWCB industry in the Philippines: lack of capital available to local communities and entrepreneurs to establish WWCB plants; lack of government support for community tree planting schemes to provide raw materials for WWCB plants; lack of funds for R & D and technical assistance; and lack of information on the raw materials suitable for the manufacture of WWCBs. This project, in part, addressed the latter two factors. In so doing it provided much needed R & D and technical assistance to the WWCB industry, and associated tree planting cooperatives in the Philippines.

Prior to this project no research had been undertaken in the Philippines to evaluate the suitability of Australian tree species for the manufacture of WWCBs despite widespread plantings of eucalypts and acacias and the presence of a burgeoning WWCB industry in the Philippines. CBBMAP indicated that unless such research was undertaken the industry might be unable to take advantage of the eucalypt and acacia plantations established in the Philippines and this would constrain further development of the industry.

The overall aim of this project was to evaluate the suitability of Australian tree species for the manufacture of WWCBs in the Philippines. Many small WWCB plants are operating in the Philippines and in other parts of SE Asia. The use of many eucalypts and acacias for manufacture in these plants is being constrained by lack of information on their compatibility with cement and suitability for board manufacture. The three research needs identified include the following: 1) improve the suitability of acacias and eucalypts by screening provenances and families to identify those with the lowest content of extractives that cause the incompatibility; 2) determine whether manipulation of storage time of timber can improve its suitability; 3) develop methods that optimise processing conditions to produce composite boards from cement and eucalypts or acacias. These research needs were addressed by four sub-projects.

The aim of sub-project 1, was to determine whether there is variation at the provenance and family levels in the compatibility of acacia and eucalypt species with cement, to identify those provenances and families which are less inhibitory and to determine the reasons for differences (if any) in their compatibility. This sub-project aimed to facilitate in the selection of provenances or families which are more suitable for the manufacture of WWCBs. This research was necessary because further expansion of the wood-cement composite industry in Asia will depend on its ability to utilise a wide variety of wood species, particularly the large resource of Australian eucalypts and acacias.

The aim of sub-project 2 was to determine the optimum storage time for *A.mangium* grown in the Philippines. The overall aim of this sub-project was to increase the compatibility of *A. mangium* with cement and improve its suitability for the manufacture of wood-cement composites. This sub-project was developed because the suitability of wood for the manufacture of wood-cement composites is greatly affected by the length of time it is stored prior to processing (Schwartz 1989). During the initial stages of storage, wood sugars and carbohydrates that interfere with cement setting decrease as they are consumed by non decay fungi (Nohara 1981). Later, decay fungi may colonise the wood breaking it down into lower molecular weight carbohydrate fractions and this greatly reduces the compatibility of the wood with cement (Schwartz 1989). Therefore during the post harvest storage of wood for the manufacture of WWCBs these competing reactions need to be carefully balanced.

The aim of sub-project 3 was to determine the processing conditions required to manufacture WWCBs from eucalypts and acacias. This subproject also compared the properties of WWCBs manufactured from such species with those of boards manufactured in the Philippines from indigenous wood species and investigated the correct amount and type of accelerator to reduce the deleterious effects of cement inhibiting compounds.

The aim of sub-project 4 was to build the capacity of Philippine and ANU students to support future research priorities.

4 Objectives

Sub-project 1 - Compatibility of Eucalypts and Acacias with Portland Cement

Research Objectives

1. Screen provenances and families of A. mangium for their compatibility with Portland cement. Screen major eucalypt and acacia plantation species of commercial importance in Asia for their compatibility with Portland cement. Develop cement inhibition indices for the different species, provenances and families and classify them with regard to their suitability for the manufacture of wood-cement composites; species will be classified as suitable, moderately suitable, unsuitable and extremely unsuitable.
2. Compare cement inhibition indices obtained using chemical and physical criteria.
3. Determine the effect of cold water extraction on the compatibility of the different species, provenances and families with Portland cement.
4. Determine whether inorganic accelerators, ie, chloride salts of calcium, magnesium, aluminium and iron, can improve the compatibility of species with high cement inhibition indices. Examine whether rice hull ash can substitute for cement in WWCBs.
5. Determine the relationship, if any, between wood properties (growth rate, heartwood percentage, and wood density) and cement inhibition.

Sub-project 2 - The Effect of Post Harvest Storage on the Suitability of *A. Mangium* Wood for the Manufacture of WWCBs

Research Objectives

1. Determine the effect of post harvest storage time on the extractive content of *A. mangium.* Determine whether the properties of WWCBs manufactured from *A. mangium* are affected by the length of time that wood is stored prior to processing.
2. Examine the effect of debarking billets, prior to storage, on the extractive content of the wood and their suitability for the manufacture of WWCBs.
3. Determine the effect of soaking logs on the extractive content and properties of WWCBs manufactured from *A. mangium*.
4. Examine the effect of bark or decayed wood on the properties of boards manufactured from *A. mangium*
5. Determine the levels of bark or decayed wood that can be incorporated in WWCBs without significantly reducing board properties.

Sub-project 3 - The Effect of Processing Parameters on the Properties of WWCBs Manufactured from Eucalypts and Acacias

Research Objectives

1. Optimise wood-wool strand geometry, pre-treatment time, accelerator type and quantity and cement:wood ratio for the eucalypts and acacias currently performing well in the Philippines and selected in sub-project 1 as being compatible with cement.
2. Manufacture WWCBs from such species and compare their properties with those of boards manufactured from indigenous wood species including, *G. arborea*, *P. falcataria,* and *L.leucocephala*.
3. Compare the properties of boards manufactured from eucalypts and acacias with those of commercially manufactured boards.

4. Subject to findings from sub-project 1 determine whether it is possible to substitute cement in WWCBs with rice hull ash. Determine the maximum level of substitution, consistent with maintaining board properties.
5. Examine the effect of incorporating rice hull ash on the properties of WWCBs.

Sub-project 4 - Training of Philippine Scientists & ANU Students

Research Objectives

1. The training of Philippine scientists in the area of experimental design.
2. The training of Philippine scientists in the manufacture and testing of wood cement composites including alternative low cost sawdust cement boards.
3. The training of ANU honours student in the area of the manufacture and testing of rice hull ash wood-cement composites.

5 Methodology

5.1 Materials and Methods

5.1.1 Compatibility of Australian acacias and eucalypts for wood-cement composites (sub-projects 1-3)

Wood samples from a wide range of temperate eucalypt and acacia species were taken from controlled species elimination and growth performance trials established by CSIRO Division of Forest Research at two locations within the Australian Capital Territory. Samples were collected from the eucalypt trials (between 22 Oct. and 1 Nov. 1999 (Uriarra) and 5 to 11 November 1999 (Kowen), and from the acacia trials on 14 February (Kowen) and 6 March 2000 (Uriarra). In both trials, all surviving species were targeted for sampling, with one tree per seed lot (treatment) cut from each of two replicate blocks at each site. This provided 4 trees per treatment. Trees were cut at ground level and two adjoining disks approximately 25 mm in thickness cut from 1.3 m height, avoiding branches and knots where necessary were removed. The disks had their under-bark diameter and heartwood diameter recorded across two axes for calculation of circular heartwood proportion. One of the disks was then stripped of bark and used in the determination of basic density. The other was also stripped of bark and air-dried under cover for about 2 months before preparation of tangential flakes for wood-cement compatibility testing. A sample of flakes which had been soaked in water for 24 h and dried was also prepared for each tree. A total of 250 unsoaked and soaked eucalypt samples and 210 unsoaked and soaked acacia samples were tested for their compatibility requiring 79 days of testing.

5.1.2 Sampling of species and determination of extractive and sugar content (sub-project 1)

Wood samples were removed from all species of interest in a non destructive manner by boring into them at breast and crown height using a 12 mm increment borer and removing cores of solid wood. Wood cores were used to obtain information on wood density, % heartwood and tree diameter. The latter together were used to estimate tree growth rate. To avoid deterioration of the wood during transport to the laboratory, cores were sealed in plastic bags and refrigerated after removal from the trees. Samples were reduced to sawdust using a Wiley mill and then screened to pass standard US sieves, namely a) -8 + 20 mesh, b) -20 + 40 mesh and c) >40 mesh. Immediately after milling the cold water extractive content of samples were determined on 2g sub-samples using a standard ASTM method (ASTM D1110, Browning 1967). The pH and reducing sugar content of the cold water leachate was determined using rapid electrochemical and spectroscopic techniques respectively (Dubois *et al*. 1967).

5.1.3 Determination of inhibition indices using cement hydration reactions (sub-project 1)

For each species fifteen grams (oven dry basis) of wood was placed in a polythene bag and mixed with 200 g of cement. The cement was representative of those used commercially in the Philippines and Australia for the manufacture of WWCBs; chemical characterisation of the cement was undertaken prior to examining any cement-wood interactions. Ninety mL of distilled water was added to the wood and cement and the mixture kneaded for 5 minutes. The mixture was placed in an insulated flask further covered with polystyrene insulation. A thermocouple was placed into the wood-cement mixture and the rise in temperature of the mixture (due to cement hydration) was plotted over 24h. Data obtained from the cement hydration reaction curves was used to obtain an index of the degree to which wood species inhibit the hydration of cement. Species were then classified into the following groups based on the similarity of their inhibition index, suitable, moderately suitable, unsuitable and extremely unsuitable.

Cement inhibition indices were also calculated on samples which had been subjected to cold water extraction or mixing with inorganic accelerators or rice hull ash. Again after such treatments, species were classified into groups based on the similarity of their inhibition indices. Those which showed little improvement on cold water soaking or treatment with accelerators or rice hull ash were deemed not suitable for the manufacture of wood-cement composites and were not subject to further investigation in sub-project 3.

5.1.4 Determination of cement inhibition using compression strength tests (sub-project 1)

An experiment was conducted to test the validity of using cement inhibition indices as a measure of the suitability of wood species for wood-cement composites. This experiment was the internal control and the rankings obtained using cement hydration data was compared with those obtained from compressive strength tests on cement blocks containing sawdust obtained from the different wood species. Two species from each of the 4 suitability classifications were sampled to obtain approximately 50g (oven dry basis) of wood per tree. Samples were reduced to sawdust using a Wiley mill and then screened to a size class of 20-40 mesh. Forty-five grams of wood were mixed as above with 600g of cement and 272g of water. After thorough mixing, wood-cement mixtures were placed in 2 x 2 (inch) square moulds and allowed to set over water saturated with ammonium phosphate (95% RH) for 2 months. Cubes were then removed from the moulds, allowed to hydrate for 2 weeks under distilled water saturated with lime. Following this, specimens were oven dried to stop hydration and tested for compression strength using a Shimadzu testing machine (UH-A type). Tests of the effect of accelerators on cement inhibition used compression tests to evaluate whether the accelerators were affecting cement curing characteristics beyond the period of initial set (>24h). The effect of rice hull ash on the mechanical properties of wood sawdust cement composites (sub-project 4, J Lynch) was examined by testing the compression of cement cubes containing different levels of cement, sawdust and rice hull ash.

5.1.5 Manufacture of WWCBs (sub-projects 2-3)

Sub-projects 2 and 3 evaluated the effects of post harvest storage and processing parameters, respectively, on the properties of WWCBs manufactured from eucalypts and acacias, and species indigenous to the Philippines. This required the manufacture of boards on a pilot scale. The methods involved in this are as follows;

1. Cutting and debarking; roundwood was cut into billets, 40 cm in length, and then debarked manually using an axe. In sub-project 2 some logs were stored and processed with bark intact.
2. Shredding; billets were converted into wood-wool, 5 mm wide and 0.4 mm thick using a shredding machine. FPRDI possesses a vertical Japanese shredder with a capacity of 1 m^3 per day which was employed in the project. As part of their training scientists from the Philippines manufactured boards in Australia. This involved the use of equipment belonging to Woodtex PTY Ltd, Australia's only manufacturer of WWCBs.
3. Soaking; a soaking tank measuring 6 m (length) x 5 m (wide) x 1 m (depth) was used to determine the optimum soaking times for the different wood species (sub-project 3).
4. Mixing; wood wool and cement was mixed in a drum mixer fabricated by staff at FPRDI. During this stage different accelerators, and rice hull ash and various cement-wood ratios were used (sub-project 3) in order to optimise board properties (sub-project 3).

5. Board formation and pressing; boards were formed by manually placing wood-wool-cement mixtures in a rectangular forming box placed on a caul plate (450 x 500 x 12 mm) manufactured from marine grade plywood. Batches of wood-cement mats were cold pressed using hydraulic jacks with a capacity of 20 tons; this equipment was available at FPRDI. Pressure was maintained on the mats by bolts and was left under pressure for 24 h. This was the time required for the initial setting and hardening of cement.
6. Board curing; boards were piled vertically and left to cure for four weeks.

