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# Wood–Cement Composites in the Asia–Pacific Region

**Proceedings of a workshop held at Rydges Hotel, Canberra, Australia, on 10 December 2000**

*Editor: P.D. Evans*

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# Contents

Foreword **5**

Acknowledgements **6**

**Summary:** An Introduction to Wood–Cement Composites
*Philip D. Evans* **7**

**Hydration Reactions of Cement and Wood–Cement Compatibility**

Manufacture of Cement-bonded Boards from Wood and Other Lignocellulosic Materials: Relationships between Cement Hydration and Mechnical Properties of Cement-bonded Boards

*Ling Fei Ma, Hidefumi Yamauchi, Orlando R. Pulido, Yasuo Tamura, Hikaru Sasaki and Shuichi Kawai* **13**

Effect of Aqueous Extraction of Wood-wool on the Properties of Wood-wool Cement Board Manufactured from Teak (*Tectona grandis*)
*Paribotro Sutigno* **24**

Screening Inorganic Additives for Ameliorating the Inhibition of Hydration of Portland Cement by the Heartwood of *Acacia mangium*
*Kate E. Semple and Philip D. Evans* **29**

Compatibility of Eight Temperate Australian *Eucalyptus* Species with Portland Cement
*Kate E. Semple, Ross B. Cunningham and Philip D. Evans* **40**

**Cement-bonded Composites from Wood and Agricultural Residues**

The Use and Processing of Rice Straw in the Manufacture of Cement-bonded Fibreboard
*Elvira C. Fernandez and Vanessa P. Taja-on* **49**

Fibre-cement Composites from Brazilian Agricultural and Industrial Waste Materials
*P.E.G. Warden, H. Savastano Jr and R.S.P. Coutts* **55**

Resistance of Wood– and Bamboo–Cement Boards to Subterranean Termite *Coptotermes gestroi* Wasmann (Isoptera: Rhinotermitidae)
*P. Sukartana, R. Rushelia and I.M. Sulastiningsih* **62**

The Effects of Bamboo:Cement Ratio and Magnesium Chloride ($MgCl_2$) Content on the Properties of Bamboo–Cement Boards
*I.M. Sulastiningsih, Nurwati, S. Murdjoko and S. Kawai* **66**

Comparative Resistance of Cement-bonded Rubberwood Particleboard, Rubberwood Medium Density Fibreboard, Rubberwood and Radiata Pine to Microfungi and Subterranean Termite Attack (poster paper)
*Andrew H.H. Wong and A.L. Chee* **72**

Cement-bonded Boards from Wastewater Treatment Sludge of a Recycled Paper Mill
*Elvira C. Fernandez, Clevan Reyve G. Lamason and Teodulfo S. Delgado* **73**

Modified Formaldehyde-based Resin Adhesives for Rice Hull–Wood Particleboard
*Chung-yun Hse and Elvin T. Choong* **81**

Rice Hulls, A Unique Building Material for the Manufacture of Extruded Biocomposites
*Peter Klatt and Simon B. Spiers* **87**

**Cement-bonded Composites from Eucalypts and Acacias**

Effect of Post-harvest Storage on the Suitability of *Acacia mangium* for the Manufacture of Wood-wool–Cement Boards
*Rico J. Cabangon, Dwight A. Eusebio, Florence P. Soriano, Ross B. Cunningham, Christine Donnelly and Philip D. Evans* **97**

Manufacture of Low-cost Wood–Cement Composites in the Philippines Using Plantation-grown Australian Species. I. Eucalypts
*Dwight A. Eusebio, Florence P. Soriano, Rico J. Cabangon and Philip D. Evans* **105**

Manufacture of Low-cost Wood–Cement Composites in the Philippines using Plantation-grown Australian Species. II. Acacias
*Dwight A. Eusebio, Florence P. Soriano, Rico J. Cabangon and Philip D. Evans* **115**

The Development of the Hybrid Poplar Processing Industry in P. R. China
*Hua Yukun and Zhou Xiaoyan* **123**

**Novel Cement-bonded Wood Composites and Applications**

Natural Fibre–cement Composites: An Australian Perspective
*Robert S.P. Coutts* **131**

Production and Properties of Oriented Cement-bonded Boards from Sugi (*Cryptomeria japonica* D. Don)
*Ling Fei Ma, Hidefumi Yamauchi, Orlando R. Pulido, Hikaru Sasaki and Shuichi Kawai* **140**

Manufacture of Wood Strand–Cement Composite for Structural Use
*Atsushi Miyatake, Tsuyoshi Fujii, Yasushi Hiramatsu, Hisashi Abe and Mario Tonosaki* **148**

Application of Wood-wool–Cement boards for Shop-fabricated Emergency Shelters in the Philippines
*Florence P. Soriano, T.R.E. Rondero, A.C. Manalo, C.R. Carino, T.C. Saralde Jr and E.A. Bonaagua* **153**

# Foreword

We are very pleased and gratified that so many regarded it as worth their while to travel very long distances to be at this important workshop on wood–cement composites — part of the 5th Pacific Rim Bio-based Composites Symposium that brought together many strands of related work after years of effort. The symposium had about 160 delegates from 16 countries, with 20 from developing countries of Asia: China, Philippines, Indonesia, Malaysia. Others came from industrialised countries of Europe, North America and the western Pacific rim. It is a measure of the importance of bio-based composites that this symposium was able to attract such a large number of delegates from such a wide range of countries.

Composites will become increasingly significant. Large volumes of small dimension wood are being used more and more as a consequence of changing forest management regimes, and there is growing use of wastes for producing solid products: wastes from wood processing, lignocellulosic wastes from agriculture, and wastes from other industrial processing.

The bonding of lignocellulose to cement raises all sorts of fascinating issues associated with the physics and chemistry of the system. Importantly, it opens up opportunities in materials science and engineering, enabling these physical and chemical relationships to be exploited through the manufacture of potentially cheap and efficient composite building products important for human welfare.

The significance of these products and their potential to contribute to the shelter needs of people in developing countries in cost-effective ways has not been lost on ACIAR, the Australian Centre for International Agricultural Research. Hence our investment in research on wood–cement building boards for housing, in a three-year collaborative effort between FPRDI (the Forest Products Research and Development Institute) Philippines, the Australian National University and CSIRO, initiated in 1997.

Why is ACIAR so interested and where do we fit in? ACIAR is a small agency of the Australian Government, funded from the overseas aid program. We have been given the job of facilitating international research in agriculture for development, by creating and financing partnerships between researchers in developing countries and Australia. These enable the researchers to work together and share expertise, resolving problems that constrain economic development, or improving the efficiency and sustainability of natural resource use. Our program defines agriculture very broadly; we cover crop and livestock husbandry, fisheries, forestry, land and water resources, policy and economics, and post-harvest technologies across all the productive sectors. Our support for the bio-composites work falls within our forestry program and has a post-harvest technology theme.

Our forestry R&D program has established a niche in Asia–Pacific regional forestry efforts by focusing on the domestication and the genetic and silvicultural improvement of Australian tree germplasm introduced to countries of the region where suitable conditions for plantation and agroforesty development occur. A continuing theme has been the use of multipurpose species in such genera as *Eucalyptus*, *Acacia* and *Casuarina* for reforestation of degraded and marginal lands. These trees have been successfully introduced into many countries, notably China, Indonesia, Vietnam, Philippines, Malaysia.

We are now at the stage where stand management, for such things as pests and diseases and water use, and the potential of the wood produced, are claiming much attention. The needs for utilisation, downstream processing to produce value-added products, and marketing of this now highly significant fibre resource will demand more emphasis in the ACIAR program in the future. We seek guidance from workshops such as this one to indicate the future directions we might take that will provide the greatest benefit to our

primary stakeholders, the poor and the marginalised of the developing countries of our region. Again, the work on bio-composites fits into this scheme of things because the outcome we seek from this research is the development and provision of good quality, cost-effective, engineered building materials, accessible to these needy groups and fulfulling their neeeds for shelter.

By using waste and small dimension materials in an energy-efficient manner wood–cement composites will also contribute to energy and resource conservation.

*Ian Bevege*
*Principal Adviser (ACIAR)*

# Acknowledgements

These Proceedings report on current research into wood–cement composites in the Asia–Pacific region. Some of this research has arisen as a result of the joint project between Australia and the Philippines on the 'Manufacture of low cost wood–cement composites in the Philippines using plantation grown Australian tree species'. We are indebted to a number of organisations and individuals who supported this project and associated activities. In particular, we thank the Australian Centre for International Agricultural Research (ACIAR) for funding, and the Australian National University, CSIRO Forestry and Forest Products, and the Forest Products Research and Development Institute in the Philippines for providing the staff, laboratory space and infrastructure and in-kind support to undertake the research. We are grateful to WoodTex Pty Ltd (Bendigo), Blue Circle Southern Cement Industries (Australia) and Provident Tree Farms (Philippines) for material support and advice. Finally, we would like to thank all the people who assisted with the project and, in particular, those who participated in the project workshop and helped to develop these Proceedings.

# Summary: An Introduction to Wood–Cement Composites

**Philip D. Evans**[1]

THERE is currently a renaissance in the manufacture of wood–cement composites around the world and in particular in the Asia–Pacific region. The successful substitution of asbestos fibres with wood fibres in cement sheeting, which arose as a result of pioneering research in Australia (see Coutts, these Proceedings), has led to the rapid expansion of the wood-fibre cement industry in Australasia and North America. Accompanying the expansion of the industry has been a diversification of the products produced by the industry, and wood-fibre cement composites are now used in a host of applications including sidings, shingles, soffits, flooring (as ceramic tile backboards), skirting, pipes and architectural columns.

The capital-intensive nature and technological sophistication of wood-fibre cement plants has acted as a brake to the development of the industry in less developed countries (LDCs), except where multinational corporations have chosen to expand their operations to such countries for reasons of market access or to benefit from lower manufacturing costs. However, such is not the case for wood-wool cement boards, the oldest and probably most well known of the family of wood–cement composites (see the details (below) of the main classes of wood–cement composites and the processes used to manufacture them). In contrast to wood-fibre cement composites and cement-bonded particleboard, wood-wool cement boards can be manufactured in small, low-cost plants, and their resistance to moisture and biodeterioration, particularly termite attack, makes them particularly suitable for building applications in tropical and sub-tropical zones. Accordingly, wood-wool cement board plants have become established in many LDCs. For example, currently in the Philippines there is a thriving wood-wool cement board industry that is using indigenous fast-growing tree species (or agricultural wastes) and locally developed plant (Fig. 1). The industry is producing a wide variety of panel products tailored to local markets (Fig. 2). Ironically, in some applications, these products are in direct competition with wood-fibre reinforced cement products. While the development of the wood-wool cement board industry in other LDCs does not match that in the Philippines, interest in the product and other wood–cement composites remains high and there are on-going research programs to support the industry in most of the larger countries in the Asia–Pacific region.

**Figure 1.** Small-scale wood-wool cement board plant in the Philippines showing the process of forming boards by hand

**Figure 2.** Attractive dwelling in Southern Philippines built using high density wood-wool cement boards

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## Manufacture of Wood–Cement Composites

There are three main types of wood–cement composites: (i) wood-wool cement board (WWCB); (ii) cement-bonded particleboard (CBP); and (iii) wood-fibre reinforced cement composites. The technology involved in the manufacture of each of these types of composites is described here briefly. More detailed descriptions are available in Moslemi and Hamel (1989).

WWCB was first developed in Europe in the 1920s (Moslemi and Hamel 1989) and it is currently manufactured in many countries around the world. WWCB is made from debarked softwood or hardwood logs that have been stored for varying periods of time to reduce the starch and sugar content of the wood. After storage, logs are cross-cut into billets and these are shredded on a cutting machine to produce wood-wool. Typical wood-wool strands used in the manufacture of WWCB are approximately 3 mm wide and 0.5 mm thick with lengths up to 40–50 cm coinciding with the lengths of the billets processed by the shredding machines. Coarser wood-wool is often used in the manufacture of very thick boards. When hardwood species with a high extractive content are used, the wood-wool may be soaked in cold water overnight to remove any soluble low molecular-weight sugars and heartwood extractives that might interfere with cement hydration reactions (Fig. 3). Wood-wool may also be treated with inorganic compounds such as calcium chloride, again to reduce the inhibitory effects of soluble wood components on the setting of cement. Wood-wool is air-dried and mixed with cement using a cement-to-wood ratio of 2-to-1 to 1-to-1 (w/w). The mixed material is conveyed to a mat former and a pre-determined weight of cement-coated wood strands is deposited on a forming board. In LDCs, mat-forming may be done by hand (Pablo 1989). The mats are then stacked and pressed in a hydraulic press at room temperature in batches of 8–12. The pressure used for pressing varies depending on the degree of densification required in the final board, but can be as low as 80 kPa for low-density insulation boards. The stack is clamped under pressure for 24 h to allow for initial cement cure to occur. Boards are then declamped and post-cured for 2–3 weeks before trimming and finishing (Fig. 4).

**Figure 3.** Soaking of wood-wool to remove water soluble extractives

**Figure 4.** Post-curing of wood-wool cement boards before trimming and finishing

Cement-bonded particleboards were developed in the 1960s and the technology used to produce them shows many similarities to that used to manufacture resin-bonded particleboard (Moslemi and Hamel 1989). There are differences, however, notably in the storage of wood before manufacture and in the forming and pressing of boards. Debarked logs, usually coniferous species, are stored for at least 2–3 months prior to processing to reduce their moisture and sugar content. Wood particles are then prepared in the same manner as for conventional particleboard. Logs are processed to produce chips approximately 10–30 mm in length and 0.2–0.3 mm in thickness, which are then further reduced in size using knife ring flakers or

hammer mills. The resulting flakes are screened into three classes; fines, standard and coarse flakes. Fines are used for the board surface and standard-size flakes are used for the core of boards. Coarse flakes are returned for further reduction in size. Wood flakes are mixed with Portland cement and water in the following ratio by weight — wood 20% : cement 60% : water 20%. The moisture content of the flakes is monitored continuously and the volume of water added to the mix is adjusted accordingly. Calcium chloride (2–3% w/w) may be added to the mix to accelerate the setting of the cement. After the mixing, cement-coated wood flakes are fed to a forming station where a continuous mat of uniform thickness is deposited on an endless series of caul plates running on a conveyor. The mat is cut into lengths corresponding to the size of the caul plate and a stack of mats is compressed to about a third of its original height over a period of 2–3 min at a pressure of approximately 2.4 N $mm^{-2}$. While the stack of cauls is still in the press, clamping arms are attached to it so that, on release from the press, the batch of mats is still held in a compressed state. These are transferred to a heated chamber at 70–80°C for 6–8 h to facilitate cement hardening. At the end of this period the clamps are released, the cauls are removed and the boards are air-dried, trimmed and then stacked for 12–18 days to allow the cement to cure. The boards are further dried and conditioned prior to shipment and can be sanded on one or both sides. Common board thicknesses are 12 and 18 mm, but boards as thin as 8 mm and as thick as 40 mm can be produced.

Wood-fibre reinforced cement composites are manufactured from wood-fibre (7–8.5%), sand (60%), cement (30%), and aluminium trihydrate (3–4%) (w/w). The wood-fibre, which is usually obtained from softwood chemical (kraft) pulp, acts as a reinforcing agent in the boards, a role previously played by asbestos fibres in an older generation of building materials. The manufacture of wood-fibre reinforced cement composites involves washing the sand and reducing it to a fine powder using a ball mill. Bales of kraft pulp are added to a vat containing water and agitated to redisperse the fibres. Fibres are then refined or beaten twice in conical refiners to increase their ability to interact with sand and cement (Coutts and Ridikas 1982). The cement, sand, fibres and additives are combined in the proportions outlined above and diluted to form a slurry with a solids content of 10%. The slurry is fed into a tub containing three screen cylinders which pick up the slurry mix and deposit it on a felt-like belt moving at 80 m $min^{-1}$. The belt is then turned so that the slurry is on top and while this is occurring the fibre-cement mat is trimmed at its edges by water jets and partially dewatered using vacuum suction boxes. The mat passes under a large drum that winds layers of fibre-cement around itself. A cut-off knife or wire releases the mat from the drum and it is then deposited onto a conveyor belt. After leaving the conveyor belt the fibre-cement mat is cross-cut; mats are cured by autoclaving for 6–8 h at temperatures and pressures of approximately 200°C and 900 kPa, respectively. In the absence of autoclaving, curing of boards takes approximately 28 h. From the autoclave, boards are transferred to a finishing plant where their edges are trimmed and their surfaces sanded.