Manufacture of WWCBs

Wood-wool cement boards were manufactured from shredded, air-dry *A. mangium* wood-wool to examine the effects of the addition of water soluble inorganic salts on board mechanical properties. Boards were manufactured according to guidelines set out in the Philippine National Standard for WWCB (PNS/CTP 07: 1990) using a wood-cement ratio of just under 1:1. Boards contained 504 g of wood-wool, 508 g Portland cement (Blue Circle Southern Batch No. 298MA00 and 523 g water to which the additives were added. The additive solution was first sprinkled through the wood-wool to wet all strands and then left to sit for 2 - 3 minutes to allow any reactions with wood constituents such as heartwood polyphenols to take place. The cement powder was then sprinkled through the wet wood-wool in stages interspersed with hand mixing to evenly coat all strands. The mix was then transferred to a formply mould measuring 300 x 380 mm placed on a rectangular sheet of formply measuring 340 x 420 x 17 mm.

The mix was evenly spread and flattened using a wooden block to form a mat, the mould removed and another piece of formply placed on top of the mat. Two wooden spacing rods measuring 12 x 12 x 300 mm were placed at either end between the two formply sheets to achieve a pressed board thickness of 10 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. This stack of mats was placed between two steel plates measuring 340 x 470 x 15 mm and pressed at ambient temperature to 20 000 psi 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, an assemblage, which could then be removed from the press. After 24 h the boards were de-clamped, stacked and conditioned for 28 days at 20 ± 1 °C and 65 ± 5 % r.h. to allow the cement to cure and gain maximum strength. During the manufacture of boards, all samples of Tree 1 (unsoaked) were made in a randomised order followed by Tree 2 (soaked), Tree 2 (unsoaked) and finally Tree 1 (soaked). Four boards were manufactured each day, resulting in a total of 58 boards from unsoaked wood-wool and 36 boards from soaked wood-wool.

Preparation of wood-wool from billets.

Two trees of *A. mangium* measuring approximately 12 m in height were cut in June 2000 from a 12 year old provenance trial plantation located at Kuranda in North Queensland. Tree 1 was 33 cm DBHOB from PNG-North (Kini province, seedlot 16938) and Tree 2 was 40 cm DBHOB from PNG-southeast (Boite province, seedlot 16992). Both trees contained approximately 75% heartwood. The felled trees were cut into logs measuring 1m or 50 cm closer to the base of the tree, colour coded by tree and shipped to Canberra where they were debarked and further cut into billets measuring 46 cm for immediate conversion into wood-wool strands. This was done at Woodtex Pty Ltd in Bendigo, Victoria using a Van Elten shredder. The shredded wood-wool was bagged, returned to Canberra and immediately spread out to dry under cover for 5 days. Around half of the total quantity of wood-wool was then soaked in water at ambient temperature (25°C) to remove soluble inhibitory constituents from the wood. This was done by filling a 70 L bin with approximately 2 kg of air-dry wood-wool and adding water to completely cover the wood-wool and fill the bin to the brim. The wood-wool was weighed down with rocks to keep it submerged and kept covered for 24 h. The leachate was poured off and the wood-wool spread out to dry under cover for 5 days. This process was repeated until approximately 20 kg of wood-wool per tree had been extracted and dried.

Prior to board manufacture, the wood-wool was screened by sifting it through a grill measuring 40 x 50 mm to remove short pieces (< approx. 10 mm). Screened wood-wool was then weighed into batches of 410 g required to make one board and stored in open bags until use.

Additives used and their preparation.

The additives used to make WWCBs from unsoaked and soaked *A. mangium* wood-wool are shown in Table 5. In most cases, two concentrations, 0.05 M and 0.1 M, were used for unsoaked wood. Exceptions to this were compounds whose effects were found to be negligible at 0.05 M i.e. $CaCl_2$, $MgCl_2$, $NaSiO_2$ and $SrCl_2$. For soaked wood-wool, 0.05 and 0.1 M strength $CaCl_2$, $MgCl_2$, $NaSiO_2$ and $SrCl_2$, were used and 0.05 M strength $FeCl_3$, $SnCl_4$, $AlCl_3$, $Al_2(SO_4)_3$, $Al(NO_3)_3$ and $Ca(NO_2)_2$, as summarised in Table 1.

Table 1. Compounds used and their concentrations

Compound	Concentration	Tree 1	Tree 1 (s)	Tree 2	Tree 2 (s)
CaCl2	0.1	•	•	•	•
	0.2	•	-	•	-
MgCl2	0.05	-	•	-	•
	0.1	•	•	•	•
SrCl2	0.05	-	-	-	-
	0.1	•	•	•	•
FeCl3	0.025	•	-	•	-
	0.05	•	•	•	•
	0.1	•	-	•	-
SnCl4	0.025	•	•	•	•
	0.05	•	•	•	•
	0.1	•	-	•	-
AlCl3	0.05	•	•	•	•
	0.1	•	-	•	-
Al2(SO4)3	0.05	•	•	•	•
	0.1	•	-	•	-
Al(NO3)3	0.05	•	•	•	•
	0.1	•	-	•	-
Na2SiO2	0.1	•	•	•	•
	0.2	•	-	•	-
Ca(NO3)3	0.05	•	•	•	•
	0.1	•	-	•	-
Pozzolith	10 mL	•	•	•	•
Water		•	•	•	•
SC + MC	0.05 + 0.05	•	•	•	•
FC + MC	0.05 + 0.05	•	•	•	•
AS + MC	0.05 + 0.05	•	•	•	•
AN + MC	0.05 + 0.05	•	•	•	•
SC + MC	0.025 + 0.05	•		•	
FC + MC	0.025 + 0.05	•		•	

Effect of heartrot on the compatibility of A. mangium with cement

A. mangium logs obtained from a 12 year old plantation in Kuranda, North Queensland, Australia were transported to the Australian National University in Canberra. Billets containing white-rot were collected and then cut into 25 mm thick discs using a band saw. The discs were further cut across their diameters producing rectangular samples measuring 25 x 25 mm with lengths depending on the diameter and part of the disc where the specimen was cut. The rectangular wood samples were shaved along the tangential direction using a guillotine to produce specimens measuring approximately 0.4 x 25 x 25 mm. The resulting shavings were conditioned at 20 $^{\pm}$1ºC and 65 $^{\pm}$5% r.h. for at least two weeks.

Sapwood, heartwood and decayed wood shavings were subjected to hydration tests. The effect of the shavings on the hydration of cement was evaluated using maximum temperature (T_{max}), time to reach T_{max} (Time), C_A-Factor (Hachmi *et al.* 1990) or the ratio of the area under the hydration curve of a wood-cement sample to that of neat OPC (Blue Circle Southern, 203MA01). The hydration rate (H-rate) or the ratio of the difference between the T_{max} and T_{min} (minimum temperature within the first 5h of hydration) to that of the time to reach T_{max} was also determined.

5.1.6 Testing of WWCBs (sub-projects 2-3)

Following their manufacture boards were trimmed and cut into the appropriate sub-samples for the following tests;

1. Bending strength tests to derive modulus of elasticity (MOE), modulus of rupture (MOR) and measures of toughness including work to maximum load (WML) and total work done (TWD). Tests were conducted in accord with standard protocols used at FPRDI for the testing of WWCBs (Pablo 1989).
2. Water immersion tests to determine thickness swelling, water absorption. Board moisture content and density tests were conducted in accord with standard methods.
3. Termite and soil burial tests to determine the resistance of selected boards to biodeterioration were undertaken at FPRDI using established procedures. Fire resistance tests used the fire tube test method.

Determination of board mechanical properties

Conditioned boards measuring 340 x 320 x 12 mm were sawn into 5 test samples measuring 230 x 50 mm. The size of the test pieces and testing procedures were based on the Japanese Standard JIS-A 5908 (1994) as used by Philippines researchers. 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 were soaked in water at ambient temperature (23°C) for 24 h. Before soaking, the samples were weighed and their thickness measured at three points along their length using a Mitutoyo digital micrometer. After soaking, the samples were drained on paper towels for approximately 20 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 testing was carried out using an Instron Universal Testing Machine, with a span of 180 mm, cross-head and bearer diameter of 25 mm and loading speed of 5 mm/min. Data on mechanical properties of samples can be found in section 7.14.

Results obtained from the above tests were compared with the results of similar tests carried out on boards manufactured commercially in the Philippines. These tests gave good indications as to the quality of boards currently being manufactured.

The performance of boards in long term weathering tests is very important. Correctly made boards show little diminution in properties during prolonged periods of exterior exposure, but poorly made boards using improper species, accelerators and wood-cement ratios show marked losses in strength during weathering. Therefore it was very important to establish exterior weathering trials of boards manufactured in Sub-project 3 even though the results were not available at the conclusion of the project. Commercially manufactured boards were included in such trials to determine their long term performance and to assess whether they were being manufactured correctly. The ANU and FRPRD continue to maintain and fund these weathering trials beyond this project.

Testing corrosivity of boards to nails

Test sample no. 5 was used to test the corrosivity of boards containing additives to four different types of commonly used nails. Four nails of each type were tested in each test peice. The nail types were:

1. normal wood nails (Otter brand bullet head bright 25 mm x 1.8 mm).
2. wood tacks (Otter brand cut tacks blued 20 x 1.6 mm)
3. hardboard nails (Otter brand hardboard zinc plated 25 x 1.6 mm)
4. fibrecement nails (Otter brand fibrecement galvanised 25 x 2 mm)

Each test piece was drawn up into four sections, into which one of each nail type was hammered until it reached the bottom of the board, leaving approximately 6 mm of nail top exposed for visual assessment and ease of removal. The weight of each nail and its position in the test piece was recorded prior to nailing. The test pieces containing nails were then cut into two halves, one half to be tested in a highly corrosive environment subjected to periodic wetting and the other a less corrosive environment protected from sources of moisture such as rain. The two types of test pieces were placed in flat plastic tubs on stiff polypropylene mesh to elevate them above a shallow bath of water in the bottom of the tub. The sealed tubs were placed in a controlled temperature room maintained at 30 ± 1 °C to create an environment of elevated humidity around the test pieces to simulate the humid conditions found in the tropics. The high corrosion environment samples were sprayed with distilled water every two weeks to simulate periodic rain wetting. After 12 months of exposure, the samples were removed and oven dried before removing the nails. Each nail was re-weighed and the mass loss as a percent of original nail weight calculated. A visual assessment of corrosion damage was made for each board and nail type.

5.2 Location of work, methods of analysis, and training, including postgraduate study

The emphasis of this project was on collaboration between the different institutions and sharing of research outputs. The locations of the different sub-projects (Table 2) were chosen in order to maximise the likelihood of achieving success and takes into account the quality and background of personnel involved and the infrastructure available at each location.

A key element of this project, to maximise the likelihood of success, was the correct design and analysis of all experiments involved in sub-projects 1-3. Because of this, statisticians from the ANU were involved in the project from the outset and also trained two of the key scientists in the Philippines, Mr Cabangon and Dr Eusebio, in experimental design, statistical analysis and interpretation. A clear objective of their training at the ANU was the preparation of experimental plans for sub-projects 2 and 3. Data from all sub-projects were analysed by ANU statisticians although all of the principal scientists in FPRDI received training in the interpretation of analyses that ANU statisticians generated.

Table 2. Location of work and scientists involved in the different projects

Sub project No.	*Location & % contribution*	*Supervising Scientist involved*	Research interest of scientist
1. Wood-cement compatibility	ANU (100%)	Dr P. Evans	Wood chem & composites
2. Post harvest storage	FPRDI (75%) FPRDI (25%)	Mr R. Cabangon Dr F. Soriano	Wood-cement composites Wood extractives
3. Board manufacture & properties	FPRDI (95%) CSIRO (5%)	Dr D. Eusebio Dr B. Coutts	Wood-cement composites Wood-cement composites
4. Training	ANU (50%) CSIRO (50%)	Dr P. Evans (ANU) Dr B. Coutts (CSIRO	as above

6 Achievements against activities and outputs/milestones

Objective 1: To determine the compatibility of Eucalyptus and Acacias with Portland Cement

no.	**activity**	**outputs/ milestones**	**completion date**	**comments**
1.1	Screen provenances and families of *A. mangium* for their compatibility with Portland cement.	Development of cement inhibition indices for different species, provenances and families of *A. mangium.*	31/12/00	A technique for the determination of cement inhibition indices has been developed from the hydration exotherm for Portland cement in the presence of Wood wool extractives. This technique has been used to show that there are considerable variations in the compatibility of different families of A. mangium with cement. No geographical or familial basis for the observed variations has been derived. (There may not be one). It may be that a simple site test may be more efficient than a species characterisation for the choice of an appropriate timber. The development of such a test is not complete.
1.2	Compare cement inhibition indices obtained using chemical and physical criteria.	Development of cement inhibition indices for different eucalypt and acacia species.	30/09/00	A technique for the sampling of live trees for suitability for WWCB manufacture has been developed. Cement inhibition indices have shown that some families of A. Mangium and E. pellita are suitable for WWCB manufacture.
1.3	Determine the effect of cold water extraction on the compatibility of the different species, provenances and families with Portland cement.	Comparison of cement inhibition indices using physical and chemical criteria.	30/09/00	Four separate parameters have been derived from the exotherms. A total reaction enthalpy (23 hours) has been shown to correlate well with mechanical properties of the product.
1.4	Determine whether inorganic accelerators, ie, chloride salts of calcium, magnesium, aluminium and iron, can improve the compatibility of species with high cement inhibition indices. Examine whether rice hull ash can substitute for cement in WWCBs.	Evaluation of the effect of aqueous extraction and accelerator type (inorganic salt) and rice hull ash on inhibition indices.	31/03/01	It has been shown that aqueous extraction of samples prepared from A. mangium has a much greater effect than on E. pellita. The hypothesis that A. mangium is not compatible with Portland cement has been disproved. The examination of a wide range of additives has shown that calcium chloride and aluminium sulphate have the major effects on compatibility.

1.5	Determine the relationship, if any, between wood properties (growth rate, heartwood percentage, and wood density) and cement inhibition.	Relationship between wood properties (growth rate, heartwood percentage, wood density) and cement inhibition.		The DBHOB, heartwood percentage and wood density of 3 acacia and 2 eucalypts were determined. The heartwood percentage showed little correlation with cement inhibition. Provenance had similarly little effect. The variation in cement inhibition among the acacias was considerable.

PC = partner country, A = Australia

Objective 2: To assess the effect of post harvest storage on the suitability of A. Mangium wood for the manufacture of WWCBs

no.	activity	outputs/ milestones	completion date	comments
2.1	Determine the effect of post harvest storage time on the extractive content of *A. mangium.* Determine whether the properties of WWCBs manufactured from *A. mangium* are affected by the length of time that wood is stored prior to processing.	Publication and dissemination of findings of the effect of log storage on the properties of *A. mangium* WWCBs	30/06/01	WWCBs with good properties have been manufactured without soaking provided that the billets were stored for six weeks prior to shredding and $CaCl_2$ was used. The properties of WWCBs prepared after varying billet storage times has been found to be very variable but a general trend has been found that both strength and stiffness have a maximum when the WWCBs are manufactured from billets stored for six weeks.
2.2	Examine the effect of debarking billets, prior to storage, on the extractive content of the wood and their suitability for the manufacture of WWCBs.	Provide guidelines on the influence of bark and decayed wood on the properties of WWCBs.	30/06/01	It was found that soaking did not appreciably affect the properties of WWCBs manufactured from E. pellita but did have a major effect on the properties of WWCBs manufactured from A. mangium
2.3	Determine the effect of soaking logs on the extractive content and properties of WWCBs manufactured from *A. mangium*.	Provide guidelines Publication of findings		
2.4	Examine the effect of bark or decayed wood on the properties of boards manufactured from *A. mangium*	Provide guidelines Publication of findings		It has been found that the incorporation of up to 20% of bark in the shavings used for the manufacture of WWCBs has no deleterious effect on their properties.
2.5	Determine the levels of bark or decayed wood that can be incorporated in WWCBs without significantly reducing board properties.	Provide guidelines Publication of findings		

PC = partner country, A = Australia

Objective 3: To assess the effect of processing parameters on the properties of WWCBs manufactured from eucalypts and acacias

no.	**activity**	**outputs/ milestones**	**completion date**	**comments**
3.1	Optimise wood-wool strand geometry, pre-treatment time, accelerator type and quantity and cement:wood ratio for the eucalypts and acacias currently performing well in the Philippines and selected in sub-project 1 as being compatible with cement.	Examination of the effect of strand geometry, pre-treatment, accelerator type and cement-wood ratio on board properties		Produced, tested and evaluated 540 boards considering the experimental design. The properties in terms of dry and wet bending, young's modulus, thickness swelling and water absorption were tested. The second replicates of the boards are being manufactured to confirm the initial findings. The determination of the effects of varying the manufacturing conditions on board properties has not been completed yet. A specific system should be treated to examine the effect of combined accelerators.
3.2	Manufacture WWCBs from such species and compare their properties with those of boards manufactured from indigenous wood species including, *G. arborea*, *P. falcataria,* and *L.leucocephala*.	Provide the data to allow comparison of the properties of WWCBs manufactured from eucalypts and acacias. with boards manufactured from indigenous tree species.	30/12/01	WWCBs were manufactured using A. auriculiformis, E. grandis, E. teritocornis, A. mangium and G. arborea. WWCBs using P. falcataria and L. leucocephala have not been manufactured yet. The data to allow comparison of the properties of WWCBs manufactured from Eucalyptus and Acacias with boards manufactured from indigenous tree species is not yet completed. The determination of origin of provenances of Eucalyptus and Acacia and other indigenous species should be considered.
3.3	Compare the properties of boards manufactured from eucalypts and acacias with those of commercially manufactured boards.	Provide guidelines Publication of findings	30/12/01	
3.4	Subject to findings from sub-project 1 determine whether it is possible to substitute cement in WWCBs with rice hull ash. Determine the maximum level of substitution, consistent with maintaining board properties, that can be made.	Provide guidelines Publication of findings		

3.5	Examine the effect of incorporating rice hull ash on the properties of WWCBs.	Provide guidelines Publication of findings		

PC = partner country, A = Australia

Objective 4: Capacity building and training for Philippine scientists and ANU students

no.	**activity**	**outputs/ milestones**	**completion date**	**comments**
4.1	The training of Filipino scientists in the area of experimental design.	Increase the ability of FPRDI scientists to conduct further relevant studies and their awareness of alternative low cost wood-cement building products.		Dwight Eusebio and Rico Cabagnon spent two months at the ANU receiving training in the factorial design of experiments
4.2	The training of Filipino scientists in the manufacture and testing of wood cement composites including alternative low cost sawdust cement boards.	Provide information on the properties of WWCB's manufactured in the Philippines.		Dwight Eusebio and Rico Cabagnon spent two months at the CSIRO FFPR division carrying out an experimental programme concerned with the manufacture and testing of different wood/cement composites.
4.3	The training of ANU honours student in the area of the manufacture and testing of rice hull ash wood-cement composites.			Jane Lynch has carried out a research project on the incorporation of Rice Hull Ash as a substitute pozzolan in WWCBs Paul Perrit, an Honours student of the University of New South Wales has been involved with the programme.

PC = partner country, A = Australia

7 Key results and discussion

7.1 Sub-project 1

7.1.1 Suitability of Australian acacias and eucalypts for wood-cement composites

The objective of this research was to test the compatibility of a wide range of acacia and eucalypt species from trees of similar age and growing conditions with Portland cement. This sub-project also developed a compatibility ranking of species and investigatea wood properties which may influence wood-cement compatibility such as heartwood content.

The proportion of heartwood and sapwood in eucalypts may play an important role in their compatibility with cement. Figure 1 indicates a positive relationship between the amount of heartwood in the wood sample and its compatibility with Portland cement. Heartwood content ranged from 0% (in *E. polyanthemos*) to almost 80% (in *E. seiberi*) of stem area. Low heartwood content was often associated with smaller tree diameters which were concentrated at the drier site, Kowen. Similar results were found in a published pilot study (Semple *et al.* 2000) of cement compatibility among a smaller selection of 8 temperate eucalypt species grown at the same two sites. In the study, trees from the same seed stock were smaller in size, contained significantly less heartwood and were significantly less compatible with cement than those grown at the wetter site at Uriarra.

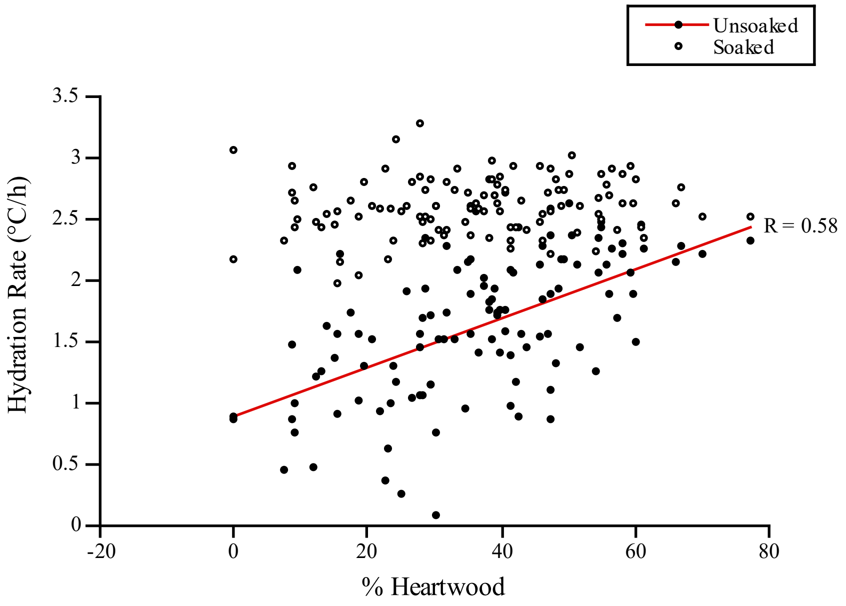

Figure. 1 Hydration rate for individual unsoaked and soaked samples of Eucalypts vs their % heartwood content. Relationship shown for unsoaked samples.

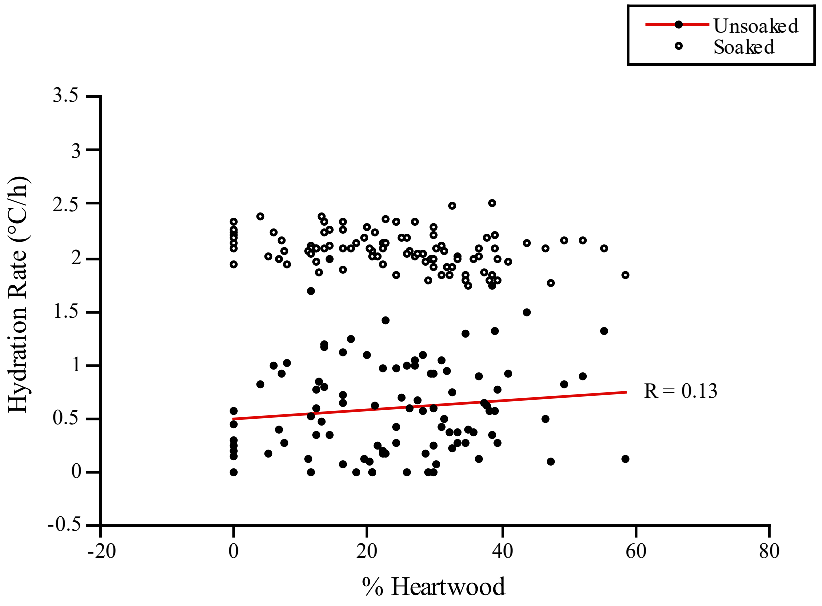

Figure. 2 Hydration rate for individual unsoaked and soaked samples of Acacias vs their % heartwood content. Relationship shown for unsoaked samples.

In contrast to the eucalypts, there was no discernible effect of % heartwood on wood-cement compatibility among the acacias as indicated in Figure 2. Tree size and variation in % heartwood among the acacias was less than the Eucalypts, with % heartwood ranging from 0% in several species to 60% in *A. dangarensis*, the species of lowest compatibility with Portland cement (Table 2). In a published pilot study (Semple and Evans 1997) the heartwood and particularly sapwood flour from temperate species *A. dealbata*, *A. mearnsii* and *A. melanoxylon* were both incompatible with cement. This finding was in contrast to that for tested tropical species *A. mangium*, *A. aulacocarpa* and *A. crassicarpa* whose heartwood was incompatible with cement but whose sapwood was rated as compatible.

Soaking in water at ambient temperature for 24 hours had a beneficial effect on compatibility of trees in both the Acacias and Eucalypts, removing any effects of % heartwood on compatibility (Figs 1 and 2). The average compatibility of soaked samples was lower in the case of the acacias than the eucalypts, and variation in compatibility was also lower compared with the eucalypts among soaked samples. Hydration rates were in the range of 1.7 to 2.5°C/h for soaked acacia samples and between 1.9 and 3.3 °C for soaked eucalypt samples. The acacia samples may have contained greater quantities of cold water insoluble inhibitory extractives such as certain hemicelluloses that inhibit cement hydration than did the eucalypt samples.

The levels of significance between main factors including site, genus, soaking and interactions between factors are shown in Table 3. All main factors significantly affected compatibility of wood samples with Portland cement ($p < 0.001$) as did interactions between factors. The site x genus x species interaction was not significant, indicating that, overall, average compatibility of species across the two genera were not significantly affected by the site at which they were grown. The average compatibility indices (expressed as hydration rate, °C/h) of wood samples from acacias and eucalypts before and after soaking are plotted in Figure 3.

Table 3. Results from the accumulated ANOVA for factors site, genus, soaking and interactions between factors.