### Compatibility of Wood with Cement

A key issue when examining the suitability of wood species for the manufacture of wood–cement composites is the effect that the wood has on the hydration (setting) of cement. When wood and water are added to cement, hydration reactions occur and heat is evolved. During the initial stages of hydration, di- and tri-calcium silicates are converted to tobermorite gel ($Ca_3Si_2O_7.3H_2O$) and calcium hydroxide ($Ca(OH)_2$). The latter increases the pH of the wood–cement mixture to approximately 12.5, which facilitates dissolution of wood constituents, particularly low molecular-weight carbohydrates and heartwood extractives. These compounds can interfere with cement hydration (Sandermann and Kohler 1964) and setting, resulting in wood–cement composites of inferior strength. Such deleterious interactions between wood and cement can be more pronounced with certain wood species, for example western larch (*Larix occidentalis*), because they possess greater quantities of cement-inhibiting compounds that are easily leached from the wood in the alkaline environment of cement (Zhengtian and Moslemi 1985). Alternatively, certain species, for example *Acacia mangium*, can contain soluble compounds which, although present in the wood in small quantities, may have strong inhibitory effects (Tachi et al. 1989). Wood species that greatly

inhibit cement hydration are classified as incompatible with cement and therefore unsuitable for the manufacture of wood–cement composites.

## The Workshop on Wood–Cement Composites in the Asia–Pacific Region

The decision to hold the 5th Pacific-Rim Biobased Composites Symposium in Canberra, Australia, in December 2000 provided an opportunity to bring researchers from the Asia–Pacific region together to discuss their current research into wood–cement composites. These edited Proceedings contain the papers that were presented at a workshop on wood–cement composites that preceded the symposium.

While there was no particular theme to the workshop the papers mainly fall into four categories. A series of papers (Ma and coworkers; Sutigno; Semple and coworkers (two papers)) examine the key issue of the compatibility of wood with cement and the development of methods to ameliorate the inhibitory effect of extractives on the hydration of cement (see discussion above). As mentioned in the foreword to these Proceedings, there is increasing interest in the manufacture of wood–cement composites from agricultural wastes and fast-growing, often exotic, tree species. Six papers in these Proceedings examine the manufacture or properties of cement composites from agricultural or pulp-mill residues, including rice straw (Fernandez and Taja-on), eucalypt, sisal and banana fibre (Warden and coworkers), bamboo (Sukartana and coworkers; Sulastiningsih and coworkers), rubberwood (Wong and Chee) and waste pulp-mill fibres and fines (Fernandez and coworkers). Also included in this section are two papers that were presented not in the workshop but in the main symposium, on rice hull composites (Hse and Choong; Klatt and Spiers). The papers are concerned with the manufacture of resin-bonded composites, but they are included in these Proceedings because of their relevance to the problem, faced by many countries, of disposing of agricultural residues.

Fast-growing tree species, particularly eucalypts and acacias, have been introduced into many countries in the Asia–Pacific region, notably China, Vietnam, Indonesia, Philippines and Malaysia. The penultimate section of the Proceedings contains papers concerned with the manufacture of wood–cement composites from eucalypts and acacias (Cabangon and coworkers; Eusebio and coworkers (two papers)). Also included in this section is a paper by Yukun and Xiaoyan, which contains information on the manufacture of mineral-bonded composites from fast-grown hybrid poplar. The final section of the Proceedings is concerned with the development of new types of wood–cement composites (Coutts; Ma and coworkers; Miyatake and coworkers) and new applications for wood–cement composites (Soriano and coworkers).

While these Proceedings do not claim to have captured all of the current research into wood–cement composites that is occurring in the Asia–Pacific region, the papers demonstrate the continuing interest in such materials and the scope for further research and product development.

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# Hydration Reactions of Cement and Wood–Cement Compatibility

# Manufacture of Cement-bonded Boards from Wood and Other Lignocellulosic Materials: Relationships between Cement Hydration and Mechanical Properies of Cement-bonded Boards

**Ling Fei Ma[1,3], Hidefumi Yamauchi[1], Orlando R. Pulido[1], Yasuo Tamura[1], Hikaru Sasaki[1] and Shuichi Kawai[2]**

*Abstract*

The hydration temperatures of mixtures of cement, additives and powders of sugi (*Cryptomeria japonica* D. Don), hinoki (*Chamaecyparis obtusa* Endl.), bamboo (*Phyllostachys heterocycla* Mitf. var. *pubescens* Ohwi), kenaf (*Hibiscus cannabinus* L.), rice hull or rice straw were measured. The total energy released (ET) during hydration was calculated from the area enclosed by the time–temperature curves of the mixtures at room temperature. The bending strength (MOR, MOE) of cement-bonded boards (CBB) made from the materials were tested according to Japanese standard JIS A 5908. Cured specimens from the CBB were analysed using x-ray powder diffractometry (XRD) and TG-DTA to determine the degree of hydration of cement in the CBB. There were correlations between the mechanical properties of bamboo CBB and the XRD intensity of the cement clinker and $C_3S$, the weight losses at 200°C and 900°C under TG-DTA, and the estimated yield of $Ca(OH)_2$. From these relationships, the mechanical properties of bamboo CBB containing carbonates as additives can be predicted. Depending on the raw material, the MOR and MOE of CBB can also be predicted from the total energy released by mixtures of cement and powdered samples from the same raw material. This can be applied to predict the strength of CBB where the degree of hydration is the dominant factor affecting strength.

AGRICULTURAL lignocellulosic residues have been steadily gaining popularity as alternative sources of raw materials for the manufacture of cement-bonded board (CBB). There have been numerous studies to determine the compatibility of such residues with cement. Most agricultural residues and some wood species need to be pre-treated before they can be used to manufacture CBB with acceptable properties. It has become obvious that the treatment and manufacturing conditions depend on the material type. One concern with the use of agricultural residues is the short period available for harvesting them. On the other hand, wood species that have a low compatibility with cement cannot solely be used for CBB production. In many cases it is necessary to work with mixed species or even to mix types of materials to make their use economically feasible.

Although it is obvious that more research is needed to determine the suitability of different lignocellulosic materials for the manufacture of CBBs, it is too costly and time consuming to manufacture and test boards from such materials in combination with various levels or types of additives, cement ratios or manufacturing

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conditions. The objective of this study was to find a rapid method of predicting the properties of CBBs from the results of hydration tests. Specifically, the study aimed to determine whether the strength and other mechanical properties of CBBs could be predicted from the hydration rate and/or the degree of hydration of mixtures of cement and lignocellulosic materials.

## Materials and methods

### Materials

Wood chips from plantation-grown sugi (*Cryptomeria japonica* D. Don) and hinoki (*Chamaecyparis obtusa* Endl.) were processed in a ring flaker. Retted kenaf (*Hibiscus cannabinus* L.) bast fibres were obtained from a commercial source. Splices from six-year-old mousou bamboo (*Phyllostachys heterocycla* Mitf. var. *pubescens* Ohwi) were processed in a chipper and then a ring flaker. Rice hulls were processed in a Willey mill and those passing a 2 mm mesh screen were used for the manufacture of CBB. Rice straw was dried and processed in a hammermill, and then classified into small or large particles using a 1 mm mesh screen.

Binder and additives were ordinary Portland cement, magnesium chloride ($MgCl_2$), sodium carbonate ($Na_2CO_3$), sodium hydrogen carbonate ($NaHCO_3$), various hydrates of sodium silicate ($Na_2SiO_3$), calcium chloride ($CaCl_2$) or combinations of these chemicals.

### Methods

*Board production*

Boards 300 mm × 300 mm × 9 mm in size were cold pressed for 20 h to achieve a target board density of 1.1–1.3 g cm$^{-3}$. The ratios of cement: lignocellulosic materials ranged from 2.2:1.0 to 2.6:1.0 and ratios of cement:water were 0.5–0.6. The general process involved in manufacturing boards is shown in Fig. 1. The boards were conditioned at 20°C and 60% r.h. for 14 d. Their properties were tested according to the Japanese Industrial Standards for Particleboards (JIS A 5908). The bending modulus of rupture (MOR) and modulus of elasticity (MOE) were obtained from such tests.

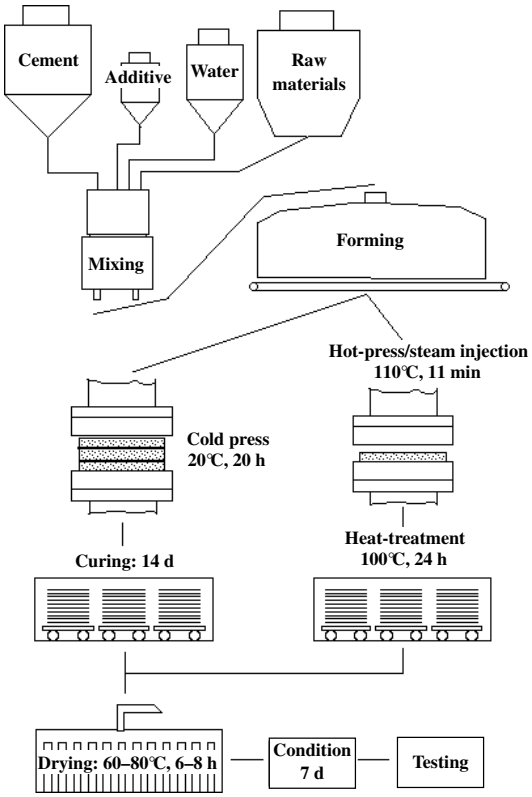



**Figure 1.** General flow diagram for the manufacture of cement-bonded boards

*X-ray powder diffraction, XRD, analyses of cured samples*

Powdered CBB samples passing through a 125 mm mesh obtained from bending test specimens were examined by XRD (MO3X-HF). Step scan measurements were made using x-ray (Cu–K*a*) at 40 kV and 20 mA; 2θ ranged from 5.0 to 60.0 degrees, at 0.02 degree scanning steps and 4 deg min$^{-1}$. The amounts of unreacted cement clinkers taken at 2θ = 32.3, 32.7 and 34.5 deg (Nagadomi et al. 1996a), $Ca(OH)_2$ at 2θ=18.2 deg (Nagadomi et al. 1996b) and $C_2S$ at 2θ=51.7 deg (Iwasaki et al. 1988) were compared.

*Thermo-gravimetric differential thermal analysis, TG-DTA, of cured samples*

Thermo-gravimetric differential thermal analyses, TG-DTA (WS002, TG-DTA2000s), were done on

22 g samples from the bending test specimens using *a*-$Al_2O_3$ as standard sample, 20°C $min^{-1}$ heating rate and nitrogen flow at 200 mL $min^{-1}$. The amounts of $Ca(OH)_2$ and $CaCO_3$ generated in the samples were determined (Lian et al. 1996).

*Hydration rate of cement-raw material pastes*

Raw materials were ground to powder in a Willey mill and those passing a #40 mesh screen were mixed with cement paste in a polyethylene cup and then enclosed in an insulated container. The weight ratio of cement:water:raw material was 200:100:15. The hydration temperatures of the lignocellulosic residue–cement mixes and cement controls were measured continuously for 50 h.

## Results and Discussion

### Relationships between the degree of hydration and the mechanical properties of CBB

Rapid-cured (steam injection or hot pressed) CBBs from bamboo were used to determine the relationships between the degree of hydration and the mechanical properties of boards. The degree of hydration was determined by TG-DTA and XRD analyses. Figure 2 shows the XRD patterns of specimens from bamboo CBBs. Figure 3 shows the TG-DTA curves. The yields of $Ca(OH)_2$ resulting from the hydration of cement clinkers were estimated from the XRD and TG-DTA analyses (Lian et al. 1996). When carbonates were assessed as cement setting additives, there was a good relationship between the mechanical properties of CBBs and the XRD intensity of the cement clinker and $C_3S$, the weight losses at 200°C and 900°C under TG-DTA, and the estimated yield of $Ca(OH)_2$. Figure 4 shows the relationship between the XRD peak intensity of cement clinker and weight loss at 200°C and the MOR, MOE and internal bond strength (IB) of CBBs. These relationships were discussed in our previous reports (Ma et al. 1997, 1998a,b). From these relationships, the MOR, MOE and IB of bamboo CBBs using carbonates as additives can be predicted.

When sodium silicate was used as an additive, there were also high correlations between the flexural properties of bamboo–cement composites and XRD peak intensity or weight loss at 900°C. It is difficult to estimate the yield of $Ca(OH)_2$ in

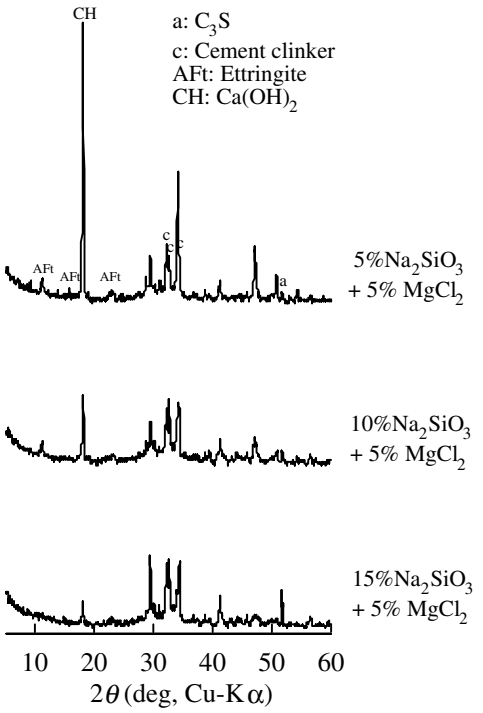



**Figure 2.** X-ray diffraction patterns of bamboo CBBs containing $Na_2SiO_3$ and $MgCl_2$ as additives. Weight ratio of bamboo:cement:water = 1.0:2.6:1.3.

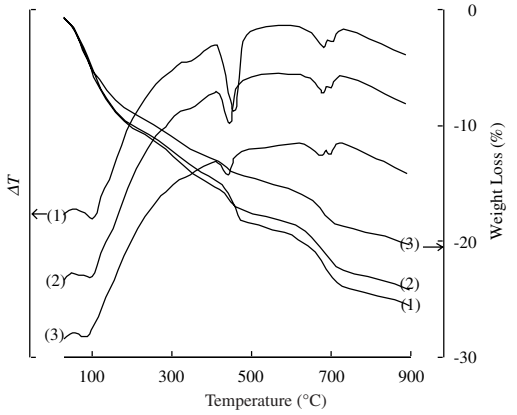



**Figure 3.** TG-TDA curves of bamboo CBBs containing $Na_2SiO_3$ and $MgCl_2$ as additives. (1) $Na_2SiO_3$ 5% + $MgCl_2$ 5%, (2) $Na_2SiO_3$ 10% + $MgCl_2$ 5%, (3) $Na_2SiO_3$15% + $MgCl_2$ 5%. Weight ratio of bamboo:cement:water = 1.0:2.6:1.3.

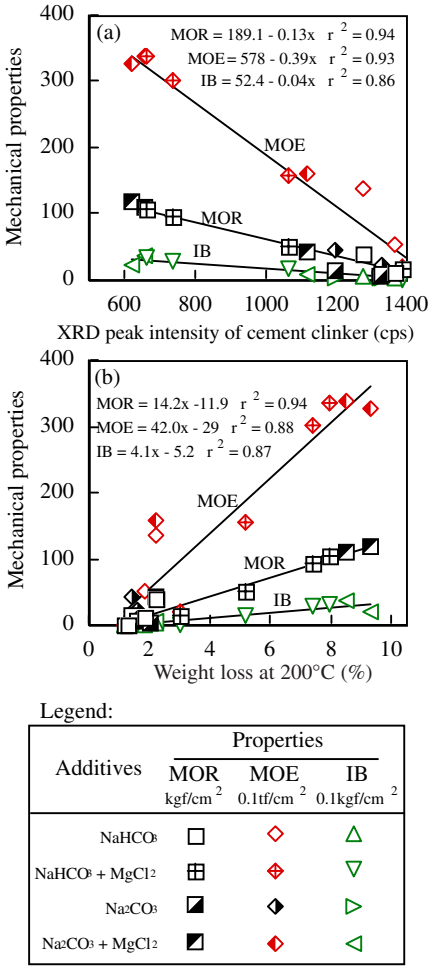



**Figure 4.** Mechanical properties of bamboo CBBs as functions of (a) XRD peak intensity of cement clinker and (b) weight loss at 200°C

boards containing $Na_2SiO_3$ because the $Ca(OH)_2$ generated during cement hydration reacts with $SiO_2$ in the additive.

These results suggest that the mechanical properties of boards manufactured from certain raw materials and additives can be predicted with a reasonable degree of accuracy using the degree of hydration of the cement-bonded composites. Such a relationship could be used as an alternative to destructive tests, although more data on boards manufactured from a greater variety of raw materials are needed. Furthermore, the method requires special equipment and is useful only for predicting the properties of manufactured composites. Therefore a simpler and more rapid method needs to be developed.

## Relationships between hydration rate and mechanical properties

The compatibility factor ($C_A$-factor) is generally accepted as an accurate index of the suitability of lignocellulosic raw materials for bonding with cement (Hachmi et al. 1990). The $C_A$-factor is the ratio of the areas under the hydration curves of the mixture of lignocellulose and cement paste, and

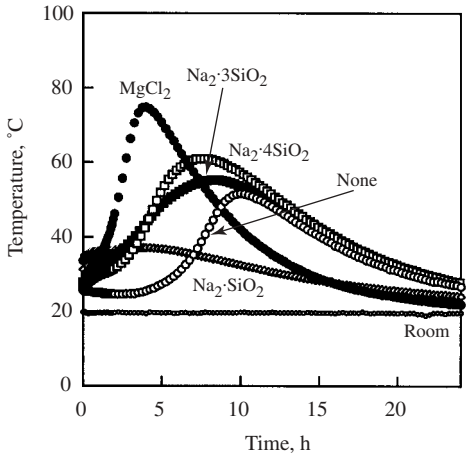



**Figure 5.** The effect of additives (at 5%) on the hydration temperatures of cement pastes

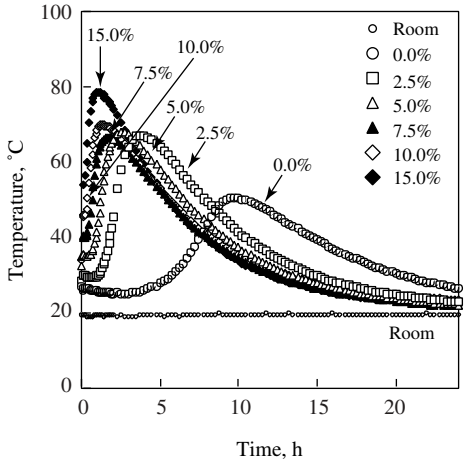



**Figure 6.** The effect of addition of $CaCl_2$ on the hydration temperatures of cement pastes

neat cement paste, and is expressed as a percentage (Hachmi et al. 1990). It is a convenient measure of whether a lignocellulosic material can be bonded with cement, or whether cement hardens sufficiently in the presence of the lignocellulose. Since the strength of CBB at any time is affected by the degree of cure of the cement, the $C_A$-factor might be used to predict the strength of CBB. However, results may be affected by raw material size, manufacturing conditions and other parameters. Nevertheless, in the above experiments on bamboo CBB high correlations were observed between the peak hydration temperature $T_{MAX}$ and the $C_A$-factor and the MOR of bamboo CBB (Ma et al. 1997). The linear relationships are

$$MOR = 1.13\,C_A - 14.80 \quad (r = 0.73),$$

$$MOR = 2.32\,T_{MAX} - 80.54 \quad (r = 0.93).$$

It is more convenient to use the total heat energy (ET) released during curing — that is, the area under the time–temperature curve — to predict the strength and other properties of CBBs. The ET is a measure of the degree of hydration of a board, which should be related to its properties.

Therefore the relationships between the properties of CBBs and the ETs of mixtures of cement and powdered parent lignocellulosic materials were studied. Initially, the bending strengths (MOR, MOE) of cold pressed (20 h) CBBs were used as the predicted variable. The ETs over a 20 h period were determined from the

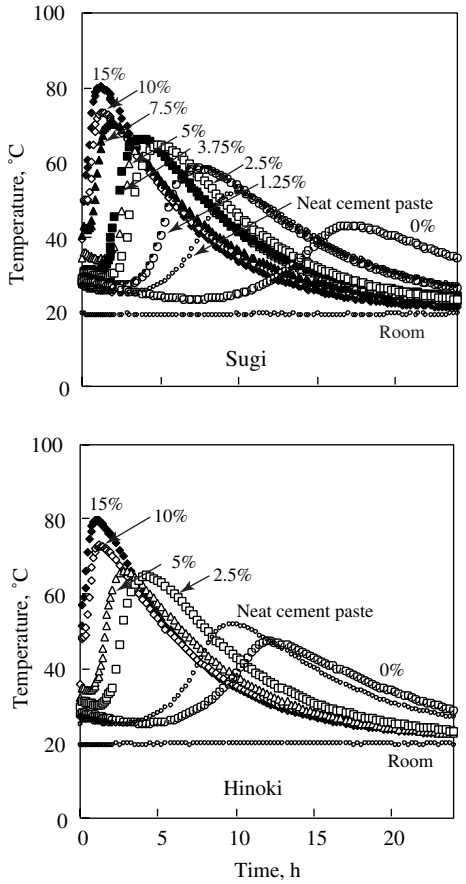



**Figure 7.** The effects of $CaCl_2$ on the hydration temperatures of cement–sugi and cement–hinoki mixtures

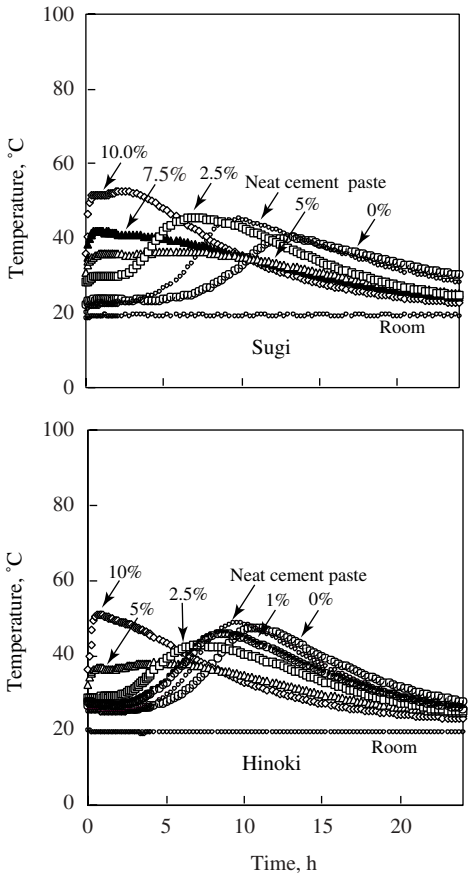



**Figure 8.** The effects of $Na_2SiO_3$ on hydration temperatures of cement–sugi and cement–hinoki mixtures

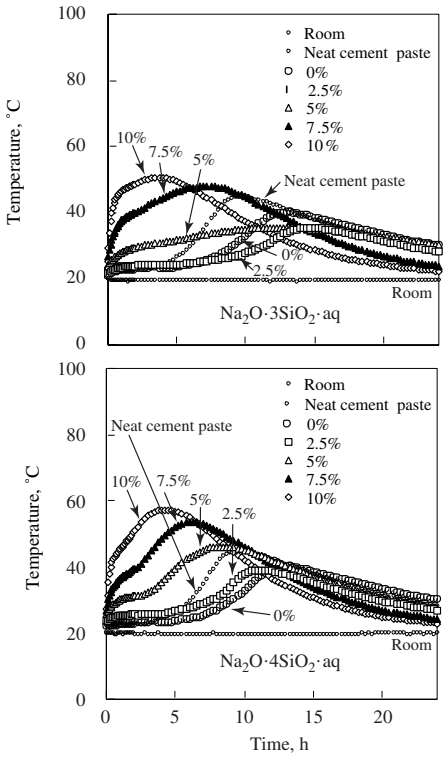



**Figure 9.** The effects of aqueous solutions of sodium silicate on the hydration temperatures of cement–sugi mixtures

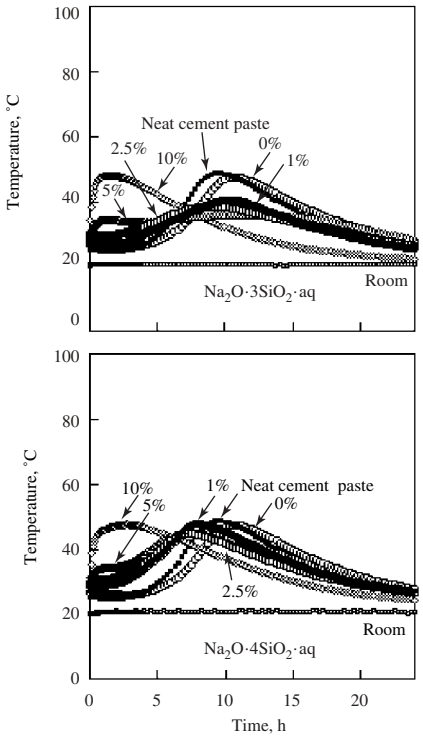



**Figure 10.** The effects of aqueous solutions of sodium silicate on the hydration temperatures of cement–hinoki mixtures

hydration curves of mixtures of cement and different raw materials.

The effects of various additives (5% addition level) on the hydration of cement pastes are shown in Fig. 5. The effects of addition levels are shown in Fig. 6. The addition of wood inhibited the hydration of cement as shown in Fig. 7. Due to the presence of inhibitory extractives in sugi (Yasuda et al. 1992), the hydration of sugi–cement paste was slower than that of hinoki, a species known to be compatible with cement. The addition of $CaCl_2$ accelerated the hydration rates, resulting in similar hydration curves for sugi and hinoki. Sodium silicate (Fig. 8) or its hydrates (Figs 9 and 10) also improved the hydration rates of both species, but to lesser degree than $CaCl_2$.

Kenaf and rice hull dramatically slowed the hydration of cement as shown in Fig. 11. However, the addition of 2.5% $CaCl_2$ accelerated the hydration of the mixtures. It was expected that the retting process would remove most of the extractives from kenaf, but clearly sufficient extractives remained or were produced during the process to interfere with cement hydration. Bamboo and rice straw also slowed the hydration of cement although a different hydration pattern to those of kenaf and rice hull was observed. An initial temperature peak developed quickly after mixing. This was followed by a decrease in hydration temperature and a subsequent rise to produce a temperature maximum $T_{MAX}$. Even the addition of 5% $CaCl_2$ did not accelerate hydration. The addition of higher levels of additives was necessary to produce faster hydration rates. The same effect was observed when sodium silicate and magnesium chloride were used as additives (Figs 12 and 13).

From the hydration curves, the total energy released by the samples after 20 h was calculated. The properties of CBB were tested according to

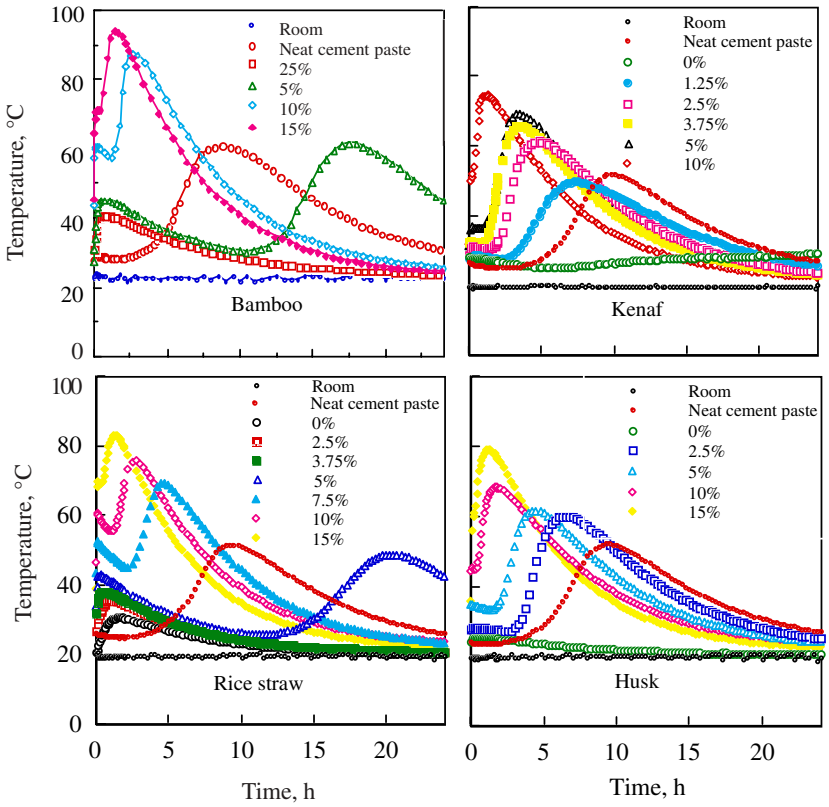



**Figure 11.** The effects of $CaCl_2$ on the hydration temperatures of mixtures of cement with bamboo, kenaf, rice straw or rice hull

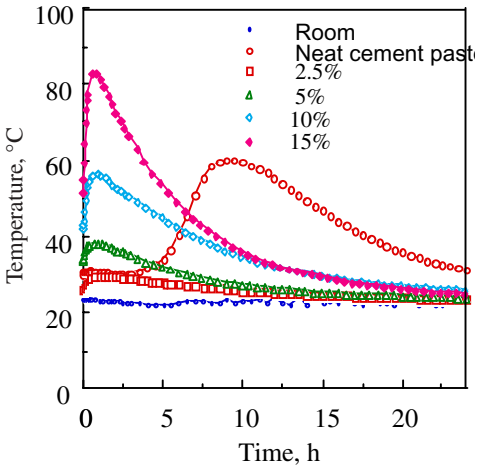



**Figure 12.** The effects of $Na_2SiO_3$ on the hydration temperatures of cement–bamboo mixtures

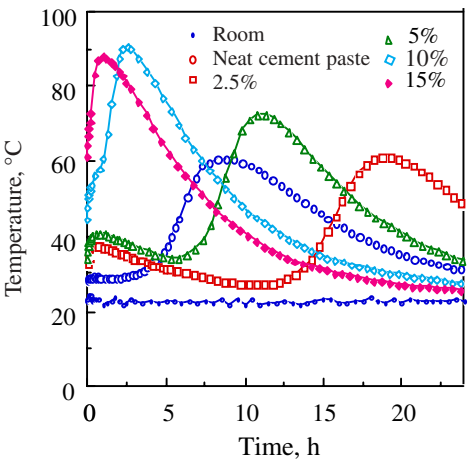



**Figure 13.** The effect of $MgCl_2$ on the hydration temperatures of cement–bamboo mixtures

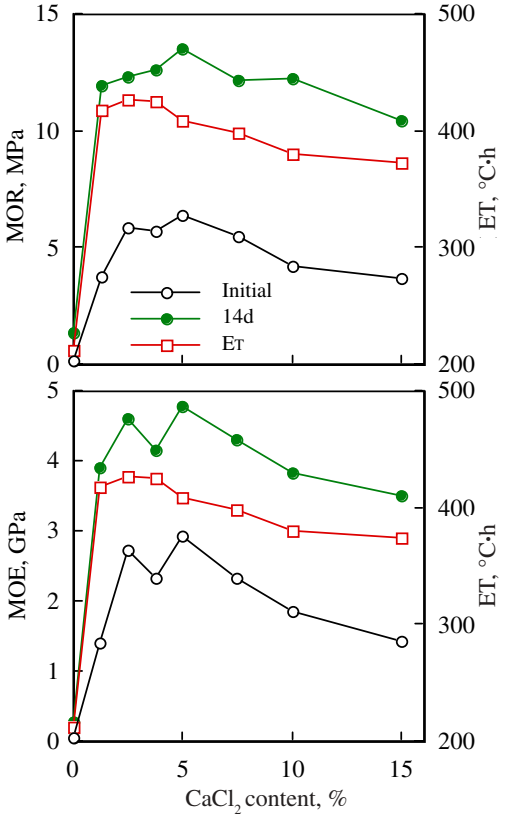



**Figure 14.** The effect of adding $CaCl_2$ on the properties of CBBs from sugi and ETs of hydration of cement–sugi mixtures (in a ring flaker, with cement:wood:water = 2.6:1.0:1.3, board density 1.1 g $cm^{-3}$, cold press 20 h, curing none or 14 d at 20°C and 60% RH)