	Temperature	Time to max.	Hydr. Rate	CA-factor
Site	<0.001	0.035	<0.001	<0.001
Genus	<0.001	<0.001	<0.001	<0.001
Soaking	<0.001	<0.001	<0.001	<0.001
site x genus	<0.001	<0.001	<0.001	<0.001
genus x ssp	<0.001	<0.001	<0.001	<0.001
site x soak	<0.001	0.03	<0.001	<0.001
genus x soak	<0.001	<0.001	<0.001	<0.001
site x genus x ssp.	N.S.	N.S.	N.S.	N.S.
site x genus x soak	<0.001	<0.001	<0.001	<0.001
genus x ssp. x soak	<0.001	<0.001	<0.001	<0.001

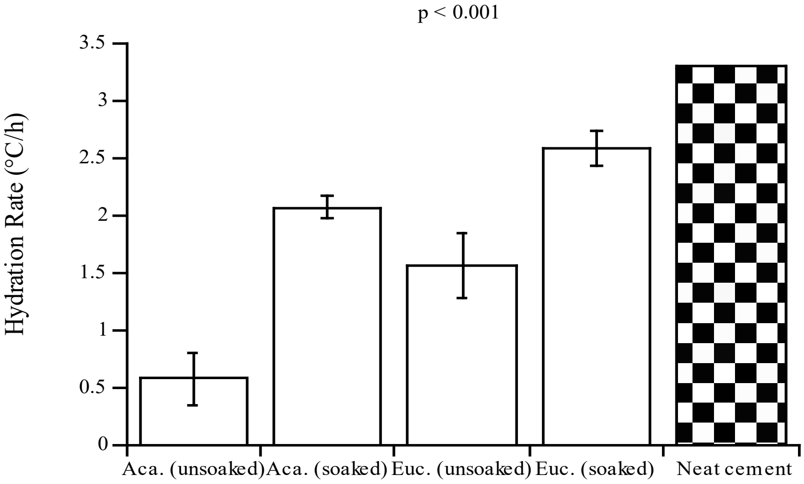

Figure 3. Average compatibility (hydration rate) for samples from the genera *Acacia* and *Eucalyptus* before and after soaking. Error bars represent S.E.D of each mean

As a group, the unsoaked samples from acacias were significantly less compatible with cement than the eucalypts (Fig. 3). Average hydration rate was 0.58 °C/h compared with that of the eucalypts (1.57 °C/h), and as shown in Table 4 which ranks species by compatibility, all species could be classed as incompatible with cement except for *A. elata*, which was of moderate compatibility (average hydration rate = 1.72°C/h). The one acacia species (*A. decurrens*) tested in a comprehensive compatibility study by Sandermann and Kohler (1964) was also found to be highly incompatible with cement and unsuitable for wood-cement composites.

Table 4. Acacia species ranking by hydration rate for unsoaked and soaked samples across both sites.

Species	Av Rate (unsoaked)*	*Species*	Av Rate (soaked)
A. elata	1.733	*A. elata*	2.509
A. mearnsii	1.396	*A. binervia*	2.389
A. nano-dealbata	1.336	*A. implexa*	2.338
A. blayana	1.135	*A. mearnsii*	2.239
A. melanoxylon	1.04	*A. parvipinnula*	2.206
A. melanoxylon	0.926	*A. melanoxylon*	2.204
A. chrysotricha	0.88	*A. sysvestris*	2.187
A. fulva	0.846	*A. mearnsii*	2.184
A. parvipinnula	0.807	*A. melanoxylon*	2.178
A. dealbata	0.794	*A. deanii*	2.167
A. mearnsii	0.781	*A. blayana*	2.162
A. irrorata	0.748	*A. chrysotricha*	2.162
A. obliquinervia	0.739	*A. irrorata velutinella*	2.159
A. decurrens	0.659	*A. dealbata*	2.114
A. glaucocarpa	0.601	*A. cangaiensis*	2.108
A. dealbata	0.598	*A. melanoxylon*	2.101
A. trachyphloia	0.593	*A. parramatensis*	2.095
A. binervata	0.589	*A. binervata*	2.075
A. filicifolia	0.585	*A. dealbata*	2.072
A. deanii	0.488	*A. leucoclada*	2.071
A. melanoxylon	0.487	*A. decurrens*	2.059
A. binervia	0.461	*A. irrorata*	2.039
A. irrorata	0.444	*A. nano-dealbata*	2.028
A. implexa	0.421	*A. leucoclada argentifolia*	2.024
A. falciformis	0.418	*A. dealbata*	2.018
A. sysvestris	0.415	*A. trachyphloia*	2.018
A. dealbata	0.391	*A. fulva*	2.003
A. parramatensis	0.366	*A. mearnsii*	1.988
A. mearnsii	0.266	*A. glaucocarpa*	1.98
A. parramatensis	0.251	*A. filicifolia*	1.972
A. mearnsii	0.221	*A. mearnsii*	1.956
A. leucoclada argentifolia	0.191	*A. parramatensis*	1.944
A. cangaiensis	0.088	*A. obliquinervia*	1.92
A. leucoclada	0.081	*A. irrorata*	1.882
A.irrorata velutinella	0.057	*A. dangarensis*	1.839
A. dangarensis	0.055	*A. falciformis*	1.835

*S.E.D. = 0.363, #S.E.D. = 0.162

░	Compatible
▒	Moderately compatib
▓	Incompatible

A species of significant importance in temperate regions of Asia, *A. mearnsii*, which performed well in the growth trials exhibited high variation in compatibility among trees from different seed lots. Seed lot 18979 was of second highest compatibility (R = 1.4 °C/h) whilst 16621 was among the lowest (R = 0.22 °C/h). Other wood-cement compatibility studies have found *A. mearnsii* in general to be highly incompatible with cement (Hachmi and Moslemi 1989, Hachmi *et al.* 1990, Hachmi and Sesbou 1991). These studies found that despite its low compatibility, the wood of *A. mearnsii* was also low in hot water soluble extractives, suggesting the presence of compounds which are highly inhibitory of cement hydration even in small amounts.

A. mearnsii is the only reported example among the sampled acacias to be tested for the manufacture of cement-bonded composite panels. In contrast to its poor rating in compatibility studies, composite panels with satisfactory strength properties were made using *A. mearnsii* flakes of various sizes and Portland cement apparently without the use of cement setting accelerators (Teixeira and Pereira 1987). *A. mearnsii* has also been reported to be suitable for the manufacture of WWCBs providing the wood wool was soaked in a 1 to 3% calcium chloride ($CaCl_2$) solution before mixing with cement (Flaws and Chittenden 1967).

After soaking in water at ambient temperature for 24 h, most of the acacias became compatible with cement. Apart from *A. elata*, certain seedlots of *A. mearnsii* (15329 and 18789) and *A. melanoxylon* (15863 and 18980) were also ranked highly in compatibility after soaking. In contrast, *A. mearnsii* seedlots 17928 and 16621 achieved only moderate compatibility after soaking. *A. dangarenis* retained its relatively low compatibility even after soaking, suggesting that this species may contain higher levels of inhibitory extractives which are not readily soluble in cold water.

In comparison to the acacias, the unsoaked wood samples from eucalypt species were highly variable in compatibility with 14 out of the 39 species being classed as compatible with cement (Table 5), 13 species were moderately compatible and 12 classed as incompatible. The better known commercial species *E. regnans*, *E. obliqua*, *E. seiberi* and *E. grandis* all attained a high compatibility ranking whereas others such as *E. bicostata*, *E. saligna* and *E. viminalis* were of moderate compatibility. The species better known for their success in planting overseas, *E. tereticornis* and *E. camaldulensis* were ranked as incompatible with cement. In contrast to our findings, previous compatibility studies have suggested the wood flour of *E. camaldulensis* to be compatible with Portland cement, with a C_A-factor of 69% (Hachmi and Moslemi (1989; 1990). Its equivalent C_A-factor in this study was 33%. Wood flour from *E. camaldulensis* was also rated among the most suitable of 36 different hardwoods tested for their compatibility with cement (Shukla *et al.* 1984; Jain *et al.* 1989). Tree age and history of the wood samples used by these workers is unknown, but may have influenced their findings if only heartwood or very old samples were used.

Despite encouraging suggestions from compatibility tests, previous attempts to use wood from *E. camaldulensis* in cement-bonded panels have not been successful. Cement-bonded particleboards were made from five-year-old plantation-grown *E. camaldulensis* wood (Yasin and Qureshi 1990). Both cold water (48 hour soak) and hot water (1 hour soak) extracted wood was tested in boards containing a wood:cement ratio of 1:2. All wood flakes were pre-treated with a 3% calcium chloride solution for 5 minutes, then dried to between 10% and 15% MC before mixing with cement. Unsoaked wood produced poorly consolidated boards with low dimensional stability, despite the calcium chloride treatment. The cold water-extracted (CWE) wood flakes produced boards of somewhat better quality whist the hot water extracted (HWE) flakes produced the best boards. The swelling (% linear expansion) of boards containing the CWE flakes was 45% higher than that of boards containing the HWE flakes and their mean MOR was 90 Kg/cm^2 compared to 111 Kg/cm^2 for HWE boards. The CWE flake boards did not meet the standard requirements for dimensional stability and bending strength. These results accord much better with the findings here and suggest that fresh wood of *E. camaldulensis* (or at least certain provenances and families of the species) is unsuitable for wood-cement composites.

In previous compatibility studies, *E. grandis* has been rated as unsuitable for use in wood-cement composites based on the pulling force required to remove test sticks set in cement (Rahim and Ong 1983). *E. grandis* required the lowest pulling force (101 N) of all of the 16 species also rated as unsuitable. *E. grandis* was also found to be unsuitable for the commercial manufacture of wood wool-cement panels in a study by Hawkes and Robinson (1978). However, WWCBs of acceptable quality have been manufactured from *E. grandis* and also *E. tereticornis* grown in the Philippines but only if cold water extraction or $CaCl_2$ are used to pre-treat the wood (Eusebio *et al.* 2000).

Table 5. Eucalyptus species ranking by hydration rate for unsoaked samples averaged across sites.

Species	Rate (unsoaked)*	Species	Rate
E. piperita	2.573	*E. brookeriana*	1.572
E. oreades	2.382	*E. nortonii*	1.563
E. regnans	2.36	*E. muelleriana*	1.528
E. dendromorpha	2.348	*E. resinifera*	1.517
E. laevopinea	2.305	*E. cinerea*	1.505
E. fastigata	2.27	*E. nova-anglica*	1.505
E. obliqua	2.27	*E. dunnii*	1.494
E. seiberi	2.25	*E. chapmaniana*	1.414
E. deanii	2.153	*E. nitens*	1.396
E. grandis	2.101	*E. delegatensis*	1.373
E. quadrangulata	2.1	*E. dalrympleana*	1.299
E. elata	2.086	*E. aggregata*	1.241
E. botryoides	2.012	*E. angophoroides*	1.198
E. cypellocarpa	2.011	*E. acaciiformis*	1.071
E. bicostata	1.918	*E. tereticornis*	1.06
E. saligna	1.813	*E. longifolia*	1.045
E. polyanthemos	1.695	*E. melliodora*	0.987
E. sideroxylon	1.68	*E. gunnii*	0.909
E. glaucescens	1.669	*E. camaldulensis*	0.519
E. mannifera	1.653	*E. malacoxylon*	0.264
E. viminalis	1.597		

░ Compatible

▒ Moderately compatible

▓ Incompatible

*S.E.D. = 0.442

Wood from the eucalypt species as a group was of higher compatibility with cement than that of the acacias. The eucalypts remained of higher average compatibility after soaking in water to remove inhibitory extractives, suggesting that inhibitory extractives present in the woods of many temperate acacias may not be as readily removed in cold water. *A. elata* was of highest compatibility among the acacias both before and after soaking. Among selected provenances of *A. mearnsii*, there was considerable variation in compatibility with cement, however in general temperate acacias could be considered as unsuitable on their own for wood-cement composites. However, our results and the few other studies dealing with temperate acacias indicate that for important species like *A. mearnsii*, problems of low compatibility with cement could be easily overcome by selecting the right seed-stock, pre-soaking and/or the use of inexpensive cement setting accelerators such as $CaCl_2$.

In contrast to the acacias, several eucalypt species were of high inherent compatibility with cement including *E. piperita*, *E. oreades* and *E. regnans*. These woods may be well suited to wood-cement composites without any further need for extractive removal given that there was no significant improvement in compatibility imparted by pre-soaking the wood. Our findings also suggest that information in the literature on the compatibility of eucalypts and acacias with cement is a poor guide to the suitability of the species for the manufacture of wood-cement composites.

The study showed that sapwood and to a lesser extent, bluestained sapwood were compatible with cement and produced strong, well consolidated panels. However, pure heartwood was incompatible with cement, causing severe retardation of wood-cement bonding in experimental panels. The occurrence of pockets of pure heartwood in commercial panels was therefore suggested to be the cause of friability. Using logs with minimal heartwood content (ie early thinnings from productive stands < 12 years old) would be the most practical way to avoid the problems caused by heartwood in commercial WWCB.

7.1.2 Methodology for rapidly assessing the suitability of wood species for their compatibility with cement

During the project, test methodology was developed that can rapidly assess the compatibility of different wood species with cement (Semple et al. 1999). The methodology involves reducing wood samples to slivers with a similar surface to volume ratio to wood-wool and then examining the effect of the wood on the exothermic hydration reaction of cement. Equipment was constructed that is capable of quantifying the reaction between cement and up to six wood samples. The apparatus uses thermocouples to record the heat of hydration generated when wood and cement/water are mixed. Wood-cement samples (a maximum of six can be tested at once) are placed in sealable plastic bags and mixed with water. The tip of a temperature thermocouple is taped to each bag and enclosed within the body of the wood-cement mix by folding and then securing the bag and its contents around the thermocouple. The bags are then placed in insulated flasks to minimise heat losses. An analog/digital card located in a PC converts the voltage output of the thermocouples to a digital form and the temperature (^{o}C) of wood-cement/water samples are recorded every 15 minutes. A computer program graphs the hydration reaction by progressively averaging and plotting every three temperature readings. Data is stored in a spreadsheet where it can be further manipulated. Temperature readings are taken over a period of 23 hours which is sufficient for the exothermic reaction to peak and allows an hour for a new set of samples to be prepared for measurement on the following day.