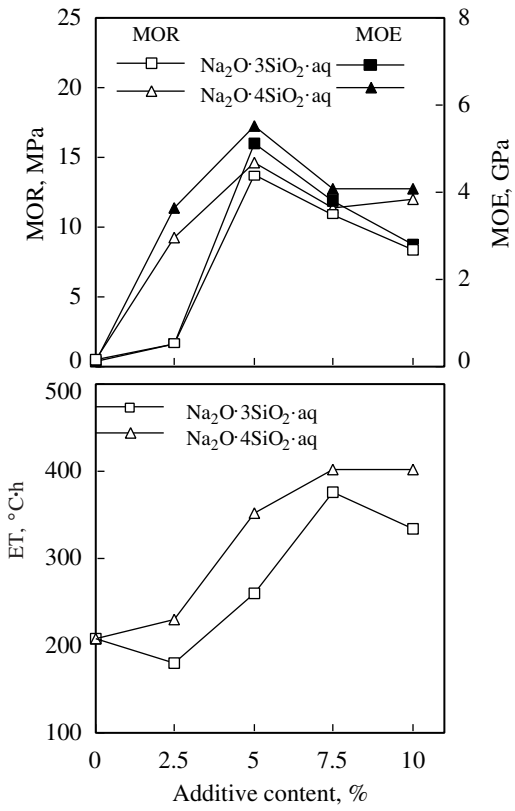



**Figure 15.** The effect of adding sodium silicate on the properties of CBBs from sugi and ETs of hydration of cement–sugi mixtures (in a ring flaker, with cement:wood:water = 2.6:1.0:1.3, board density 1.1 g $cm^{-3}$, cold press 20 h, curing 14 d at 20°C and 60% RH)

JIS A 5908. The MOR and MOE were determined after 20 h cold pressing and after a 14-day curing period. Figure 14 shows the results for MOR and MOE after 20 h cold pressing and 14 d curing of CBB made from sugi. The ET of sugi powder–cement mixtures at the same levels of $CaCl_2$ additions are shown for comparison. The trends in the ET and MOR or MOE after 20 h with respect to additive content followed similar patterns. The degree of hydration is a reasonable predictor of the strength of the mixture, as discussed in the previous section on TG-DTA and XRD analyses. Figure 14 shows that total energy release, which is related to degree of hydration, can also be used to predict the strength of boards at 20 h. Prediction of the initial strength of boards from the results of a quick test could be useful for industry. As expected, trends in the initial MOR and MOE were related to those of the final MOR and MOE and any differences; that is, the increase in strength after conditioning is uniform at all levels of addition. Therefore ET shows promise as a means of predicting the final strength of CBB.

The same relationship was observed between ET and the strength of boards when sodium silicate was used as an additive, although the correlation was not as strong (Fig. 15). The reaction of $Ca(OH)_2$ generated during cement hydration with $SiO_2$ from the additive may account for the poorer correlation.

Bamboo (Fig. 16) and rice straw (Fig. 17) also exhibited a relationship between the ETs of cement–powder mixtures and the bending strength

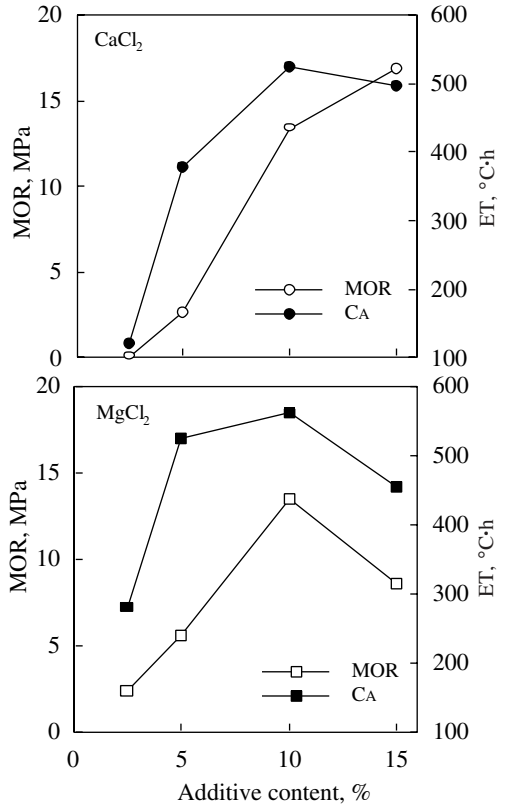



**Figure 16.** The effect of adding $CaCl_2$ or $MgCl_2$ on the properties of bamboo CBBs and total energy release of cement–bamboo mixtures (cement:wood:water = 2.2: 1.0:1.32, board density 1.2 g $cm^{-3}$, cold press 20 h, curing 14 d at 20°C and 60% RH)

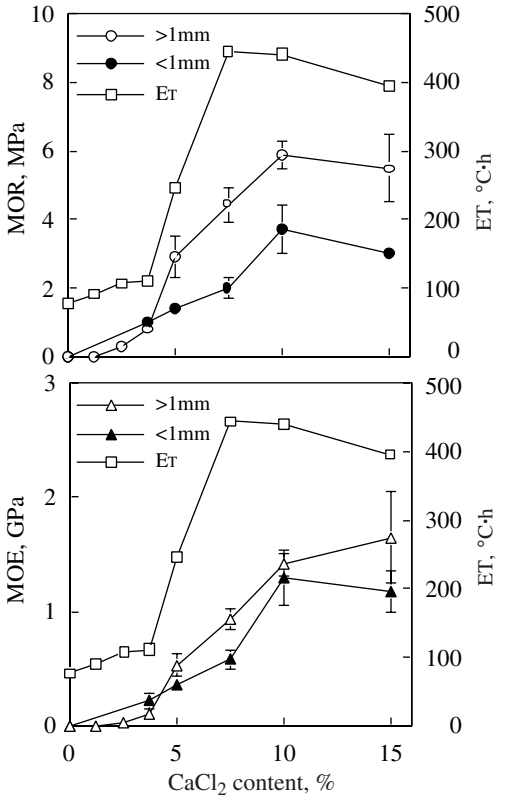



**Figure 17.** The effect of adding $CaCl_2$ on the properties of rice straw CBBs and total energy release of cement–rice straw mixtures (cement:wood:water = 2.6:1.0:1.3, board density 1.2 g $cm^{-3}$, cold press 20 h, curing 14 d at 20°C and 60% RH)

of CBBs. Raw material size affected the MOR and MOE of rice straw CBBs; that is, large particles (retained on a 1 mm mesh screen) gave higher strength than small particles (passing a 1 mm mesh screen). Both types of board showed a correlation between ET and mechanical properties. Low ET output was correlated with poor strength of rice straw CBB, and vice versa. Cement hydration was not sufficient at low additive contents to produce boards with satisfactory mechanical properties. Bamboo CBBs containing magnesium chloride as an additive also showed the same pattern as calcium chloride.

It is difficult to predict the properties of rice hull CBB from ET as shown in Fig. 18. Other factors such as particle dimensions may have a more dominant effect than degree of hydration. The same was true in the case of three-layer boards. Figure 19 shows the MOR and MOE of CBBs using hinoki as the core and oriented kenaf fibres as surface materials. The ET for kenaf and hinoki at various levels of $CaCl_2$ are also tabulated beneath the figure. The strengths of the boards were significantly affected by the orientation of fibres and by the mode of fracture during tests. However, it may be possible that when there is shear failure in the core, the strength can be predicted by the ET of core materials (hinoki). The strength of boards cannot be predicted from ET when there is failure in tension, because the kenaf fibre strength and orientation are more dominant factors than cement hydration.

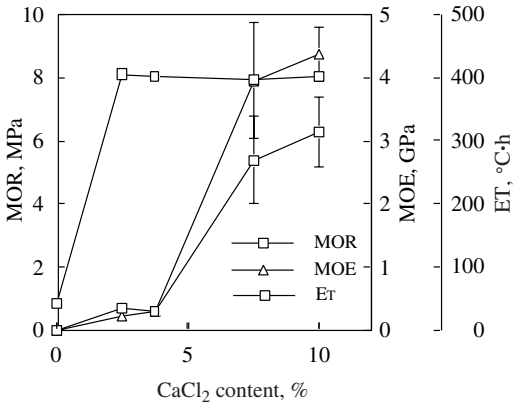
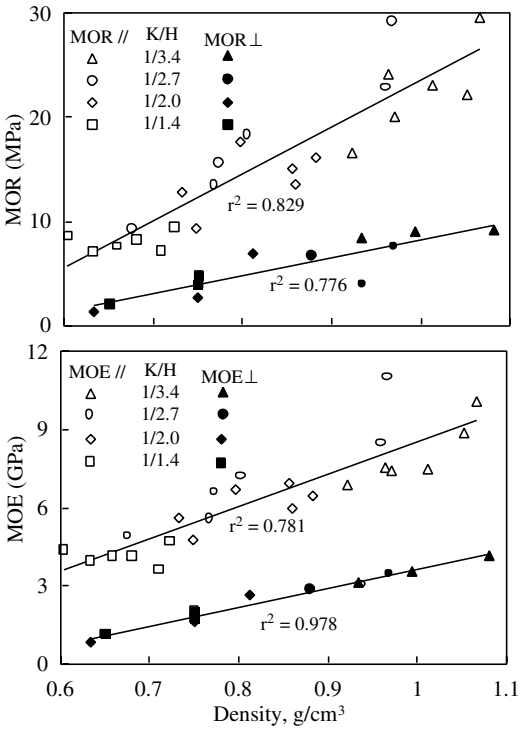



**Figure 18.** The effect of adding $CaCl_2$ on the properties of rice hull CBB and ET of cement–rice hull mixtures (pass 2 mm mesh, cement:wood:water = 2.6:1.0:1.3, board density 1.2 g $cm^{-3}$, cold press 20 h, curing 14 d at 20°C and 60% RH)

## Conclusion

When the degree of hydration is the dominant factor that determines the strength of CBBs, the mechanical properties can be predicted from the total energy released by the mixtures of cement and powdered samples from the same raw material that was used to manufacture boards. This method is useful as a quick way of determining the suitable material-mixing proportions in the production of CBB from new materials or mixtures of different materials. However, more research should be conducted on the effects of shapes and dimensions (i.e. actual lengths, widths, thicknesses, instead of powder form) of the raw materials on the hydration temperatures to obtain more specific relationships. Studies on the relationships between the hydration rate and the initial and final properties of CBB are currently underway to determine the proper amounts of additives that suit the capacities of production lines, specifically the mixing to pressing time. In the case of bamboo CBBs containing carbonates as additives, correlations were observed between the mechanical properties and the XRD intensity of cement clinker and $C_3S$, the weight losses at 200°C and 900°C under TG-DTA, and the estimated yield of $Ca(OH)_2$. These can be used as an alternative to destructive tests or to estimate the strength of installed CBBs. More data and larger sample sizes are needed to verify these results. This method will also be tested on CBBs from other raw materials.




| $CaCl_2$ | % | 0 | 2.5 | 5 | 10 | 15 |
|---|---|---|---|---|---|---|
| Hinoki | °C·h | 290.9 | 411.1 | 383.5 | 380.1 | 385.8 |
| Kenaf | °C·h | 134.8 | 411.5 | 452.2 | 372.6 | |

**Figure 19.** Moduli of rupture (MOR) and elasticity (MOE) and internal bond strength (IB) of three-layer CBB made from oriented kenaf fibre surfaces and hinoki core materials (K/H = kenaf:hinoki weight ratio. // or ⊥ = properties in the oriented or cross direction, respectively)

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# Effect of Aqueous Extraction of Wood-wool on the Properties of Wood-wool Cement Board Manufactured from Teak (*Tectona grandis*)

**Paribotro Sutigno**[1]

*Abstract*

Extractives in teak (*Tectona grandis*) inhibit the setting of cement and reduce its suitability for the manufacture of wood–cement composites. Wood-wool was pre-treated by soaking it in cold water for 1, 2 and 3 d or soaking it in hot water for 1, 2 and 3 h. Pre-treated and untreated wood-wool were used to manufacture wood-wool cement boards. Portland cement was used as a binder (175% of the weight of wood-wool) and 2% $CaCl_2$ was used as a cement setting accelerator. The extractive content of teak decreased from 2.75% to 1.34% after soaking in cold water for 3 d. Hot water extraction for 1, 2 and 3 h was not as effective as prolonged cold water extraction in removing extractives from teak and after 3 h hot water extraction the extractive content of teak was 1.5%. Hot water extraction was more effective at increasing the compatibility of wood-wool with cement and increasing its suitability for the manufacture of wood-wool cement boards. For example, after 3 d soaking in cold water the hydration temperature of wood–cement mixtures increased by 4.5% whereas after 3 h soaking in hot water it increased by 9.0%. Similarly the bending strength of wood-wool cement boards increased by 10.66 kg $cm^{-2}$ after 3 d soaking in cold water whereas it increased by 17.58 kg $cm^{-2}$ after 3 h soaking in hot water. Cold and hot water extraction had similar effects on reduction of thickness due to compression of 3 kg $cm^{-2}$. Irrespective of the differences in the properties of boards made from wood-wool subjected to the different pre-treatments, all boards made from pre-treated wood-wool met the F DIN 110 standard requirements for wood-wool cement board. It can therefore be concluded that aqueous extraction of wood-wool is a highly effective method of increasing the suitability of teak for the manufacture of wood-wool cement board.

TEAK or jati (*Tectona grandis*) is a popular species in Indonesia, especially in Java. It is planted mainly in Java and in 1998 the teak forest in that region amounted to about 1.5 million ha (Anonymous 1999). The teak forest in other regions, such as in Lampung (Sumatra), South Sulawesi, South-East Sulawesi, Sumbawa (West Nusa Tenggara) and Maluku, occupies small areas. Teak may reach a height of 45 m and the clear bole can be 15–20 m long. Its diameter, which is normally 50 cm, may exceed 220 cm on good sites. The stem is irregularly shaped and grooved (Martawijaya et al. 1986).

Teak wood has specific gravity of 0.67, strength class of II and durability class of II. The wood is easily worked by machine as well as hand tools and has a beautiful figure. The extractive content of teak is 4.6% in alcohol benzene, 1.2% in cold water and 11.1% in hot water (Martawijaya et al. 1986). Based on its alcohol benzene extractive content, teak is classified as having a high extractive content (more than 3%) (Anonymous 1959).

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Owing to its favourable properties, teak wood is extensively used for a variety of purposes. It is especially suited to all kinds of structural members such as columns, beams and girders of houses and bridges, piers and floodgates in fresh water, railway sleepers and railcar construction timber, the hull and decking of ships, flooring boards and parquets, doors, windows, furniture and face veneer for fancy plywood (Martawijaya et al. 1986).

Research has been carried out on the possibility of using teak wood waste as a raw material for cement-bonded board. Sandermann and Kohler (1964) mentioned that, based on results from a hydration test, teak was classified as being suitable ('good') for cement-bonded boards; but according to Kamil (1970) teak is only of moderate suitability for cement-bonded board. Extractives in teak reduce its suitability for cement-bonded board (Sandermann and Kohler 1964 in Kamil 1970). Methods of reducing the inhibitory effect of such extractives on cement hydration are needed if teak is to be used commercially in Indonesia for the manufacture of wood-wool cement boards. In this study the effects of cold and hot water extraction of teak wood-wool on the extractive content, hydration exotherm of cement and physical properties of wood-wool cement boards were assessed. The aim was simply to determine whether aqueous extraction of wood-wool is an effective method of improving the suitability of teak for the manufacture of wood-wool cement boards.

## Materials and Methods

Wood-wool (excelsior) was made from the upper part of a girdled teak tree, 40 cm long. The wood-wool, which was 10–40 cm long, 3 mm wide and 0.3 mm thick, was air-dried to a moisture content of about 15% before treatment.

The wood-wool was given seven treatments: no soaking (control), soaking in cold water for 1, 2 or 3 d, or soaking in hot water for 1, 2 or 3 h. Water was boiled and the wood-wool was then immersed in it. After treatment, the wood-wool was air-dried to a moisture content of about 15%. The cold water solubility of wood-wool was determined according to ASTM D 1110–56 (Anonymous 1959). The hydration test was performed in a thermos flask (Kamil 1970) using wood flour. There were three replications for the solubility and the hydration tests.

Experimental wood-wool boards were prepared by wetting wood-wool with an aqueous solution (2% w/v) of calcium chloride. Cement (175% of wood-wool weight) was mixed thoroughly with the wet wood-wool. The quantities of wood-wool, water and cement used to make each board were 315, 550 and 315 g respectively. The mixture was hand-formed into a mat in a wooden deckle box (30 cm × 30 cm internal dimensions). The mat was pressed to a thickness of 2.5 cm and clamped for 24 h at room temperature. The boards produced, which measured 30 cm × 30 cm × 2.5 cm with a target density of 0.46 g $cm^{-3}$, were left at room temperature for one month prior to testing. Five replications were made for each treatment.

The boards were cut to the desired specimen dimensions for determining board properties such as board density, moisture content, bending strength and thickness reduction due to a compression of 3 kg $cm^{-2}$. The tests were performed to DIN 1101 with some modifications (Kamil 1970).

## Results and Discussion

Soaking wood-wool in cold water and hot water decreased its extractive content (Table 1). The average extractive contents of wood-wool after soaking in cold water (1.49%) and after soaking in hot water (1.90%) were lower than those of the control (2.75%). Soaking wood in cold water dissolves tannins, gums, sugars and colouring matter, while soaking wood in hot water dissolves tannins, gums, sugars, colouring matter and starches in wood (Anonymous 1959). The extractive content of wood-wool decreased as the soaking period increased. The extractives decreased 1.41% after soaking in cold water for 3 d and decreased 1.25% after soaking in hot water for 3 h.

Soaking wood-wool in cold water and hot water increased the hydration temperature of wood–cement mixtures (Table 1). The average hydration temperatures of wood flour–cement mixtures containing wood soaked in cold and hot water were higher than for the control. Kamil (1970) examined the effect of sengon wood (*Paraserianthes falcataria*) on the hydration of cement and found that the hydration temperature

**Table 1.** Some properties of teak wood and its wood-wool board

| No. | Properties | Control | Soaking period in cold water (d) | | | Soaking period in hot water (h) | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 1 | 2 | 3 |
| 1 | Extractives (%) | 2.75 | 1.63 | 1.51 | 1.34 | 2.37 | 1.82 | 1.50 |
| 2 | Hydration behaviour | | | | | | | |
| | Temperature (°C) | 54.13 | 60.33 | 60.93 | 61.83 | 60.10 | 60.70 | 63.13 |
| | Duration (h) | 15 | 12.00 | 11.67 | 12.33 | 10.33 | 10.67 | 10.67 |
| 3 | Bending strength of wood-wool board (kg $cm^{-2}$) | 2.81 | 10.37 | 10.73 | 13.47 | 10.82 | 14.23 | 20.39 |
| 4 | Thickness reduction of wood-wool board due to compression of 3 kg $cm^{-2}$ (%) | 12.40 | 7.02 | 6.50 | 4.50 | 7.50 | 4.70 | 2.70 |

Remarks: Hydration behaviour of cement: 67°C, 10 h.
The average density and moisture content of the board were 0.50 kg $cm^{-3}$ and 12% respectively.

of untreated wood was 39.0°C. After wood-wool was soaked in cold water for 24 h the hydration temperature increased to 42.0°C (Table 2), in accord with the data in Table 1.

According to Sandermann and Kohler (1964), wood species with hydration temperatures greater than 60°C are good in quality (suitable) for cement-bonded boards. Wood with hydration temperatures of 55°C to 60°C and less than 55°C were classified as moderate and bad (unsuitable), respectively, for cement-bonded composites. Kamil (1970) developed three hydration temperature classes: >41°C was good, 36–41°C was moderate, and <36°C was bad for cement-bonded boards.

Using the classification of Sandermann and Kohler (1964) untreated teak can be regarded as unsuitable for wood–cement composites whereas after soaking in cold and hot water it becomes suitable. On the other hand, if the Kamil classification is adopted, both the control and soaked wood-wool are suitable (good) for the manufacture of wood–cement composites. Sandermann and Kohler (1964) found that the hydration temperature of teak wood was 68°C after 22 h, whereas Kamil (1970) obtained a hydration temperature of 39°C after 5 h. These differences point to the difficulties of comparing the results of hydration tests that employ different methods and use wood of different origin. Site and felling time of tree affects the extractives content of wood and its suitability for cement-bonded boards (Sandermann and Kohler 1964), but since teak is generally girdled, which tends to reduce the influence of felling time on extractive content, the effect of the site could be greater than the effect of felling time.

There is usually an inverse relationship between the extractive content of wood and the hydration temperature of wood–cement mixtures. After soaking in cold water and hot water, the tannins and the sugars in wood, which inhibit cement hydration, decrease so that hydration temperature increases.

The average bending strengths of cement-bonded boards made from wood-wool soaked in cold water (12.00 kg $cm^{-2}$) or hot water (15.15 kg $cm^{-2}$) were higher than the average bending strength of the control (2.81 kg $cm^{-2}$), as shown in Table 1. This indicates that soaking wood-wool in cold water or hot water can significantly improve the bending strength of wood-wool cement board. A previous study on the properties of wood-wool board made from sengon, in which wood-wool was soaked in cold water for 24 h also showed that cold water extraction improved the bending strength of wood-wool cement board (Table 2). The densities of wood-wool cement boards were 0.49 g $cm^{-3}$ and 0.53 g $cm^{-3}$ for control and soaked wood-wool, respectively (average 0.51 g $cm^{-3}$).

The bending strength of the control (2.81 kg $cm^{-2}$) here did not meet the requirement of DIN 1101 because its value was less than 10 kg $cm^{-2}$, but the bending strength of wood-

**Table 2.** Some properties of sengon (*Paraserianthes falcataria*) wood and its wood-wool board

| No. | Properties | Control | Soaked wood-wool |
|---|---|---|---|
| 1 | Hydration behaviour | | |
| | Temperature (°C) | 39 | 42 |
| | Duration (h) | 15 | 18 |
| 2 | Bending strength of wood-wool board (kg cm$^{-2}$) | 7.0 | 18.7 |
| 3 | Thickness reduction of wood-wool board due to compression of 3 kg cm$^{-2}$ (%) | 11.2 | 8.0 |

Source: Kamil (1970)

wool board in which the wood-wool had previously been soaked in cold water and hot water (10.37–20.39 kg cm$^{-2}$) met the requirement. This finding accords with the study carried out by Kamil (Table 2).

The bending strength of wood-wool cement board increased as the soaking period of the wood-wool increased. The bending strength of the board increased by 10.66 kg cm$^{-2}$ and 17.58 kg cm$^{-2}$ if the wood-wool had been soaked in cold water for 3 d or in hot water for 3 h, respectively.

The average thickness reductions of boards resulting from a compression of 3 kg cm$^{-2}$ were lower for boards made from cold water (6.0%) or hot water (5.0%) soaked wood-wool compared to the untreated control (12.4%) as shown in Table 1. This indicated that soaking wood-wool in cold water and hot water significantly improves the thickness reduction of the board due to compression. The same result was obtained by Kamil (1970) in his study of the manufacture of wood-wool board from sengon (Table 2).

The thickness reduction of all boards, due to compression, conformed to the requirement of DIN 1101 because the values were not more than 15%.

The thickness reduction of the board due to compression decreased as the soaking period increased. The decreases were 7.9% and 9.7%, respectively, if the wood-wool had been soaked in cold water for 3 d or in hot water for 3 h. This accords with the finding that extractive content of wood-wool decreased as the soaking period increases.

Soaking in hot water for 1–3 h was more effective at improving board properties than soaking in cold water for 1–3 d, even though the average extractive content of wood-wool after hot water soaking (1.90%) was higher than after cold water soaking (1.49%). For example, the mechanical properties of wood-wool boards in which the wood-wool had previously been soaked in hot water were better than if the soaking had been in cold water, as indicated by higher average bending strength (15.15 kg cm$^{-2}$ compared to 12.00 kg cm$^{-2}$) and by lower average thickness reduction due to a compression of 3 kg cm$^{-2}$ (5.0% compared to 6.0%). It is possible that there were fewer sugars and tannins in wood-wool after soaking in hot water than after soaking in cold water.

Based on data from 73 wood species, Sutigno and Sulastiningsih (1986) predicted wood-wool cement board properties according to hydration temperatures. The results showed that the properties of wood-wool cement board from wood species classified as 'good' did not always meet the requirements of DIN 1101. On the other hand, the properties of wood-wool cement board from wood species classified as 'moderate' and 'bad' sometimes did meet the requirements. The probability of meeting the requirements was higher for thickness reduction due to compression of 3 kg cm$^{-2}$ than for bending strength. Data in Table 1 and Table 2 are similar, to the extent that the thickness reduction due to a compression of 3 kg cm$^{-2}$ of the board without treatment (control) met the requirement, while the bending strength of the board did not meet the requirement. After wood-wool treatments, all the boards met the requirements for bending strength and thickness reduction due to compression.

## Conclusions

1. The average extractive content of teak wood-wool after soaking in cold water was 1.49% and after soaking in hot water was 1.90%,

whereas for the control it was 2.75%. The extractive content of the wood-wool decreased as the soaking period increased.

2. The average hydration temperature of teak wood flour–cement mixtures (54.1°C) increased if the wood was soaked in cold water or hot water. The hydration temperature increased as the soaking period of wood-wool increased.
3. The average bending strengths of teak wood-wool cement board in which the wood-wool had been previously soaked in cold water (12.00 kg $cm^{-2}$) and hot water (15.15 kg $cm^{-2}$) were higher than that of the control (2.81 kg $cm^{-2}$). The bending strength of the board increased as the soaking period of wood-wool increased.
4. The average thickness reductions of teak wood-wool cement board, due to a compression of 3 kg $cm^{-2}$, were lower for boards containing wood-wool previously soaked in cold water (6.0%) and hot water (5.0%), than for the control (12.4%). The thickness reduction of the board due to compression decreased as the soaking period increased.
5. Aqueous extraction of teak wood-wool allowed the wood-wool cement board to meet the requirements for bending strength and thickness reduction due to compression. In boards made from unsoaked teak wood-wool (control), only the thickness reduction due to compression met the requirement.

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# Screening Inorganic Additives for Ameliorating the Inhibition of Hydration of Portland Cement by the Heartwood of *Acacia mangium*

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*Abstract*

The suitability of *Acacia mangium* for the manufacture of cement-bonded wood composites is adversely affected by the presence of heartwood tannins — water soluble polyphenolic extractives that strongly inhibit the hydration of Portland cement. Once the inhibitory extractives have been removed from the wood by soaking it in fresh water, wood–cement composites such as wood-wool cement boards (WWCBs) can be manufactured from *A. mangium*. However, if a sufficient supply of fresh water is not consistently available, alternative strategies are needed to ameliorate the effect of polyphenols in *A. mangium* wood on cement hydration. Certain compounds such as calcium chloride are commonly used in the manufacture of wood–cement composites to reduce the inhibitory effect of heartwood extractives on the hydration of cement. It is well known that calcium chloride achieves this effect by accelerating the hydration of cement. This alone is not sufficient to overcome the inhibition of cement hydration caused by heartwood polyphenols in species like *A. mangium*. Compounds that accelerate cement hydration and also chelate or chemically modify polyphenols to prevent them from interfering with cement hydration may be more effective than calcium chloride at improving the compatibility of *A. mangium* wood with cement. This study used laboratory-scale cement hydration tests to screen a wide range of soluble and insoluble inorganic additives to identify those most effective at strengthening the hydration of Portland cement. The ability of compounds to form insoluble chelates with inhibitory heartwood polyphenols from *A. mangium* was tested, as was their capacity to strengthen the hydration of cement containing *A. mangium* heartwood. The results showed that compounds with the ability to strongly accelerate cement hydration and form insoluble chelates with inhibitory heartwood tannins were the most effective at reducing the inhibitory effect of *A. mangium* heartwood on cement hydration. Most of the compounds were chlorides and nitrates, including $SnCl_4$, $AlCl_3$, $(NH_4)_2Ce(NO_3)_6$ and $FeCl_3$. These compounds accelerate cement hydration and also contain cations such as $Sn^{4+}$, $Al^{3+}$ and $Fe^{3+}$ which can strongly chelate heartwood tannins in *A. mangium*. Accordingly, these compounds were more effective than calcium chloride ($CaCl_2$), which, although it accelerated cement hydration, did not form insoluble chelates with heartwood tannins. The treatment of wood with compounds that can accelerate cement hydration and chelate heartwood extractives may facilitate the manufacture of wood–cement composites from fresh *A. mangium* wood, a goal that hitherto has not been possible to achieve using conventional cement-hardening additives.

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Wood–wool cement boards (WWCBs) are becoming an important building material in several tropical countries because of their low cost and ease of manufacture, good mechanical and insulation properties, modular construction capabili-

ties, and good resistance to biodeterioration and fire (Pablo 1989; Ramirez-Coretti et al. 1998). Extensive planting of acacia and eucalypt species in the Asia–Pacific region in recent decades (Vercoe 1993) could provide an abundant supply of wood for the manufacture of WWCBs. *Acacia mangium* Willd. is one of the most successful of the species introduced into South-East Asia, and it has therefore generated considerable interest as a possible raw material for WWCB manufacturing industries in countries such as the Philippines. However, water-soluble and alkali-soluble polyphenolic substances present in the heartwood of *A. mangium* severely retard the normal course of cement hydration (Tachi et al. 1989), resulting in poor bonding in wood–cement composites. This is a major impediment to the use of *A. mangium* as a raw material for WWCB manufacture. Inhibitory polyphenols in *A. mangium* heartwood are water soluble (Tachi et al. 1988) and therefore can be easily removed by soaking wood in water for 12 to 24 h, but in dry regions and in some seasons there can be insufficient fresh water available for soaking wood-wool. Therefore it is important to develop alternative methods of improving the compatibility of *A. mangium* with cement so that this species can be used for WWCBs in countries where it is widely planted and readily available.

Certain inorganic compounds are commonly used during the manufacture of wood–cement composites to reduce the inhibitory effect of heartwood extractives on the hydration of cement (Zhengtian and Moslemi 1985). Calcium chloride ($CaCl_2$) in particular has been successfully used to improve the strength properties of WWCB (Kayahara et al. 1979; Lee and Short 1989; Soriano et al. 1998). It is well known that $CaCl_2$ achieves this effect by accelerating the hydration of cement particularly the tri-calcium silicate phase ($C_3S$), reducing setting time, and, in some cases, increasing maximum hydration temperature (Lea 1971; Ramachandran 1994). This alone is not sufficient to overcome the severe inhibition of cement hydration caused by heartwood polyphenols in species like *A. mangium*. Compounds that accelerate cement hydration and also chelate or chemically modify polyphenols to prevent them from interfering with cement hydration may be more effective than $CaCl_2$ at improving the compatibility of *A. mangium* wood with cement. This study screened a wide range of soluble and insoluble inorganic chemical additives for their ability to accelerate the hydration of cement and also chelate heartwood polyphenols in *A. mangium*. The aim was simply to determine whether compounds that possessed both attributes were more effective than $CaCl_2$ at ameliorating the inhibitory effects of *A. mangium* heartwood on cement hydration.