Currently in the Philippines, wood species are assessed for their suitability for the manufacture of WWCBs by manufacturing test boards and then comparing their properties with those of commercially manufactured boards. Such trials are costly and time consuming. If the technology that was developed at the ANU for assessing wood species for their compatibility with cement was transferred to the Philippines, scientists at FPRDI would then be free to undertake their own research into the compatibility of indigenous and plantation species with cement. Information would thus be obtained which would eliminate the need for costly manufacturing trials for species whose wood proved to be incompatible with cement. As part of the project extension, the process similar to that currently used at the ANU to assess the compatibility of different wood species with cement was built and installed at FPRDI in the Philippines. Training for FPRDI scientists was also carried.

7.1.3 Manufacture of WWCBs from *A. mangium*: The use of simple inorganic additives

An important aspect of the project was to develop ways of improving the suitability of *A. mangium* for the manufacture of WWCB. Work reported here examined whether the addition of simple inorganic cement setting accelerators to *A. mangium* wood-wool-cement mixtures significantly improved the mechanical strength properties of WWCBs manufactured from A. mangium. A second experiment tested whether the addition of small amounts of accelerators can significantly improve the strength and mechanical properties of WWCBs manufactured from pre-soaked *A. mangium* wood-wool. Finally the corrosivity of accelerators on different kinds of metal fastners was examined.

Issues such as cost and corrosivity of various accelerators need to be assessed before making recommendations as to the widespread use of the additives investigated in this project. There is also considerable scope for significantly reducing or eliminating the requirement for $SnCl_4$ and $FeCl_3$ by combining mildly effective, cheaper and less corrosive additives such as $MgCl_2$ and $Al_2(SO_4)_3$. Boards of acceptable quality can potentially be made using combinations of $SnCl_4$ (1 to 1.8%) and $MgCl_2$ (1%) or $Al_2(SO_4)_3$ (1.8%) and $MgCl_2$ (1%). The addition of commonly used accelerators, $CaCl_2$ or a $CaCl_2$-based commercially produced accelerator (Pozzolith 530) resulted in very weak board consolidation owing to its inability to effectively counteract the inhibitory effects of heartwood polyphenols. Although the use of soaked wood-wool resulted in boards of just above standard stiffness, the addition of small amounts of several additives increased board strength by up to 75%, and increased resistance to moisture to within standard specifications. These included $CaCl_2$ 'Pozzolith 530', $FeCl_3$ and $AlCl_3$.

Determination of board mechanical properties

When manufacturing boards from unsoaked *A. mangium* wood-wool, many compounds resulted in moderate to good board consolidation and densification compared with controls, as shown in Figure 4. However, only two compounds, $FeCl_3$ and $SnCl_4$ were effective in producing boards exceeding PNS/CTP 07 (1990) for non-structural 12 mm WWCB of 6.75 MPa and JIS-A 5908 (1994) of 7 MPa in stiffness for 12 mm particleboard. Boards made using 0.1 M solutions of $FeCl_3$ and $SnCl_4$ averaged 10.9 and 10.8 MPa respectively (figure. 4). In the case of $SnCl_4$, slightly higher board stiffness (11.6 MPa) could be achieved if solution concentration was halved to 0.05 M, equivalent to 1.8% of cement weight. In the case of $FeCl_3$, board strength was diminished significantly to 4.7 MPa when 0.05 M solution strength was used.

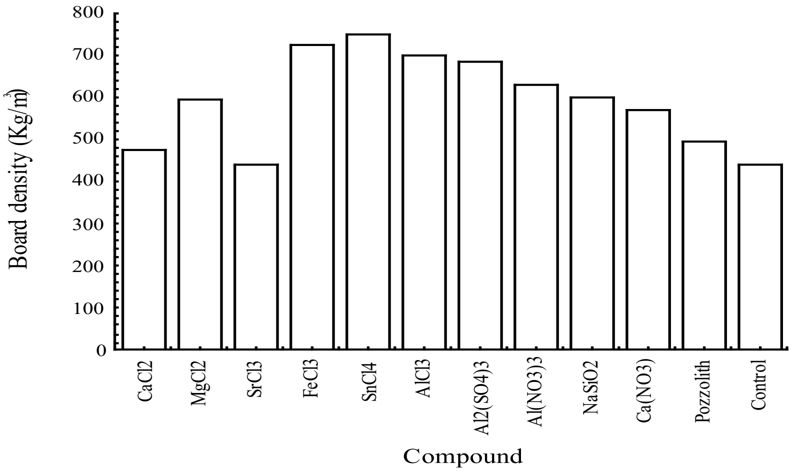

Figure 4. Average basic density of boards manufactured from unsoaked *A. mangium* wood-wool using different accelerators at 0.1 M solution strength.

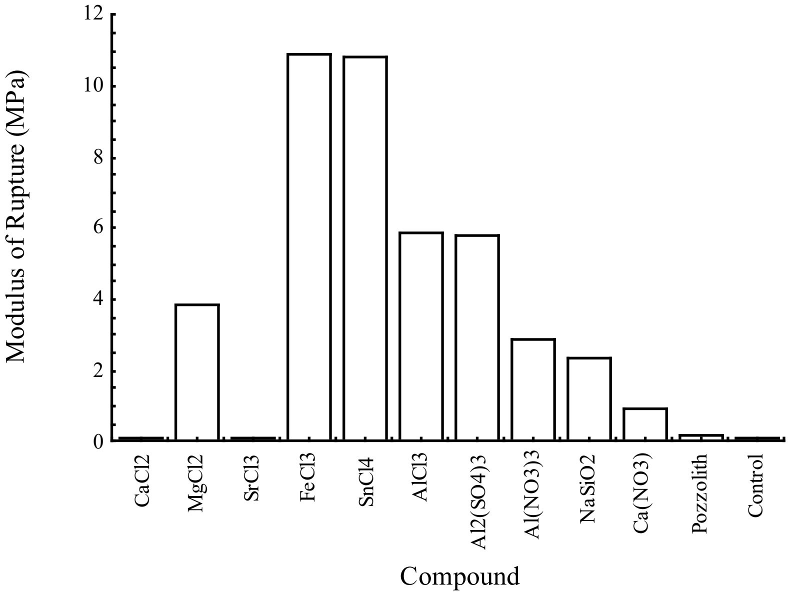

Figure 5. Average MOR of boards manufactured from unsoaked *A. mangium* wood-wool using different accelerators at 0.1 M solution strength.

All other compounds added at 0.1 M strength failed to produce boards of acceptable stiffness. However, the addition of $Al_2(SO_4)_3$ and $AlCl_3$ resulted in boards of 5.8 MPa, whilst $MgCl_2$ achieved 3.8 MPa, suggesting that a relatively small increase in their solution strength or their combination with another compound may bring board Modulus of Rupture (MOR) up to standard. This was found to be the case with $Al_2(SO_4)_3$, which when added in combination with $MgCl_2$ at the same strength, increased MOR to 8.5 MPa. Like $MgCl_2$, sodium silicate is also a mildly effective and less corrosive additive, but is not readily combined with transition metal chlorides because of the immediate formation of precipitate. Strong reactivity was also a problem when combining accelerators with the corrosion inhibitor $Ca(NO_2)_2$ which was ineffective on its own as an accelerator.

In contrast, boards containing $CaCl_2$ and 'Pozzolith' (a $CaCl_2$-based mix containing polymers for added strength) failed to consolidate, even when the solution concentration was doubled to 0.2 M. Previous research by Tachi *et al.* (1989) and Subiyanto and Firmanti (1998) have also found $CaCl_2$ to be ineffective at counteracting the inhibitory effects of heartwood extractives (namely Teracacidin) during the manufacture of wood-cement composites from untreated *A. mangium* wood.

Wood of *A. mangium* has widely been considered as unsuitable for wood-cement composites without some form of pre-treatment (Rahim and Ong 1983, Tachi *et al.* 1988; 1989). Soaking in water at ambient temperature is effective at boosting compatibility and it is necessary to soak A. *mangium* wood-wool in water for at least 6 hours to facilitate the manufacture of WWCBs of acceptable quality (Soriano *et al.* 1997, Cabangon *et al.* 1998, Eusebio *et al.* 2000). Some researchers suggest 24 hours soaking is necessary e.g. Sulastiningsih *et al.* (1990). In our study, the use of wood-wool that had been pre-soaked for 24 hours resulted in boards which reached 7 MPa MOR regardless of whether accelerators were used, however several accelerators significantly improved board strength as shown in Figure 6.

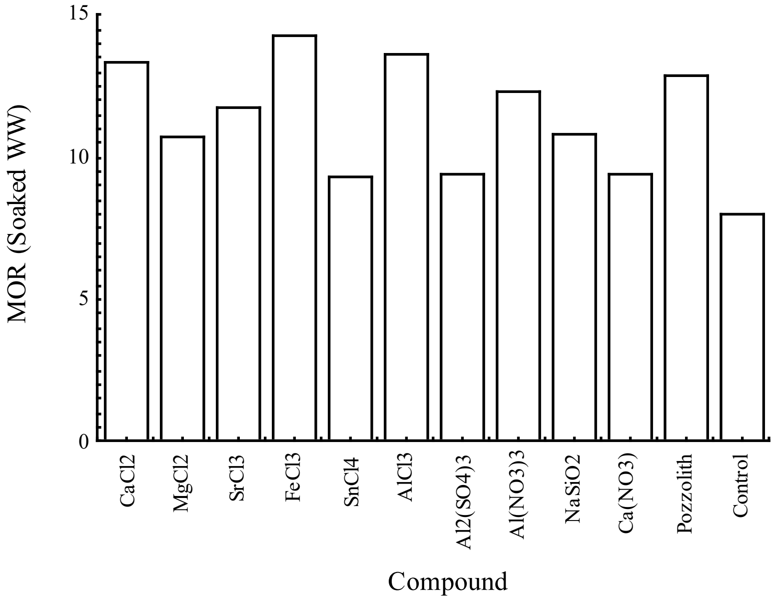

Figure 6. Average MOR of boards manufactured from soaked *A. mangium* wood-wool using different accelerators at 0.05 M solution strength.

All boards made using soaked wood-wool and accelerator at 0.5 M strength achieved a basic density above 750 kg/m^3, above the minimum target density of 600 kg/m^3 for WWCBs of 12 mm thickness specified in PNS/CTP 07 (1990). Some of the accelerator compounds including $FeCl_3$, $AlCl_3$, $CaCl_2$ and the $CaCl_2$-based commercial accelerator 'Pozzolith' increased board MOR by up to 75% compared to if no accelerator is used. Provided the wood is free from inhibitory heartwood tannins, simple inexpensive accelerators based on $CaCl_2$ can be among the most effective at improving board strength. Most additive types used at 0.1 M strength resulted in moderate to good dimensional stability of boards manufactured using unsoaked wood-wool, however only $SnCl_4$ and $FeCl_3$ resulted in sufficient board consolidation and densification to reduce thickness swelling to 5% or below, as specified in JIS-A 5908. These boards also absorbed the least water during immersion, less than 35%. Because boards containing $CaCl_2$, $SrCl_3$, pozzolith or no additive failed to consolidate during pressing, no data on dimensional stability are available for them. However moderately consolidated boards such as those containing $Al(NO_3)_3$ and $Ca(NO_3)_3$ swelled by over 10% and absorbed over 50% of their weight in water. Further details on the effects of board densification on strength properties, resistance to water and dimensional stability can be found in section 7.1.4.

The results indicate that there are only a few additives that will enable the manufacture of WWCBs from unsoaked wood-wool of *A. mangium*. These include $SnCl_4$ and $FeCl_3$ which are effective if used at approximately 2% of cement weight. Additives based on $CaCl_2$, a common, inexpensive cement set accelerator were ineffective for the manufacture of WWCBs from unsoaked wood-wool. $MgCl_2$, whilst only mildly effective on its own, has the potential to form a powerful combination with other additive types and amounts which are also ineffective on their own such as 1% $SnCl_4$ or 2% $Al_2(SO_4)_3$.

Several of the inorganic salts tested significantly improved the mechanical properties of WWCBs made from soaked wood-wool. These were mainly the chloride-based accelerators, $SnCl_4$ (in very small quantities), $CaCl_2$, $FeCl_3$ and $AlCl_3$. The ability of salts (individually or in combinations) to consolidate the cement matrix was critical to achieve good board densification (greater than about 640 kg/m^3) which in turn imparted higher strength and resistance to water. Good strength and resistance to water are important properties of building materials in tropical climates and the judicial application of small quantities of cement setting accelerators by manufacturers can significantly improve the quality and durability of WWCBs made from the wood of tropical acacias.