## Materials and Methods

### Wood sample collection and preparation

Wood-wool was obtained from two eight-year-old Brown Salwood (*Acacia mangium* Willd.) trees grown in provenance trials at Damper (18°24′S 146°06′E, altitude 20 m asl) in North Queensland, Australia. Two end-matched logs, 1.15 m long, were removed from the felled trees and two end-matched billets measuring 0.46 m were cut from the middle of each log. The eight billets were shredded in the green condition into wood-wool strands measuring 0.3 mm × 3 mm × 460 mm at Woodtex in Bendigo, Victoria, keeping the wood-wool from the two trees separate. The wood-wool was air dried under cover for about two weeks and grab-samples (approx. 100 g) were then randomly taken for sorting to isolate and retain strands of pure heartwood. The heartwood strands were cut into pieces approximately 50 mm in length using scissors and stored for at least two weeks in a conditioning room maintained at 20 ± 1°C and 65 ± 5% RH, until needed.

### Compounds and their preparation

In total, 137 inorganic compounds were studied. These comprised chlorides, sulphates, nitrates, acetates, oxides, carbonates and fluorides of the cations Al, Ba, Ca, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Na, Ni, Pb, Sr and Zn. Several miscellaneous compounds including citrates, tartrates, bromides and oxalates of Na and K were also tested. The solubility in water of each compound was checked (Weast 1970) to determine whether to add each one to cement as a solid or liquid. The water-soluble compounds were dissolved in distilled water at room temperature to 0.1 M strength in 250 mL volumetric flasks. Four 40 mL aliquots of each compound solution were poured into separate 50 mL capacity vials for addition to

cement hydration samples: two for addition to wood–cement samples and two for addition to samples containing cement only. The two vials to be added to wood–cement samples were prepared with an extra 0.7 mL of distilled water per g of wood used, in accordance with the recommendations of Hachmi et al. (1990). The insoluble compounds were pulverised to remove lumps, using a mortar and pestle, and four equal amounts were weighed out into four 5 mL capacity vials for addition as dry powder to cement hydration samples. The amount of each compound used in a hydration test corresponded to the amount that would be present in 40 mL of a 0.1 M solution if the compound were soluble in water. This ensured consistency in concentration of additives across soluble and insoluble compounds.

### Measurement of cement hydration exotherms

Each aliquot of the compounds was added to 100 g of fresh dry Portland cement Type I (Blue Circle Southern brand, batch no. 090MA99) in a sealable 'Dalgrip' polyethylene bag and thoroughly mixed by hand kneading for about 2 min at 20°C. Insoluble compounds were added as a dry powder to 100 g of dry cement in a 'Dalgrip' bag and evenly mixed though the cement, after which distilled water was added to mix the cement slurry as described above. For samples containing only neat cement or cement plus compound but no wood, 40 mL of distilled water or compound solution was added. For each cement sample to which wood was to be added, 43.5 mL of distilled water or compound solution was first added and mixed. Then 5 g of chopped *A. mangium* heartwood-wool was added and massaged though the cement slurry until evenly coated. Immediately after the mixing of a cement hydration sample, the tip of a temperature thermocouple (Type J) was taped to the outside of the sample bag and enclosed within the body of the cement or wood–cement mix by folding the bag and contents around it. The folded bag was then secured with adhesive tape, placed in a polystyrene cup and sealed inside a 1 L capacity thermos flask. This process was carried out for six samples. A cement hydration temperature-logging apparatus, similar to that used by Irle and Simpson (1993), was used to measure the heat of hydration of the six wood–cement samples over 23 h. Temperatures were recorded at 15 min intervals. The curves were smoothed by plotting the progressive average of each three successive readings. Maximum heat of hydration temperature ($T_{MAX}$) and time taken to reach $T_{MAX}$ ($t$) were recorded, and two wood–cement compatibility indices, $C_A$-factor (Hachmi et al. 1990), and hydration rate (R) = $(T_{MAX} - T_{MIN})/t$, were calculated. The $C_A$-factor is the ratio of the areas under the hydration curves of a wood–cement sample and the control (cement only), expressed as a percentage. The $T_{MIN}$ component of hydration rate is the minimum temperature attained during the first 5 h of hydration. All experiments were done in a controlled temperature room maintained at 20 ± 1°C.

### Experimental design and execution

In addition to the two cement control (cement only) and two wood–cement control samples, 137 compounds were tested with two replicates for neat cement and two replicates (trees) for wood–cement samples. The experimental design contained a nested structure of cement and cement + wood hydration samples within the compounds stratum. In each daily six-replicate run of hydration samples, three compounds were tested at random. For each compound, two matched samples were run, one with cement + compound and the other with cement + compound + wood. All compounds were run in random order for replicate 1 (cement) and wood from tree 1 (cement + wood) over the first 46 days followed by replicate 2 and wood from tree 2, again randomised by compound over the next 46 days.

Compounds were ranked in order of their efficacy in improving the strength (expressed as $T_{MAX}$ and hydration rate) of the exothermic reaction of cement containing the inhibitory heartwood-wool of *A. mangium*. Compounds were also assessed for their effects on the normal course of hydration of Portland cement by comparing the hydration exotherms $T_{MAX}$ and hydration rate of cement containing compound mixtures with those of cement alone. Average hydration rates in wood–cement mixes generated by compounds grouped by anion/cation content

are shown in Figs 1 and 2. For each compound the $T_{MAX}$ and hydration rate of the wood–cement mix were graphed against those obtained for samples containing cement and compound only (Figs 3 and 4).

### Determination of polyphenol–metallic complexes

Freshly mixed cement slurry is highly alkaline (pH 11) and it increases in alkalinity with time as calcium hydroxide is produced (Lea 1971; Taylor 1997). This has a strong leaching effect on wood and will dissolve and remove more than just the water soluble heartwood extractives (Goldstein 1984). Therefore, sodium hydroxide was used to obtain a leachate containing alkali-soluble inhibitory polyphenols from *A. mangium* heartwood. To obtain the heartwood leachate, 10 g of chopped *A. mangium* heartwood wool was placed in a beaker containing 300 mL of alkali solution at pH 11.5–12 (0.01 M NaOH) and soaked in a waterbath for 6 h at 25°C. After the soaking, the wood-wool was removed and the leachate was filtered under vacuum through a 40 mm diameter sintered glass crucible (frit no. 3) to remove any sludge and solids such as wood fibre. Then 100 mL of the dark leachate was diluted with 150 mL of 0.01 M NaOH to produce a transparent brown liquid in which any insoluble precipitate, if formed, could be clearly seen. A small amount (1 mL) of solution containing the soluble compound was added to 7 mL of dilute alkali leachate in a glass vial to test its ability to form an insoluble precipitate with heartwood polyphenols in alkaline medium. The strength and colour of any precipitate and the time it took to form were noted. To illustrate the effect of complexes formed with heartwood polyphenols in the extract, 10 drops of selected compound solutions were added to larger quantities of dilute extract in 25 mL test-tube bottles (Plate 1).

## Results and Discussion

Several of the 137 compounds tested markedly strengthened the hydration of cement containing inhibitory *A. mangium* heartwood-wool. Around 50 of the compounds raised the average $T_{MAX}$ and hydration rate of cement containing wood-wool from 31°C and 0.5°C $h^{-1}$, respectively, to over 37°C and ≥1°C $h^{-1}$. The 20 compounds that resulted in the greatest increase in hydration rate for cement containing inhibitory wood-wool are listed in Table 1. Of these, nine compounds were chlorides, seven were nitrates and two were chromium salts. In a study by Zhengtian and Moslemi (1985), 30 compounds, mainly chlorides and sulphates, were tested for their effects on the hydration of Portland cement containing Western Larch (*Larix occidentalis*) heartwood flour. Western Larch is one of the least compatible wood species with cement (Sandermann and Kohler 1964; Hofstrand et al. 1984). The most effective compounds for ameliorating cement inhibition identified by Zhengtian and Moslemi (1985) were the chlorides $SnCl_2$, $FeCl_3$, $AlCl_3$ and $CaCl_2$. Our findings accord well with theirs, despite the fact that these workers used a softwood that does not contain tannin polyphenols. They did not test the effect of their additives on neat cement and therefore could not gauge the accelerating effect of each compound.

In our study, $CaCl_2$ performed well as an accelerator in the presence of inhibitory wood-wool of *A. mangium*, but it was not as effective as the chlorides of $Sn^{4+}$, $Al^{3+}$, $Fe^{3+}$, $Mg^{2+}$, $Ba^{2+}$, $Ni^{2+}$ and $Sr^{2+}$ (Table 1). Here $SnCl_4$, $AlCl_3$ and $FeCl_3$ were ranked 1st, 2nd and 4th respectively, whereas $CaCl_2$ was ranked 11th. $CaCl_2$, a by-product of sodium carbonate manufacture, has long been favoured as a cement setting accelerator due to its low cost, availability and predictability (Lea 1971; Taylor and Fuessle 1994; Taylor 1997). The anion–cation combination in $CaCl_2$ acts as an accelerator mainly on the tri-calcium silicate ($C_3S$) phase in Portland cement and is one of the most effective anion–cation combinations for use in neat cement (Ramachandran 1994). Our findings suggest that several other inorganic salts may be better suited than $CaCl_2$ for use in wood–cement composites. Other studies have also found alternative compounds to be more effective than $CaCl_2$ for ameliorating the inhibitory effects of certain woods used in the manufacture of wood–cement composites. For example, $AlCl_3$ was found to be the most effective chloride compared with $MgCl_2$, $FeCl_3$ and $CaCl_2$ for the manufacture of wood–cement composites from the inhibitory wood of *Shorea* spp. (Kayahara et al. 1979). Also, Soriano et al. (1997) found that $Al_2(SO_4)_3$ was a

**Table 1.** Top 20 compounds by hydration rate of wood-cement mix, with corresponding maximum hydration temperature and time

| Compound | Hydration rate (°C/h) | Max. temp. (°C) | Time (h) |
|---|---|---|---|
| $SnCl_4$ | 5.3 | 59.9 | 6.9 |
| $AlCl_3$ | 4.5 | 53.6 | 6.9 |
| $(NH_4)_2Ce(NO_3)_6$ | 4.3 | 55.5 | 5.2 |
| $FeCl_3$ | 3.6 | 51.5 | 8.1 |
| $ZrNO_3$ | 3.5 | 54.6 | 7.2 |
| $Al(NO_3)_3$ | 2.9 | 48.4 | 6.4 |
| $MgCl_2$ | 2.8 | 48.9 | 9.5 |
| $BaCl_2$ | 2.6 | 47.2 | 9.4 |
| $NiCl_2$ | 2.5 | 46.6 | 9.2 |
| $SrCl_2$ | 2.4 | 47.1 | 10.0 |
| $CaCl_2$ | 2.3 | 45.4 | 9.9 |
| $Al_2(SO_4)_3$ | 2.2 | 48.5 | 8.9 |
| $Fe(NO_3)_3$ | 2.3 | 47.3 | 8.9 |
| $PbCl_2$ | 2.1 | 46.0 | 22.9 |
| $Na_2CrO_7$ | 2.0 | 47.8 | 11.4 |
| $Ni(C_2H_3O_2)_2$ | 1.9 | 46.6 | 11.0 |
| $Co(NO_3)_2$ | 1.9 | 44.2 | 13.9 |
| $Ag(NO_3)_2$ | 1.9 | 47.4 | 11.6 |
| $Cr_2O_3$ | 1.8 | 45.7 | 11.4 |
| $Ba(NO_3)_2$ | 1.8 | 43.4 | 10.4 |
| Wood control | 0.5 | 31.0 | 18.5 |

more effective additive than $CaCl_2$ or waterglass (sodium silicate, $Na_2O.3SiO_2$) for manufacturing WWCB from *A. mangium* wood.

The effects of the presence of particular cations on the hydration of Portland cement are illustrated in Fig. 1. The addition of compounds containing $Al^{3+}$, $Ba^{2+}$, $Ca^{2+}$, $Cr^{3+}$, $K^+$, $Li^{2+}$, $Na^+$ and $Sr^{2+}$ generally had an accelerating effect on the hydration of neat cement. In the cases of $K^+$ and $Na^+$, this did not translate into any beneficial effect on the low hydration rate (0.5°C $h^{-1}$) of cement caused by the presence of inhibitory heartwood. The hydration rate of cement containing heartwood was doubled by the addition of compounds containing $Al^{3+}$, $Ba^{2+}$, $Ca^{2+}$, $Co^{2+}$, $Cr^{3+}$, $Fe^{3+}$, $Mg^{2+}$, $Li^+$, $Ni^{2+}$, $Pb^{2+}$ and $Sr^{2+}$, even though some of these (such as $Co^{2+}$ and $Ni^{2+}$) had relatively little effect on the hydration of neat cement. The presence of $Pb^{3+}$ greatly delayed cement setting. The addition of compounds containing $Cu^{+/2+}$, $Mn^{2+}$ and $Zn^{2+}$ retarded the hydration of neat cement and did not increase the hydration rate of cement containing *A. mangium* heartwood. Such heavy metal ions are thought to retard cement hydration reactions by forming a sheath of insoluble hydroxide and silicate complexes of metal–calcium in the alkaline cement paste, which blocks access to water by newly hydrating C–S–H grains (Taylor and Fuessle 1994; Yousof et al. 1995).

The general effectiveness of the chlorides, nitrates and acetates as groups in ameliorating the inhibitory effects of the wood is shown schematically in Fig. 2. There was high variation within these groups that was caused by the effects of the cations shown in Fig. 1. The compounds in the more effective groups, i.e. chlorides, nitrates and acetates, were all added as solutions. Compounds added mainly as insoluble powders, i.e. oxides, carbonates and fluorides, were not effective in increasing the hydration rate of cement containing wood; in fact the addition of most carbonates and fluorides adversely affected the hydration of Portland cement. Addition of the higher molecular-weight organic acids, citrate and tartrate, completely retarded cement setting (Fig. 2).

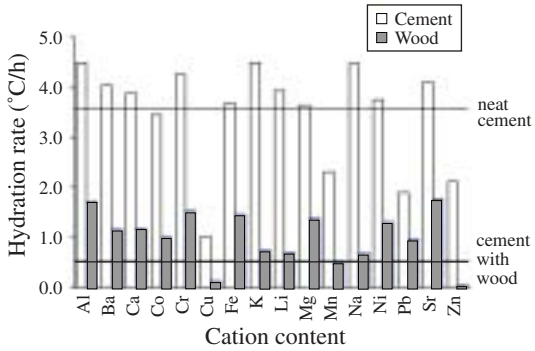


**Figure 1.** Average hydration rates of neat cement and cement containing *A. mangium* heartwood, for compounds grouped by cation content. Rates for neat cement and for cement containing wood-wool are indicated by lines.

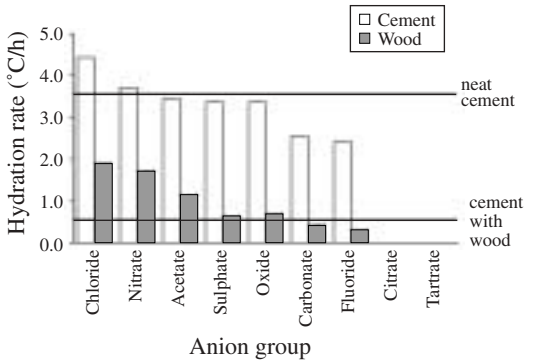


**Figure 2.** Average hydration rates of cement and cement containing *A. mangium* heartwood, for compounds grouped by anion content. Rates for neat cement and for cement containing wood-wool are indicated by lines.

The hydration rates produced by individual compounds are shown for neat cement (Fig. 3) and for cement containing heartwood of *A. mangium* (Fig. 4). These figures illustrate the variability among compounds, grouped by anion, caused by various cations. The cation component of the compound is indicated on the *x*-axis and its anion component is indicated in the legend. Again, the efficacy of chlorides and nitrates is apparent, but there were also significant interactive effects between cation and anion components. For example, chlorides of compatible cations such as $Al^{3+}$ and $Fe^{3+}$ produced highest hydration rates of all anion groups, whereas incompatible cations such as $Cu^{+/2+}$ and $Zn^{2+}$ were most inhibitory when

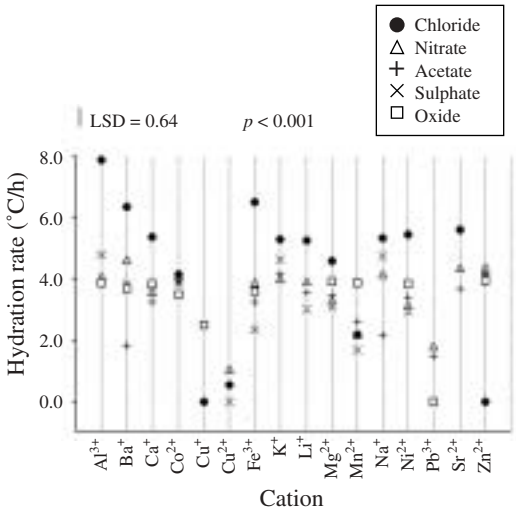


**Figure 3.** Hydration rates for individual compounds denoting cation and anion groups for samples containing cement only. Error bar indicates least significant difference.

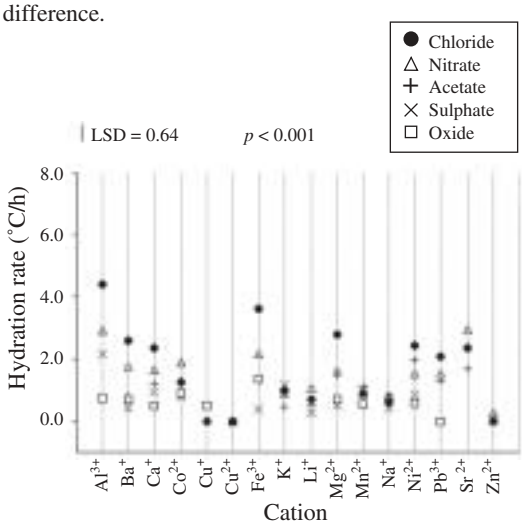


**Figure 4.** Hydration rates for individual compounds denoting cation and anion groups for samples containing *A. mangium* heartwood. Error bar indicates least significant difference.

added as chlorides. This effect can be most clearly seen in Fig. 3. Note the low variability in the effect of cations when added in the insoluble oxide form.

Figures 5 and 6 illustrate the distribution of effects of all compounds. Their effects on $T_{MAX}$

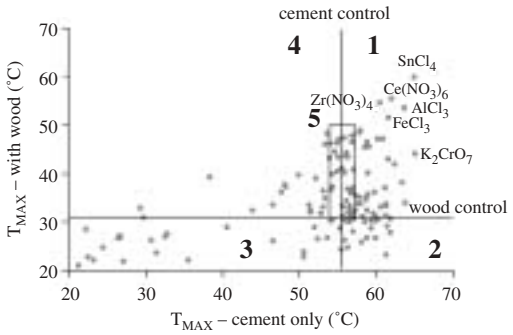


**Figure 5.** $T_{MAX}$ for cement containing compound only vs. $T_{MAX}$ for cement containing compound plus wood-wool, showing four quadrats. $T_{MAX}$ for neat cement (cement control) and for cement containing wood only (wood control) indicated by lines.

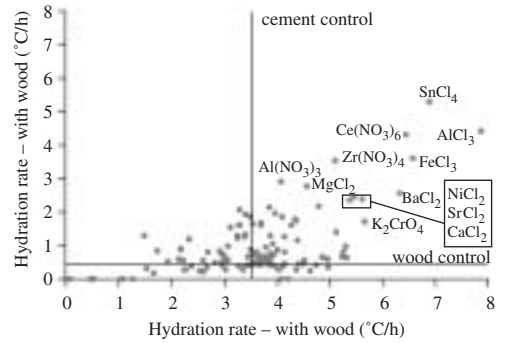


**Figure 6.** Hydration rate for cement containing compound only vs. hydration rate for cement containing compound plus wood-wool. Rate for neat cement (cement control) and for cement containing wood only (wood control) indicated by lines.

(Fig. 5) and hydration rate (Fig. 6) are graphed for neat cement + compound (*x*-axis) and the wood + cement + compound mix (*y*-axis). The results indicate that the most effective compounds for ameliorating the inhibitory effects of *A. mangium* heartwood were also those which produced the greatest increases in maximum hydration temperature and rate of hydration of neat cement.

Figures 5 and 6 suggest an interactive effect between the efficacy of certain compounds and the presence or absence of wood. Compounds in quadrat 1 (see Fig. 5) increased $T_{MAX}$ and hydration rate in both the neat cement and cement + wood samples. Almost all compounds that increased the rate of hydration in the wood–cement mix increased that of neat cement as well (Fig. 6). Compounds in quadrat 2 had their positive effects on the hydration of neat cement nullified by the presence of inhibitory *A. mangium* heartwood. Such compounds included NaCl, $Na_2SO_4$ and KBr: these are compounds that when added in small amounts accelerate cement hydration to some degree (Lea 1971) but whose action does not appear to be strong enough to counteract the inhibitory effects of the wood. Additives in quadrat 3 were clearly inhibitors of cement hydration, and comprised compounds containing $Cu^{+/2+}$, $Pb^{2+}$, $Co^{2+}$, $Zn^{2+}$ and $Mn^{2+}$ or citrates and tartrates. A fifth group of compounds (enclosed on Fig. 5) had little effect on maximum hydration temperature of cement on its own, but increased the temperature attained in cement containing heartwood. These included nitrates and acetates of $Al^{3+}$, $Ni^{2+}$, $Ag^{2+}$, $Fe^{3+}$ and $Co^{2+}$, compounds that also had no strong accelerating effect on the hydration rate of neat cement. An alternative mechanism to that of simply accelerating cement hydration reactions is needed to explain how such compounds can ameliorate the inhibitory effects of unextracted *A. mangium* heartwood on cement hydration. One possibility alluded to in the introduction is that the formation of insoluble organo-metallic complexes (chelates) between free cations and reactive sites on heartwood polyphenols may contribute significantly to neutralising their inhibitory effects, allowing cement hydration reactions to proceed.

## Organo-metallic complexes

Heartwood tannins have deleterious effects on cement hydration, as has been demonstrated experimentally by Sandermann and Brendel (1956) and Miller and Moslemi (1991). These studies indicate that the addition of more than about 0.2% will effectively inhibit cement hydration. However, certain cations in cement accelerators may be capable of neutralising their inhibitory effects on cement hydration reactions by chelating phenolic groups in the tannins, resulting in the formation of insoluble complexes.

Condensed tannins can be abundant in the heartwood and bark of acacias (Sherry 1971; Hillis 1987). Their molecules have *o*-dihydroxyphenyl groups which have excellent chelation affinity

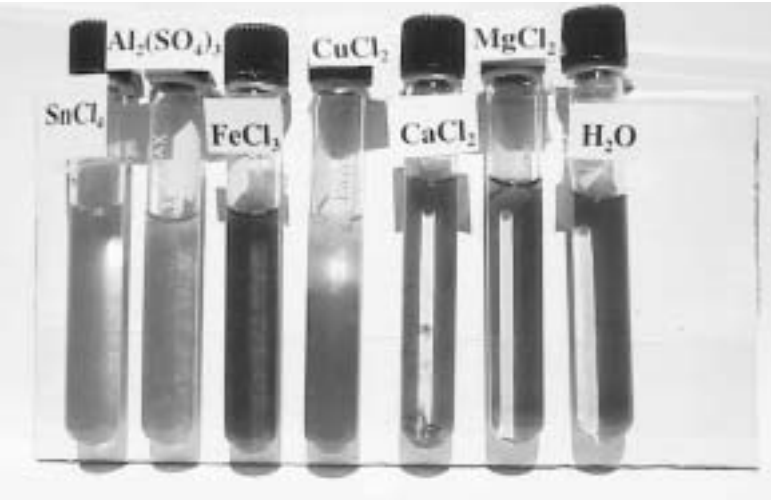


**Plate 1.** Effect of addition of accelerator compound solution to dilute alkali-soluble extract from *A. mangium* heartwood

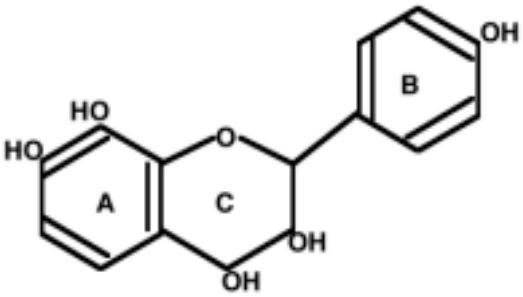


**Figure 7.** Schematic structure for teracacidin

$2FeIII + 1,2\text{-diphenol} \rightarrow 2FeII + \text{quinone} + 2H^+$

**Figure 8.** Schematic diagram of catechol bi-dentate chelation with ferric ($Fe^{3+}$) ion

with metal ions including $Cu^{2+}$ (Scalbert et al. 1998; Yamaguchi and Okuda 1998), $Fe^{3+}$ and $Al^{3+}$ (Yoneda and Nakatsubo 1998; Ni et al. 1999). In our study, soluble solutions containing the cations $Sn^{4+}$, $Al^{3+}$, $Fe^{3+}$ and $Ni^{2+}$ all formed insoluble complexes with the coloured polyphenols leached from *A. mangium* heartwood in alkaline solution as shown in Plate 1, leaving a light coloured solution behind. Solutions containing the inhibitory cations $Cu^{2+}$ and $Pb^{2+}$ also immediately produced heavy precipitates, whereas $Co^{2+}$ and $Mn^{2+}$ formed lighter precipitates. Note in Plate 1 the very small precipitate formed with $Ca^{2+}$ and no evidence of complex formation with $Mg^{2+}$.

A compound known as teracacidin (Clark-Lewis et al. 1961) shown in Fig. 7, was first isolated from the heartwood of *A. mangium* and shown to be highly inhibitory to cement hydration (Tachi et al. 1989). Teracacidin is one of four distinct types of heartwood polyphenols in the leucoanthocyanidin series that characterise different taxonomic groupings within the genus *Acacia* (Tindale and Roux 1969; Clark-Lewis and Porter 1972). These are flavan-3,4-diols which differ from each other in their phenolic hydroxylation patterns.

Teracacidin differs from other leucoanthocyanidins in that it contains only a 4'-monohydroxy B-ring, unlike mollicacidin and melacacidin which are characterised by a 3',4'-dihydroxylated B-ring. This dihydroxy configuration on the flavonoid B-ring of condensed tannins is a catechol unit and is the main group involved in metal chelation (Slabbert 1992). According to Slabbert (1992) and Yoneda and Nakatsubo (1998) it is the distinctive phenolic hydroxylation pattern of the B-ring that determines the metal chelating capacity of tannins, with 3',4',5'-tryhydroxylated B-rings having the highest affinity for metals followed by 3',4'-dihydroxy,

then 4'-monohydroxy B-rings with low chelating capacity. Chelate formation between catechol units and a transition metal such as $Fe^{3+}$ is shown in Fig. 8 (Powell and Taylor 1982; Kennedy and Powell 1985). The A-ring of the flavonoid is considered to be of little importance in tannin-metal chelating reactions (Slabbert 1992; Yoneda and Nakatsubo 1998). If this is correct, it would seem unlikely that teracacidin can be effectively chelated since it contains only 1 hydroxyl group (4') on the B-ring (Fig. 7). It is also known that acidic conditions are optimal for the formation of tannin–metal complexes (McDonald et al. 1996). Despite this, the extract from *A. mangium* in our study formed strong complexes in alkaline conditions. Teracacidin has been found to be accompanied by much larger quantities of apparently polymeric, intractable phenolic material (condensed tannins) in the heartwood of certain other acacia species such as *A. sparsiflora* (Clarke-Lewis and Dainis 1967), but no studies are available to confirm this to be the case in *A. mangium*. It is therefore unclear at this stage whether the teracacidin component in our *A. mangium* heartwood extract was being chelated by cations such as $Sn^{4+}$, $Al^{3+}$ or $Fe^{3+}$ or was similarly associated with larger quantities of other inhibitory tannins that were preferentially chelated. This question requires further investigation.

The formation of polyphenol–metallic complexes in or on the surface of wood-wool may render them less mobile and hence reduce their ability to diffuse out into the surrounding cement paste and inhibit cement hydration reactions. Chelated polyphenols, without free hydroxyl groups, may also be unable to chemically interfere with diffusion of $Ca^{2+}$ ions, Ca(OH) production and the hydration of calcium silicates in cement paste. Such actions may have contributed to the chlorides and nitrates of $Al^{3+}$ and $Fe^{3+}$ being significantly better than $CaCl_2$ at neutralising the effects of *A. mangium* heartwood on cement hydration. It was difficult to determine the relative contribution of chelation of inhibitory polyphenols to ameliorating incompatibility of the heartwood, considering the strong accelerating effect of these chlorides on the hydration of neat cement. However, as shown in Fig. 1, several compounds containing $Fe^{3+}$, $Co^{2+}$ and $Ni^{2+}$ had little effect on the hydration of neat cement, but their addition resulted in a two-fold increase in hydration rate of cement containing wood-wool. This provides some evidence that chelation and immobilisation of inhibitory heartwood polyphenols may play an important role in reducing their inhibitory effects. An additive mix that contains small amounts of both an accelerator agent (such as $CaCl_2$) and an accelerator or chelating agent (containing such ions as $Al^{3+}$, $Sn^{4+}$ or $Fe^{3+}$) may have considerable synergistic effects and potentially enable WWCB to be manufactured from *A. mangium* without the need for complete removal of extractives.

## Conclusion

A wide range of inorganic additives were screened for their effects on the hydration of Portland cement and their potential to ameliorate the low compatibility of *A. mangium* heartwood with cement. Many compounds were found to be more effective than $CaCl_2$, the most well known and widely used cement setting accelerator. These compounds were all soluble in cold water and comprised mainly chlorides and nitrates, including $SnCl_4$, $AlCl_3$, $(NH_4)_2Ce(NO_3)_6$ and $FeCl_3$. The most effective compounds produced a strong accelerating effect on the hydration of neat Portland cement. They also contained cations that formed insoluble chelates when the compound solution was added to alkali soluble *A. mangium* heartwood extract.

The latter effect may also contribute to ameliorating the effect of inhibitory *A. mangium* heartwood polyphenols on cement hydration. In support of this suggestion it was found that several compounds that did not strongly accelerate cement hydration partially neutralised the inhibitory effects of *A. mangium* heartwood on cement hydration, resulting in an increase in maximum hydration temperature attained in wood–cement mixes. These compounds often contained cations such as $Ni^{2+}$, $Ag^{2+}$, $Fe^{3+}$ and $Co^{2+}$ — transition metals that can, like $Al^{3+}$ and $Fe^{3+}$, form insoluble complexes or chelates with inhibitory acacia heartwood polyphenols. Additives that could not be added in soluble form, mainly oxides, carbonates and fluorides, were ineffective at ameliorating the inhibitory effects of heartwood on cement hydration. Compounds containing heavy metals

such as $Zn^{2+}$, $Pb^{3+}$, $Cu^{2+}$, $Mn^{2+}$, and organic acids such as citrate and tartrate strongly inhibited the hydration of Portland cement and were unsuitable as additives.

The results from this study suggest there may be merit in testing additives that combine a strong accelerating effect with the ability to form insoluble chelates with inhibitory heartwood tannins during the manufacture of WWCB from *A. mangium* wood. If such compounds are successful then they could provide a useful alternative to the current method of soaking wood-wool in water, which is used to ameliorate the inhibitory effect of *A. mangium* heartwood on cement hydration.

## Acknowledgements

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# Compatibility of Eight Temperate Australian *Eucalyptus* Species with Portland Cement

**Kate E. Semple[1], Ross B. Cunningham[2] and Philip D. Evans[1]**

*Abstract*

Wood samples of eight temperate *Eucalyptus* species grown at two sites in south-eastern Australia were tested for their compatibility with Portland cement to assess their suitability for the manufacture of cement-bonded composites. The species were chosen for their performance in growth trials and good potential for commercial establishment on farms. Species varied significantly in their compatibility with cement, with *E. badgensis* having the highest compatibility. The site at which trees were grown also significantly affected wood–cement compatibility, probably because trees at the two sites contained different amounts of sapwood. High sapwood content decreased average compatibility with cement. Soaking of wood in water at ambient temperature for 24 h was sufficient to remove much of the soluble extractive material responsible for inhibiting cement hydration. The wood–cement compatibility and use of other eucalypt wood species for cement-bonded composites are discussed.