7.1.4 Dimensional stability of WWCBs made from *A. mangium* and the effect of board densification on board properties.

Figures 7 and 8 illustrate the effect of adding different accelerators on the thickness swelling and dimensional stability of WWBs made from unsoaked *A. mangium* wood-wool. Most additive types used at 0.1 M strength resulted in moderate to good dimensional stability of boards, however only $SnCl_4$ and $FeCl_3$ addition resulted in sufficient board consolidation as to reduce thickness swelling to 5% or below. These boards also absorbed the least water during immersion, less than 35% (Fig. 4). Because boards containing $CaCl_2$, $SrCl_2$, pozzolith or no additive failed to consolidate during pressing, no data on dimensional stability are available for them. However moderately consolidated boards such as those containing $Al(NO_3)_3$ and $Ca(NO_3)_3$ swelled by over 10% and absorbed over 50% of their weight in water.

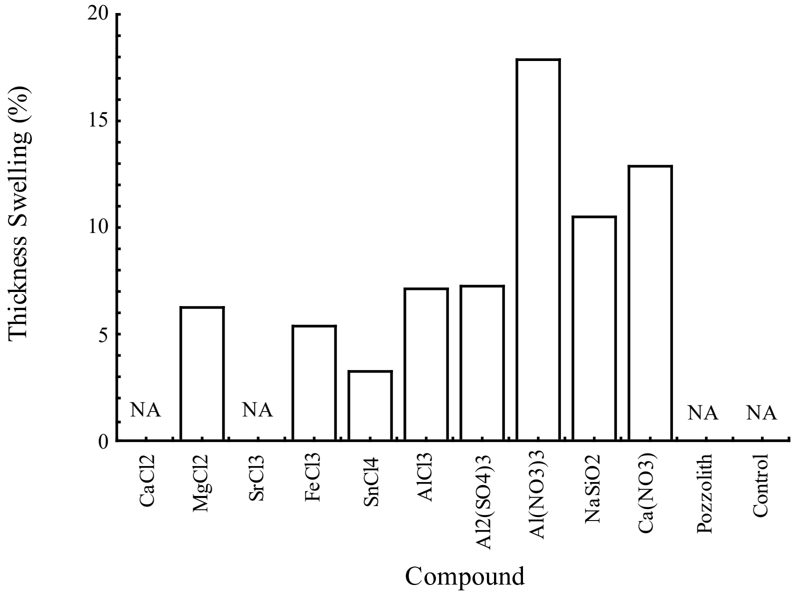

Figure 7. Average thickness swelling of boards manufactured from unsoaked *A. mangium* wood-wool using different accelerators at 0.1 M solution strength.

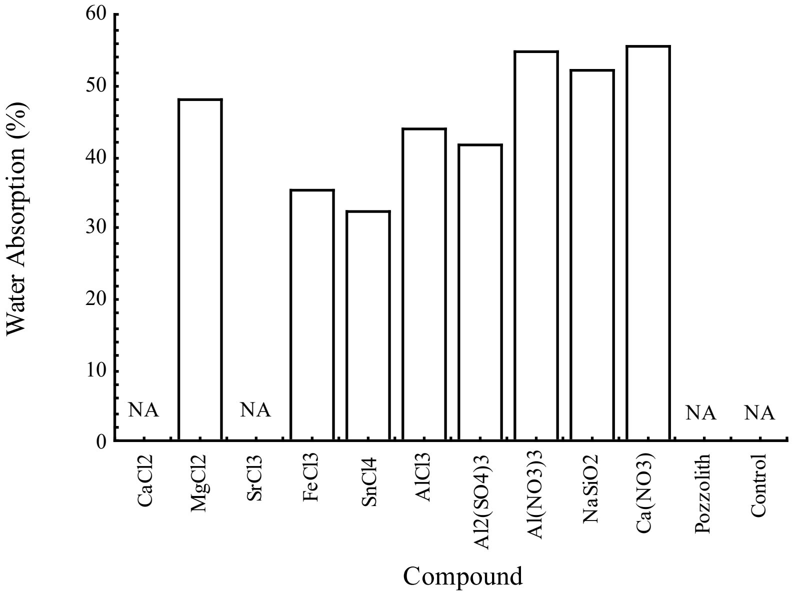

Figure 8. Average water absorption of boards manufactured from unsoaked *A. mangium* wood-wool using different accelerators at 0.1 M solution strength.

When soaked wood-wool was used, the dimensional stability of boards was greatly improved, with the addition of all accelerator types at 0.05 M strength reducing thickness swelling to below 5% and water absorption to below 35%, lower than control boards. Other studies have also found that cement hardening accelerators can significantly increase dimensional stability of wood-cement composites by virtue of their ability to improve wood-cement bonding and board consolidation, however there are considerable variations and contradictions reported as the efficacy of compounds. Accelerators such as $MgCl_2$, $CaCl_2$, $FeCl_3$ and $Al_2(SO_4)_3$ have been found to significantly improve consolidation and water resistance of wood-cement composites using 'difficult' woods such as *A. mangium* and bamboo which have been pre-soaked (Sudin and Ibrahim 1990, Soriano *et al.* 1997, Sulastiningsih *et al.* 2000, Cabangon *et al.* 1998, Eusebio *et al.* 2000), however reports on the effect of $Al_2(SO_4)_3$ are contradictory. Studies by Sudin and Ibrahim 1990 on CBP and Soriano *et al.* 1997 on WWCB containing soaked *A. mangium* wood have found $Al_2(SO_4)_3$ to be most effective at increasing dimensional stability of finished boards, whereas Cabangon *et al.* 1998 and Eusebio *et al.* 2000 found $Al_2(SO_4)_3$ to be ineffective at reducing TS and WA in WWCBs made from soaked *A. mangium* in their studies. In the present study, $Al_2(SO_4)_3$ resulted in a moderate decrease in TS and WA compared with other compounds such as $FeCl_3$ and $SnCl_4$.

The importance of board densification for strength and dimensional stability

The ability of boards to consolidate well and attain medium to high basic density was important factor in determining their stiffness and other mechanical properties. Figure 9 indicates that only boards above about 615 kg/m3 could potentially achieve above the standard 7 MPa in stiffness, although several samples above this density were also below standard. This was often due to physical imperfections and localised zones of weakness arising from inadequate distribution of material in the mat during manufacture. The main factor contributing to low density of poorly consolidated boards was the loss of water from the board by drying after removal from the press after little or no cement hydration had taken place during the press cycle. Board volume was increased due to spring-back of poorly consolidated mats, further contributing to low density.

Strand alignment of the surface layers has been shown to significantly improve panel stiffness and reduce the propensity for creep deformation with time under its own weight. However, since this must be done by hand it slows down productivity and adds to product cost. Such products are therefore being designed to suit specific, higher performance applications such as flooring.

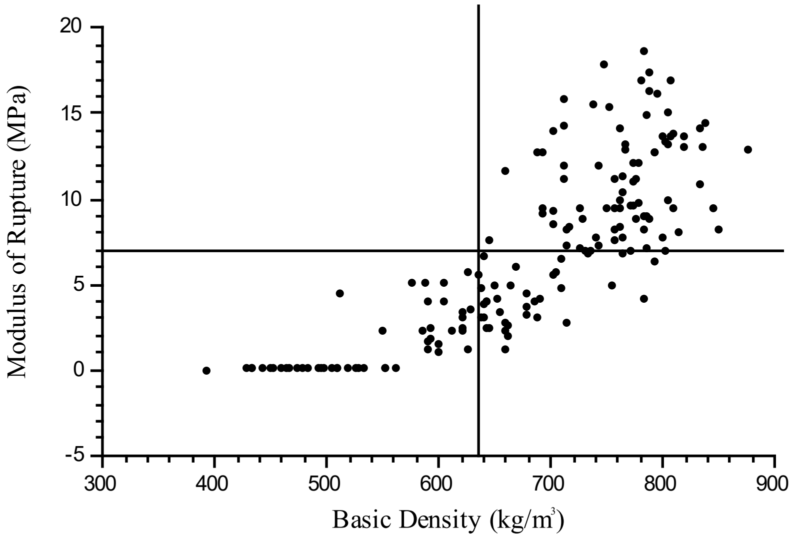

Figure 9 MOR of all dry test samples vs. their basic density.

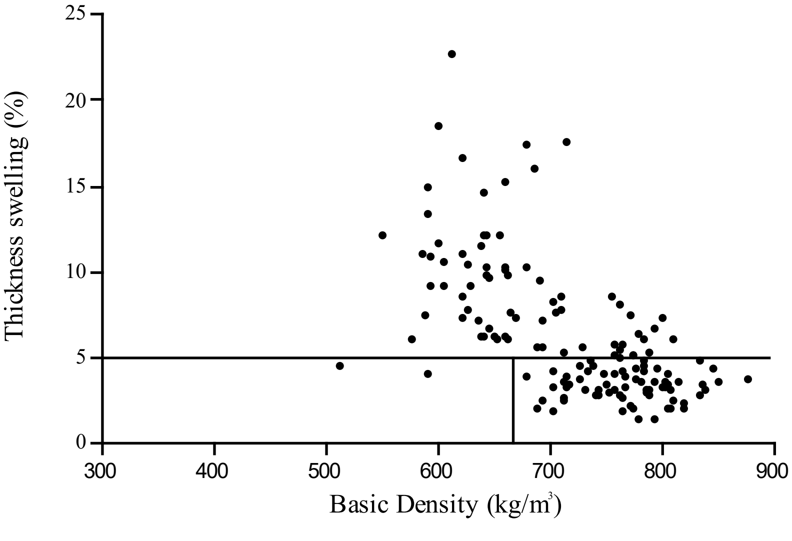

Figure 10 Thickness swelling of samples vs. their basic density.

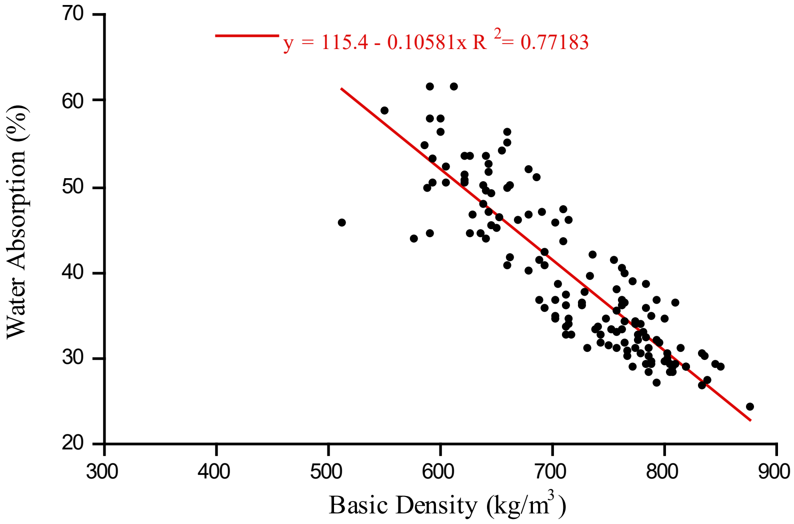

Figure 11 Water absorption capacity of samples vs. their basic density.

With regards to thickness swelling and water absorption of board samples after immersion for 24 h in water at ambient temperature, only strongly consolidated boards over about 670 kg/m3 achieved less than 5% swelling and 50% water absorption as indicated in Figures 10 and 11. Water absorption by boards was strongly correlated with board density as shown in Figure 11 although this relationship was not so strong among the lower density and poorly consolidated boards. This strong relationship suggests that the degree of consolidation of the cement matrix around the wood strands effectively reduces accessibility to water.

7.2 Sub-project 2

7.2.1 Post harvest storage

This research has shown that post-harvest storage of logs may also be used to improve the suitability of *A. mangium* for the manufacture of WWCBs. This beneficial effect of storage appears to be due to decreases in cold water-soluble substances in *A. mangium* wood during storage. However, soaking wood-wool in water before the manufacture of WWCBs is a more effective method of improving the suitability of *A. mangium* wood for the manufacture of WWCBs. The use of $CaCl_2$ as a cement setting accelerator may also be used to improve the suitability of *A. mangium* wood for the manufacture of WWCBs. The use of such an additive is however not required if the wood has been subjected to prolonged storage before it is used for the manufacture of WWCBs. The beneficial effects of storage on the suitability of *A. mangium* for the manufacture of WWCBs may be accelerated by storing logs in the bark free condition. It is possible to substitute up to 20% of *A. mangium* wood with bark without adversely affecting the mechanical properties of WWCBs. Prolonged storage of wood in log form can result in the decay, and A. mangium in its natural state is susceptible to heartrot caused by white rot fungi. Results here showed that white rotted and non-decayed *A. magium* wood had similar effects on the hydration charactersistics of Portland cement. Therefore it can be concluded that the presence of small amounts of heartrot in *A. mangium* logs should not prevent them from being used for the manufacture of WWCB.

7.2.2 Effect of heartrot on the compatibility of *A. mangium* with cement

The results of the hydration test on the compatibility of OPC (Blue Circle Southern, 203MA01) with sapwood, sound heartwood and white-rotted *A. mangium* heartwood are shown in Table 6.

Table 6. Average cement compatibility indices for sapwood, sound heartwood and white-rotted heartwood of *A. mangium*.

Wood type	T_{max} (ºC)	Time (h)	H-rate (ºC/h)	C_A-Factor (%)
Sapwood	45.32	11.75	1.66	85.80
Heartwood	40.95	13.50	1.08	78.76
White-rotted	40.42	12.50	1.08	74.83
Neat OPC	53.40	10.00	2.77	100.00

As expected, sapwood was more compatible with OPC (Blue Circle Southern, 203MA01) than sound heartwood. More surprising was the similarity between the hydration characteristics of OPC (Blue Circle Southern, 203MA01) containing heartwood or decayed wood, compared with previous studies which indicated that decayed wood strongly inhibits cement hydration (Simatupang 1986; Schwarz 1989; Meier 1990: Weatherwax and Tarkow 1964; Weatherwax and Tarkow 1967). Decayed wood is weaker than sound wood and wood-wool from decayed wood, if included in significant amounts in WWCBs would reduce their mechanical properties. Our findings suggest however that the presence of heartrot in *A. mangium* logs which are converted into wood-wool should not interfere with curing of WWCBs and therefore it may be possible to tolerate small amounts of decayed wood in *A. mangium* logs used for the manufacture of WWCB.

7.3 Sub-project 3

7.3.1 Application of WWCBs in housing construction

It was found that unfinished WWCBs manufactured commercially in the Philippines were highly susceptible to the deleterious effects of the weather, but coating of boards with a cement-based plaster was an effective way of protecting them. Boards that contain a higher cement to wood ratio were also more resistant to weathering. Coating of boards with an elastomeric paint was ineffective in protecting boards from the weather. The simplest and most effective coatings to extend the service life of WWCB panels are fine concrete render or stucco, which significantly reduce moisture-induced thickness swell of WWCB. Elasto-polymers are also now commonly mixed with cement render to give the surface finish greater flexibility and resistance to moisture.

7.3.2 Manual mat formation as a practical means of improving the strength of WWCBs

A novel aspect of the manufacture of WWCBs in the Philippines is that the process of forming cement-coated wood-wool strands into mats is done by hand. Potentially this feature could allow much greater control over the mat forming process than can be achieved using machines and opens up the possibility of orientating strands in order to improve strength properties of WWCBs. As part of a PhD program, funded by a John

Allwright Fellowship, work has been undertaken by Mr Rico Cabangon to investigate whether manual orientation of wood-wool strands can improve the properties of WWCBs. His results have shown that by modifying the way that wood-wool strands are orientated in WWCB, specifically adopting a cross-ply orientation of strands (similar to plywood), it is possible to double the strength of WWCBs. This dramatic increase in the strength properties in WWCBs has the potential to extend their application into structural end uses and/or produce cost savings in terms of the material required to make boards of a certain strength. The research undertaken to date has occurred in the ANU using a small-scale laboratory facilities and temperate wood species (radiata pine and poplar). Further research is needed to determine the feasibility of manipulating the mat forming process on a larger scale using Filipino species and also to familiarise researchers in FPRDI with the technique. Therefore as part of the extension we propose to determine the feasibility of strand orientation in WWCBs on a semi-commercial basis, employing the pilot-scale WWCB facilities at FPRDI and utilising Philippine woods and bamboo. The result of this study will determine the feasibility of transfering this technology to commercial WWCB plants in the Philippines. If the pilot-scale study is successful FPRDI will ensure that the technology is transferred to industry.

8 Impacts

8.1 Scientific impacts – now and in 5 years

The impacts of this project have been primarily scientific. Some of the main scientific achievements include: understanding the effect of water-cement ratio and cement setting accelerators on the properties of woodwool cement boards made from *Acacia mangium;* procedures for the manufacture of wood-fiber cement boards from *A. mangium* and *E. Pellita;* determining the effect of wood/cement ration and accelerators on the properties of wood wool cement boards made from *Acacia mangium*; the suitability of tropical acacias and eucalypts for wood-wool cement composites; the use of cement hydration tests to predict the suitability of *Acacia mangium* and *Eucalyptus pellita* for the manufacture of WWCBs; categorisation of the effect of additives on the hydration of cement in the presence of wood extractives. These achievements will contribute to scientific outcomes, and increase the knowledge base beyond the scale of this project.

This project investigated the suitability of Australian acacias and eucalypts for wood-cement composites. Research has shown that the proportion of heartwood and sapwood in eucalypts may play an important role in their compatibility with cement. Figure 1 indicates a positive relationship between the amount of heartwood in the wood sample and its compatibility with Portland cement. In contrast to the eucalypts, there was no discernible effect of % heartwood on wood-cement compatibility among the acacias as indicated in Figure 2. This project has demonstrated that soaking wood in water at ambient temperature for 24 hours had a beneficial effect on compatibility of trees in both the Acacias and Eucalypts, removing any effects of % heartwood on compatibility. In addition this project has shown that the levels of significance of main factors site, genus, soaking and interactions between factors significantly affected compatibility of wood samples with Portland cement ($p < 0.001$) as did interactions between factors. Althought the research has shown the adverse effects of heartwood on the mechanical properties of wood-wool cement boards manufactured from radiata pine wood, WWCBs manufactured from *P. radiata* showed better mechanical properties than those manufactured from *A. mangium.*

The research has shown that to determine the strength of a wood wool composite it is not sufficient to just measure the exotherm peak for the hydration of cement in the presence of wood wool. This is particularly true when the exotherm test is carried out on fine particles of wood. ANU has developed a new method of sampling timbers that much more closely mirrors the results obtained from fibres subjected to commercial practice conditions. The whole concept of screening for compatibility by a relatively cheap and rapid thermochemical method has therefore been changed and a sounder method introduced. Ultimately the only real test of the compatibility of wood wool and cement is the manufacture and mechanical testing of the product. These results may cast doubt on some earlier reports that the heartwood is incompatible with Portland cement.

Observations on WWCBs that had been used as part of a construction project confirmed that the use of calcium chloride as an accelerating additive promoted the rapid corrosion of any metals with which the WWCB was in contact.

The effect of Rice Hull Ash as a substitute for cement in WWCBs was examined and a 20% substitution of this pozzolan was found to improve durability. This indicates that to some degree Rice hull ash could to be used as a substituted for Cement.

Technical papers and posters were presented on local and international conferences. Likewise, technical reports and papers were published in scientific journals. The list of papers presented and published is shown in Appendix II.

8.2 Capacity impacts – now and in 5 years

Research Management and Technical knowledge

The management of a project involving a large number of people (7.4 effective full time research workers, 17 personnel involved) and an expenditure of some $666,000 has been a valuable capacity building exercise for the Project Leaders in Australia and the Philippines.

This work has built the capacity of personnel within the Forest Products Research and Development Institute about the scientific processes for the manufacture of Wood Wool Cement Boards. It will undoubtedly make a major contribution to the improvement of this important building material for use in the Philippines.

The scientific knowledge gained by the FPRDI researchers in the conduct of the project will be shared with manufacturers of WWCBs. The Training programs undertaken by the FPRDI staff in the statistical design and analysis of multivariate experiments will have a lasting impact on their research undertakings at the Institute.

Training

As a result of the contacts established through this project Rico Cabagnon successfully applied for a John Allwright Fellowship to enable him to undertake a PhD training at the ANU, to work on the creep properties of wood cement composites. Dr. Phil Evans successfully applied for a grant to undertake research on “Inorganic-bonded wood composites manufactured from mallee eucalypt and melaleuca species” in cooperation with the Western Australian Department of Conservation and Land Management.

Undergraduate and higher degree students at both the ANU and the UNSW were involved in aspects of this project. The exposure of the students to problems of developing countries and the methods of creating technological solutions to these problems has the potential to promote technological cooperation between countries, Australia and the Philippines in particular.

The training programmes offered to FPRDI staff on the statistical design and analysis of mutivariate experiments will have a lasting impact on scientific rigour at FPRDI. This outcome has the potential to extend far beyond the immediate limits of this project.

A number of staff associated with this project have participated in international conferences concerned with wood cement composite materials. These conferences have been held in Melbourne, Kuala Lumpur, Llandudno and Bogor. The contacts established have the potential to increase the technological contributions which can be made with other countries.

8.3 Community impacts – now and in 5 years

Ultimately this project is most relevant to the rural and urban poor in the Philippines who require low cost, ‘socialised housing’. Development economics literature advances the provision of basic needs and rural industrialisation through appropriate technology as two important development strategies for developing countries (Meier 1984). This project relates to the heart of the development of rural and urban poor, and alleviation of poverty through the ’basic needs’ approach, of which housing is fundamental. This project provides a valuable small-scale technology at the community level making use of a sustainable input, low quality wood. The WWCB technology is suitable for the Philippines and other Asian economies, where capital is relatively scarce and labour abundant. Successful industrialisation depends crucially on the choice of appropriate technologies, i.e., technologies matching factor proportions (see Echaus 1955; Stewart 1972). Given its linkage with tree planting activity in rural areas, and its forward linkage with housing construction activities, the WWCB technology will have a much wider multiplier effect on income, employment and general well-being of the poor.

8.3.1 Economic impacts

This project clearly demonstrates that eucalyptus and acacias currently being grown in Asia can be used to manufacture wood-cement composites particularly WWCBs under particular circumstances. It was important to demonstrate this point, because such products are an obvious outlet for the low quality component of the wood that will be generated by current eucalyptus and acacia plantations. In economic terms there are a number of beneficiaries that can be delineated from this research. These include farmers and women's tree cooperatives growing trees to supply wood to WWCB plants, the plant owners and employees and the rural and urban poor seeking low cost housing. Economic justification for each of these stakeholders is given below.

Income and employment for farmers and tree cooperatives

The finding that the eucalypts and acacias grown in the Philippines and elsewhere in Asia are suitable for the manufacture of wood-cement composites provides a clear economic incentive for farmers to plant trees to produce wood for WWCB plants. This can best be illustrated by comparing the price of fuelwood with that paid for wood by WWCB plants. The most recent statistics on the price of forest products in the Philippines estimates the price of fuelwood to vary between \$ A 5/m^3 in Mindanao and \$A 9/m^3 in Visayas. In contrast, the price paid for wood by WWCB plants is \$40 per m^3 (Abbaro 1995). Thus the sale of Eucalypt and acacia wood to WWCB plants could provide a valuable source of enhanced income to farmers and tree cooperatives, and encourage further afforestation. WWCB plants would also provide an avenue for employment in rural areas and reduce the extent of migration from rural to urban areas. Typically 30-40 people are employed in a WWCB plant although up to 200 to 300 people may be employed in associated activities such as tree planting and harvesting of wood. There are few other wood processing industries that could provide an outlet for the local processing of lower quality eucalypt and acacia wood.

Impact on the manufacturing costs of a WWCB plant

The identification and selection of suitable eucalypt and acacia species and the identification of suitable processing conditions for these species has the potential to reduce the manufacturing cost for WWCB plants. During the manufacture of WWCBs, wood and cement are mixed on a weight basis and because eucalypts and acacias grow faster and yield greater biomass they may lead to reduced overall wood costs.

During the manufacture of WWCBs wood wool is soaked in water prior to incorporating it in cement. Soaking times vary from 4 hours for a suitable species to 12 hours for an unsuitable one and the water in the tanks is changed every 4 hours. By finding species, provenances or families of eucalypts and acacias which are more compatible with cement means that less soaking is required and reduces the cost of water. Shorter soaking times might also increase productivity by allowing plants to operate one rather than two shifts. Wood species that are highly compatible with cement often do not require the addition of a cement accelerator. This not only reduces manufacturing costs but also lessens the risk of calcium chloride initiated corrosion of any metallic component which comes into contact with the material.

The manufacturing cost per board (6.0 to 25.0 mm in thickness) and daily running costs of a WWCB plant in the Philippines are given in the following Table 7. All the figures were obtained from the production costs for a commercial plant (Zamboard Pty Ltd) except for water costs which were estimated to be approximately 10% of total production costs. Figures in brackets estimate the cost saving of processing a fast growing eucalypt or acacia species which is compatible with cement. Overall the figures indicate that as a result of processing such a species, plants could achieve a modest cost saving of approximately 10%.

Table 7. Manufacturing costs of WWCBs in the Philippines

WWCB Thickness			
Unit Costs (P)	**6.0**	**12.0**	**25.0**
Cement (p102/40 kg)	11.0	22.0	44.0
Wood (p800/m^3	9.5(1.5)	19.0 (3.0)	40.0 (7.0)
Accelerator (p2800/drum)	1.0 (2.0)	4.0 (4.0)	8.0 (8.0)
Water	5.5 (4.0)	10.0 (8.0)	20.0 (12.0)
Electricity (p2472.5/mo)	5.5	10.0	17.25
Gasoline (9.71L)	0.25	0.5	1.0
Oil (p40.0L)	0.5	0.75	1.5
Grease (p38 kg)	0.2	0.25	0.5
Labourers (22 people)	10.5	18.0	32.0
Admin (& people)	6.5	11.0	20.0
Depreciation	2.25	4.25	8.0
Maintenance	4.5	8.25	16.0
Total	58.2	108	208.25
Plant Capacity B/day	221	128	72
Grand Total	12 862.2	13 824	14 994

Cost Comparison between WWCBs and other building materials

WWCBs are significantly cheaper than other wood based panel products. For example, the average retail prices at the time of this project (years 1997-2001) for plywood and plyboard (19mm thick and a standard 4 x 8 ft panel) in the Philippines were approximately P 1000 ($A 40) and ($A 32.5) respectively (Anon 1994). In contrast, WWCBs of similar thickness measuring 2 x 8 ft retailed for P200 ($A 8). Even accounting for the difference in size of the panels it is clear that WWCBs are significantly cheaper. Evidence gathered during the development of this project suggested that WWCBs are being widely used in the construction of low cost housing in Mindanao in the Philippines. The use of WWCBs facilitates modular construction techniques thereby allowing faster construction times and reducing labour costs. For a typical house with a floor area of 36m^3 there is a cost saving of 20% if build with WWCBs compared to house built using hollow cement blocks (Abbaro 1995). The property advantages that wood-cement composites have over other board products, notably their fire and termite resistance, and the price differential suggest that there will be an increasing demand for them in the future.

8.3.2 Social impacts

Housing

The annual production of WWCBs at the time of this project (years 1997-2001) was about 1.98 million boards. This represents about 2.5% of the new houses that are required in the Philippines each year. An increase in the potential of this new material for the housing construction market will contribute to one of the most pressing social needs in the Philippines. Houses built using WWCBs have demonstrated a very considerable range in performance (durability of cut edges exposed to an intermittently wet environment, corrosion of fasteners, sagging of ceiling panels etc.) depending on the standard of workmanship employed in their construction. Already a local entrepreneur has established a marketing organisation for WWCBs. The improved performance of WWCBs (including most importantly, durability) will have a major impact on the ability of a new material to provide additional resources in an area where it is needed.

Dr. Florence Soriano's team at the FPRDI is developing a prefabricated WWCB housing unit that in pre-construction is sufficiently small to enable a number of the units to be easily transported in a lorry or a helicopter. These units are capable of being assembled in two or three hours with perhaps six unskilled labourers and can provide housing for a family. These have an obvious potential for disaster relief in emergency situations such as post hurricane or post earthquake. This development has reached a prototype model stage but requires additional funding before a pre production stage can be reached.

8.3.3 Environmental impacts

Reforestation

There is an urgent need in the Philippines and in many countries for reforestation in order to maintain or improve air, water and soil quality. It is widely recognized that reforestation on the scale that is required must involve the extensive participation of local communities in tree planting schemes. In countries such as Australia government funds have been used to catalyze community involvement in various tree planting schemes such as Greening Australia. In poorer developing countries this option is not available and therefore the incentives for tree planting must be related to the ability of the plantations to generate income either directly through the sale of wood or tree products or indirectly by improving the productivity of adjacent farming systems. In the case of the former it is well established that the sale of fuelwood does not provide sufficient incentive for farmers to plant trees (Turnbull 1991), and few forest products industries are small enough to be integrated at the local level with rural communities. The WWCB industry is the exception to this. By paying prices at least four time greater than for pulpwood the sale of wood from agro-forestry schemes to the industry can provide sufficient financial incentive for farmers to plant trees and improve their environment.

Competition with other building materials

WWCBs compete with a number of building materials that are not produced on a sustainable basis, for example, hollow cement blocks for exterior walls and corrugated iron for roofs. While WWCBs are composed of 50% cement the presence of the wood wool means that cement can be used more economically, sustaining the supplies for longer. WWCBs are resistant to decay, termites and fire and unlike most other wood products do not require preservation with toxic organic or metal based preservatives.

Wood and Water

The WWCB industry in the Philippines uses smaller sized plantation grown wood. The impact of the industry on the availability of fuelwood for local communities is not known, but is expected to be small as WWCB plants use wood with a diameter greater than 10 centimeters, which is larger than the preferred diameter for fuelwood.

The main raw materials used in the manufacture of WWCBs are cement, wood and water. The use of these raw materials involves certain environmental costs. The results of this project will reduce the water consumption of WWCB plants because compatible species identified in this project require less soaking time and improved manufacturing reduces water consumption. This will further reduce impact on the environment.

During the manufacture of WWCBs in the Philippines large volumes of water are consumed during the soaking of wood wool. During the development of this project Dr. P.

Evans visited three plants in the Philippines that were manufacturing WWCBs. There was no attempt at any of the plants to recycle the wastewater from the soaking tanks. While the effluent from such tanks is unlikely to be highly toxic, as it simply contains dissolved wood sugars and extractives, its environmental effect, in particular the supply of nutrients to streams and rivers, are unknown. The development of methods of recycling the wastewater from WWCB plants would be highly desirable but lies outside the scope of this project.

8.4 Communication and dissemination activities

The results from this project require were disseminated in a way that ensure they reach the broadest audience possible. This was be achieved by publishing the results in the international wood science and forest products journals. The CBBMAP will also disseminate reprints to its members in the Philippines while the ANU will use its alumni to ensure that reprints are received by the major forest products laboratories in Asia. Information generated by the ANU, CSIRO and FPRDI during the course of the project were disseminated to manufacturers of WWCBs in the Philippines by CBBMAP. The head of CBBMAP, General Jose B. Commendador, will ensure that results from this project are given favourable publicity at the highest levels of Government.

9 Conclusions and recommendations

9.1 Conclusions

This project contributed significantly to the depth of scientific knowledge and practical experience required to foster the development of a viable WWCB manufacturing industry in the Philippines. In contrast to the acacias, several eucalypt species were of high inherent compatibility with cement including *E. piperita*, *E. oreades* and *E. regnans*. These woods may be well suited to wood-cement composites without any further need for extractive removal given that there was no significant improvement in compatibility imparted by pre-soaking the wood. Our findings also suggest that information in the literature on the compatibility of eucalypts and acacias with cement is a poor guide to the suitability of the species for the manufacture of wood-cement composites.

The results from this project show that the compatibility of some important plantation species of acacias and eucalypts grown in the Philippines are suitable for wood-cement boards, overcoming a fundamental lack of information about utilisation options for plantation-grown wood.

Despite the increasing importance of cement-bonded wood panels as building materials in certain tropical countries, there has long been a dearth of information about the potential of Australian acacia and eucalypt species, several of which are widely planted in these countries. This project has obtained for the first time information on the compatibility of wood from a wide range of Australian acacias and eucalypts in a form actually used in wood-cement composite panels. The information was also compiled in a manner that allows for direct comparison between species by drawing upon material grown in well designed species field trials. The results therefore provide a realistic assessment of the species of acacias and eucalypts that are suitable for wood-cement composites. A greater range of eucalypt species are potentially suited to wood-cement composites than are acacias.

The study showed that sapwood and to a lesser extent, bluestained sapwood were compatible with cement and produced strong, well consolidated panels. However, pure heartwood was incompatible with cement, causing severe retardation of wood-cement bonding in experimental panels. The occurrence of pockets of pure heartwood in commercial panels was therefore suggested to be the cause of friability

Product development research from the project (carried out mostly at FPRDI in the Philippines) resulted in a selection of medium-weight WWCBs ranging from 450 to 900 kg/m3 in density and 8 to 50 mm in thickness. These are suitable for a range of non-load-bearing applications, including walls, roofing and flooring in housing and emergency-shelter construction. They are best manufactured in a ratio of 60% cement to 40% wood by weight, from strands measuring 3 to 5 mm in width, 0.3 mm in thickness and anywhere from 300 to 500 mm in length.

The research on the optimisation of the basic board manufacturing process, including correct wood/cement ratios, billet pre-storage to reduce soaking time, and mat quality, has been successfully transferred to WWCB plants, often in combination with simple mat internal reinforcement using stiffer materials. Project research also benchmarked the quality of commercially produced WWCB products in the Philippines and evaluated the performance of surface coatings for exterior panelling. Wide variation was found in product physical properties, particularly strength and stiffness, thereby providing focus areas for product improvement through subsequent research.

Boards from different suppliers in the Philippines were tested for strength, stiffness and toughness before and after exposure to an outdoor environment. Variability within boards supplied by a given manufacturer often exceeded the variability between manufacturers, this indicates the need for standards for this material.

Exposure trials in Australia and in the Philippines have shown that uncoated WWCBs are susceptible to short term environmental degradation. Whilst the work in this research has been concerned with the selection of timbers and the delineation of appropriate manufacturing processes for WWCBs it is suggested that further work on WWCBs should be strongly based upon composite materials technology. Very simple calculations suggest that strength improvements in excess of 30% could be obtained by changes in cement:wood ratios or decreases in the void content.

Subsequent ACIAR-funded project activity resulted in the development of product performance standards for WWCB along with building codes for one- and two-storey structures containing WWCB wall, floor and roofing systems. These are in the process of being formalised through the Philippines Bureau of Product Standards (Department of Trade and Industry).

This project laid the foundation knowledge necessary for the development and growth of the WWCB industry in the Philippines to help meet the need for low-cost, locally produced building materials. It has demonstrated that low-density plantation-grown wood, which is unsuitable for applications requiring the use of solid sawn wood, can be used to manufacture WWCBs at relatively low cost and with natural durability in tropical conditions.

The Philippines is the first country to adapt a material, hitherto manufactured and used only as light-weight, non-structural sound-insulating panels for interior use, to a wide range of structural and non-structural applications in housing and commercial buildings. This project effectively builds on this foundation to expand the range of tree species known to be suitable for cement-composite manufacture, to improve product quality and develop new products.

9.2 Recommendations

The project has inexpensively achieved some good results. However, there needs to be more emphasis on transfer of technology to ensure long term impacts from the research. Houses built using WWCBs have demonstrated a very considerable range in performance (durability of cut edges exposed to an intermittently wet environment, corrosion of fasteners, sagging of ceiling panels etc.) depending on the standard of workmanship employed in their construction. Concurrently with the introduction of a more standardised quality product, a major education program is needed at the elementary trade level to expose the advantages of WWCBs and the particular precautions that have to be taken in their use. The provision of simple information on the manufacture of WWCBs might encourage the entry of more entrepreneurs into the manufacturing field. Thus, it will be necessary that appropriate standards are introduced as soon as possible. In addition, it is recommended that an early standard be established to prevent the use of uncoated WWCB in out of doors applications.

The following recommendations are made according to each sub-project.

Sub-project 1

The second objective of this sub-project was the determination of the hydration index for cement in the presence of wood extractives by comparing cement inhibition indices obtained using chemical and physical criteria. This objective has yielded considerable success, however it is suggested that far more information on both the thermodynamics and the kinetics of inhibited hydration is probably obtainable from a more detailed study of the exotherm over periods in excess of 23 hours. It is further suggested that, although it is entirely appropriate that the initial work (particularly in a forestry department) should have concentrated on the timber aspects of the composite, a subsequent stage of this work should be concerned with the cement or composite aspects of the material. The determination of extractives content and other factors (i.e. fiber length) that influence boards properties should be taken into consideration so that there will be a scientific basis on why different wood species have different compatibility with cement and exhibits different board properties. This work might focus on a study of the kinetics of hydration of the cement and the effect of different cements. This could have major impact on the practices employed in the manufacturing plants.

Sub-project 2

In this sub-project the mechanical properties of the WWCBs were determined from the 28 day strengths and stiffness of the fabricated boards. This is a standard that has long been adopted in the concrete industry and is certainly appropriate for the initial investigations in this field. However as the investigators are concerned with a retarded cure it is suggested that the relationship between the 28 day cure strength and the working strength may vary with the amount and type of the extractives. It is suggested that subsequent work might be carried out on other cure times.

Sub-project 3

Boards from different suppliers in the Philippines were tested for strength and stiffness before and after exposure to an outdoor environment and a great variation found in their properties. The fact that the variability within boards supplied by a given manufacturer may exceed the variability between manufacturers is indicative of the need for the preparation of standards for this material. The results of exposure trials in Australia and in the Philippines have shown that uncoated WWCBs are susceptible to short term environmental degradation. Some protection may be obtained by coating the boards but the results so far obtained are equivocal in determining whether mortar coatings or elastomeric paint coatings are superior in this respect. The thin 50:50 sand cement ratio plaster coatings used have proved to be very susceptible to carbonation and if plaster coatings are to be persisted with (cracking of the plaster may decrease the attractiveness of the material) it is suggested that further investigations should be carried out into the effect of an anti carbonation coating in combination with a plaster coating.

Work in this sub-project has concentrated on the selection of timbers for WWCBs and the delineation of the appropriate manufacturing processes for the different timbers. This work has been successful and it is suggested that a next stage of the work on WWCBs should be strongly based upon composite materials technology. A typical WWCB could be characterised by the following volume fractions.

Reinforcement	32 %
Matrix	26 %
Void	42 %

It has been noted elsewhere that the cement contributes only 8% of the cost of the Board and so comparatively small changes to the processing conditions could probably lead to a Board with volume fractions of

Reinforcement	40 %
Matrix	40 %
Void	20 %

A very superficial “law of mixtures” calculation suggests that such a Board would have strength which would be 30% greater than existing boards. Such an approach may increase the marketability of WWCBs in the construction market. It may be noted that both Cement Bonded Particle Board and Wood Fibre Cement Board have considerably higher cement:wood ratios than the WWCBs.

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