THERE is substantial and increasing interest in growing trees on rural land in Australia, mainly to ameliorate environmental damage but also to increase farm incomes through the sale of wood and non-timber products (Vercoe and Clarke 1996). However, returns for timber grown on farms, particularly those located in drier regions of <600 mm annual rainfall, are often reduced by trees being small and of poor quality, and by difficult access to distant markets (Stewart and Hansen 1998). Small-diameter low quality wood is traditionally used for fuel and posts, but other possible options include wood-based composite panels.

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Cement-bonded panels are potentially a good processing option for such wood, because they can be easily manufactured using small localised facilities that need relatively little capital (Simatupang et al. 1977). Cement-bonded panels also have very good resistance to weathering, fire, decay (rot) and insects (Moslemi 1993) and make ideal modular components for low-cost agricultural buildings (Stillinger and Wentworth 1977).

The first step in assessing the suitability of wood species for use in cement-bonded composites is to test whether the wood significantly inhibits the hydration reactions of Portland cement (Sandermann and Kohler 1964). There are over 500 species of eucalypts (Boland et al. 1984) and few have ever been screened for their compatibility with Portland cement and suitability for the manufacture of wood–cement composites. This study measured the compatibility between Portland cement and eight temperate species of *Eucalyptus* that have good potential for farm planting in south-eastern Australia. It also

assessed the effects of sapwood content and extractive removal on wood–cement compatibility.

## Materials and Methods

### Sample collection

Eight tree species, *Eucalyptus globulus* ssp. *bicostata*, *E. smithii*, *E. nitens*, *E. viminalis*, *E. macarthurii*, *E. benthamii*, *E. badgensis* and *E. kartzoffiana*, were sampled at two sites, Kowen and Uriarra, near Canberra, Australia. These eight species were chosen because of their good survival and growth at these sites (Vercoe and Clarke 1996; Clarke et al. 1997) in controlled species elimination trials and growth performance trials. At each site, the species were represented in plots of 16 trees, with plots randomly distributed within three replicate blocks. One of the sampled trees is shown in Plate 1. Two trees were cut at random from each plot, resulting in a sample of six trees per species per site. Climatic and soil details for the two sites are given in Table 1. Trees were 15 years old at the time of cutting.

**Plate 1.** *Eucalyptus viminalis* growing at Kowen. Diameter at breast height over bark is 35 cm.

### Wood properties, aqueous extraction and hydration sample preparation

From each felled tree a disk 30 cm thick was cut at 1.3 m from ground level. On each disk, the under-bark diameter and heartwood diameter were measured at right angles and used to calculate circular sapwood/heartwood proportions. The disks were air dried under cover for about two months and then a wedge was cut from each disk, radiating from the centre of the disk and representing approximately one sixth of the disk area. The wedges were reduced to a series of smaller wedges measuring 15 mm x 15 mm at the wide end. They were sliced through the tangential plane into flakes 0.2–0.5 mm thick using a framers guillotine (Ramefabriken Jyden) as illustrated in Plate 2. Approximately 12 g of the resulting wood flakes were stored in a conditioning room maintained at 20 ± 1°C and 65 ± 5% RH for about two weeks. A 5 g sample of flakes was compiled from each tree for cement hydration testing. The remaining portion of flakes was placed in a 500 mL beaker to which 350 mL of distilled water at 23°C was added and stirred.

**Table 1.** Location, climate and soil types for field trial sites Kowen and Uriarra, ACT (Clarke et al. 1997).

| | Kowen | Uriarra |
|---|---|---|
| Latitude | 35°19'S | 35°17'S |
| Longitude | 149°19'E | 148°53'E |
| Altitude above sea level | 700 m | 680 m |
| Mean annual rainfall | 450–500 mm | 700+ mm |
| Mean minimum temperature* | –0.2°C | 0.12°C |
| Mean maximum temperature* | 26.5°C | 27.2°C |
| Soil type | Sedimentary shale | Red podzolic merging to silty clay |

* mean minimum and maximum temperatures during the coldest (July) and hottest (January) months respectively

**Plate 2.** Guillotine used to slice wood flakes with catcher bag attached

After 4 h the water was strained through a 0.5 mm sieve and a fresh 350 mL aliquot of distilled water was added to the beaker. This process was repeated after 18 and 24 h. After 24 h, the strained sample was washed with 350 mL of distilled water, dried at 30°C for 48 h and then reconditioned at 20 ± 1°C and 65 ± 5% RH for two weeks. Extraction took place in a controlled temperature room at 23 ± 1°C. After extraction, drying and conditioning of flakes a cement hydration test sample of 5 g was compiled for each tree.

### Measurement of wood–cement compatibility

To measure the compatibility of wood and cement, 100 g of cement Type I (ASTM Type A, Adelaide Brighton Batch No. 282MA99) was first mixed evenly with water at 20°C in a sealable polyethylene bag for 2 min. The amount of water used was fixed at 0.4 mL $g^{-1}$ of cement plus an extra 0.7 mL $g^{-1}$ for wood (oven-dry basis) in accordance with the recommendations of Hachmi et al. (1990). Cement control samples (containing no wood sample) contained 100 g of cement and 40 mL of water. The wood sample was evenly mixed into the cement slurry. Immediately after mixing, the bag was sealed and the tip of a temperature thermocouple (Type J) was taped to the outside of the sample bag and enclosed within the body of the wood–cement mix by folding the bag and contents around it and securing the folded bag with adhesive tape. The bag was then placed in a polystyrene cup and sealed inside a 1 L capacity thermos flask. This process was carried out for six samples.

**Plate 3.** Hydration temperature-logging apparatus in controlled climate room

A cement hydration temperature-logging apparatus similar to that used by Irle and Simpson (1993) was used to measure the heat of hydration of the six wood–cement samples over 23 h (see Plate 3). Temperatures were recorded at 15 min intervals and the curves were smoothed by plotting the progressive averages of every three successive readings. Maximum heat of hydration temperature ($T_{MAX}$) and time taken to reach $T_{MAX}$ ($t$) were recorded, and two wood–cement compatibility indices, $C_A$-factor (Hachmi et al. 1990), and hydration rate (R) = $(T_{MAX}–T_{MIN})/t$, were calculated. The $C_A$-factor is the ratio of the areas under the hydration curves of a wood–cement sample and the control (cement only), expressed as a percentage. The $T_{MIN}$ component of hydration rate is the minimum temperature attained during the first 5 h of hydration. All

experiments were done in a controlled temperature room at 20 ± 1°C.

The cement hydration testing experiment was undertaken over 20 test days, testing all permutations of trees and species in random order for Site 1 (Uriarra) followed by Site 2 (Kowen). Each daily run tested six hydration samples: two matching unsoaked and soaked samples for each of three random species or tree permutations.

Statistical analysis was based on a general linear mixed model with species and soaking as fixed effects, and random effects arising from sites, plots and trees. Variance components analysis was used to assess interactive effects of site and % sapwood on the compatibility of the species with cement. Significant results are presented graphically and an error bar (least significant difference, LSD) is included on each graph.

## Results and Discussion

The wood of all eight eucalypt species reduced the normal hydration rate of Portland cement to approximately half that of neat cement, and there were significant ($p = 0.004$) differences between species as shown in Fig. 1. *Eucalyptus badgensis* and *E. smithii* had the highest compatibility (R = 1.27°C $h^{-1}$ and 1.19°C $h^{-1}$, respectively) whereas *E. macarthurii* and *E. benthamii* had the lowest compatibility (R = 0.88°C $h^{-1}$ and 1.01°C $h^{-1}$, respectively).

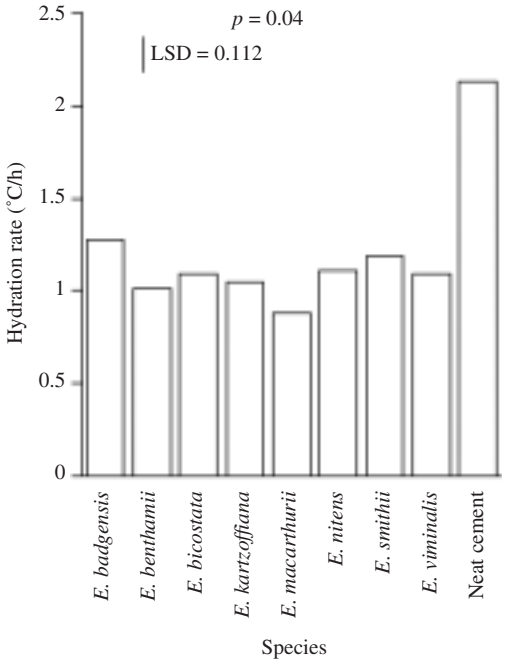


**Figure 1**. Hydration rate (°C $h^{-1}$) for unextracted wood by species

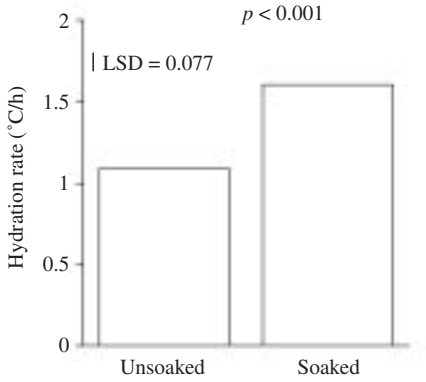


**Figure 2**. Effect of aqueous extraction (by soaking) on compatibility

These differing compatibilities could occur if there were variations in the content and/or composition of extractives between the different species. Eucalypt wood can contain polysaccharides and phenolic extractives in the sapwood and heartwood that inhibit the hydration of Portland cement (Yasin and Qureshi 1990; Yang et al. 1992).

The compatibility between wood and cement improved significantly ($p < 0.001$) when the wood samples were soaked at ambient temperature, probably because water removed many of the extraneous substances that inhibit cement hydration (Fig. 2). Hydration rate for cement containing wood flakes increased from an average of 1.1°C $h^{-1}$ for unextracted wood to 1.6°C $h^{-1}$ when extracted flakes were added.

Wood obtained from the drier site, Kowen, was significantly lower ($p < 0.001$) in average compatibility than wood from Uriarra (Fig. 3) and remained slightly lower after soaking. The trees grown at Kowen were smaller in diameter and contained a greater proportion of sapwood (60–70%), as shown in Fig. 4. Sapwood content was mostly below 50% for trees from Uriarra.

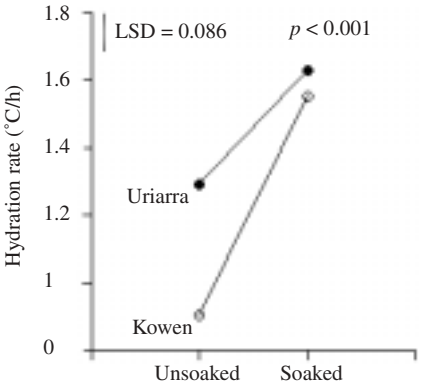


**Figure 3.** Effects of site and extraction on compatibility

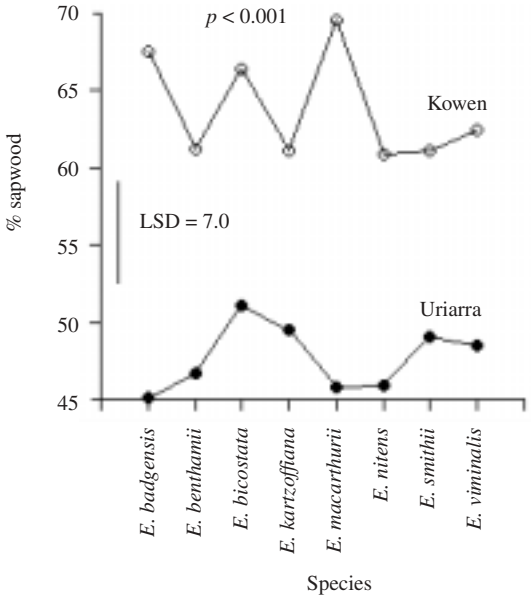


**Figure 4**. Average percentage sapwood content by species and site

Polysaccharides present in fresh sapwood strongly inhibit hydration processes in Portland cement (Biblis and Lo 1968; Fischer et al. 1974). Eucalypt wood also contains phenolic extractives and hemicelluloses that may be insoluble in cold water, and this might account for the slightly reduced compatibility of wood from Kowen even after soaking.

Information about the compatibility of eucalypts with cement is available for only a very limited range of species. There is even less information about the use of eucalypt wood in cement-bonded composites. Selected species of *Eucalyptus*, mainly sub-tropical and tropical species of importance in plantations overseas, have been tested for compatibility with Portland cement with varied results. The compatibility information has been mainly derived from hydration tests that use finely ground wood flour (e.g. Sandermann and Kohler 1964; Hofstrand et al. 1984; Iddi et al. 1992). However, this method does not adequately simulate the effects of larger wood flakes on cement hydration (Semple et al. 1999), and therefore it is difficult to compare the results of previous studies with ours. For *E. gomphocephala*, Hachmi and Moslemi (1989) reported that wood flour was of intermediate compatibility ($C_A$ = 54%). Mature wood from the important native Western Australian species *E. diversicolor* (karri) and *E. marginata* (jarrah) gave poor results in wood flour–cement hydration tests (Sandermann and Kohler 1964). In contrast, reports on the compatibility of *E. camaldulensis*, one of the most important commercial eucalypt species in the Asia–Pacific region, have been positive. This species has been recommended for use in the manufacture of wood-wool cement board (WWCB) on the basis of wood flour–cement compressive strength tests (Shukla et al. 1984) and hydration studies using wood flour (Jain et al. 1989). Wood flour of *E. camaldulensis* was also classed as compatible with cement ($C_A$ = 69%) by Hachmi and Moslemi (1989). For *E. saligna*, wood particles from 3- and 4-year-old plantation thinnings were found to have low to moderate compatibility with cement (Manzanares et al. 1991). Compatibility improved slightly for wood from older trees.

Studies on the use of eucalypt wood in cement-bonded wood composites have often found that the wood requires extraction and/or pre-treatment with chemical additives before it can be used to manufacture composites of acceptable quality. For *E. camaldulensis*, in contrast to the compatibility reports above, a study by Yasin and Qureshi (1990) found that cement-bonded particleboards (CBPs) could not be consolidated unless the *E. camaldulensis* wood particles had been pre-treated by either cold water or, preferably, hot water extraction. The extractives present in the wood of *E. citriodora* were also found to strongly

retard the setting of Portland cement (Yang et al. 1992). However, after pre-treatment of particles with hot water, or the addition of a cement setting accelerator ($CaCl_2$), CBPs could be manufactured from this species. Untreated wood of *E. deglupta* has generally been found to be unsuitable for the manufacture of WWCBs (Kamil and Gingoa 1975; Paribotro and Suwandi Kliwon 1977). However, when comparing *E. deglupta* wood from two different sites in Indonesia, Paribotro and Suwandi Kliwon (1977) found that WWCBs containing wood-wool from Lembang, a highland site on Java, had bending strengths averaging 20 kg $cm^{-2}$; the standard is 10 kg $cm^{-2}$. These results suggest that there can be considerable variation in the amounts and/or chemical composition of inhibitory extractives in trees of the same species when they originate from different seed-stocks or provenances, or are grown in different locations. This agrees with our results.

Difficulties in producing particles of correct size and geometry from eucalypt timber can confound otherwise good compatibility between wood and cement. Tachi et al. (1988) tested 9-year-old plantation-grown *E. deglupta* in CBPs using a wood:cement ratio of 1:2.5. The boards containing *E. deglupta* had only 70% of the bending strength of those made from other fast-growing tree species *Albizia falcataria* and *Gmelina arborea*, contradicting the good compatibility observed by the authors for wood of *E. deglupta* in standard cement hydration tests. During flaking, the wood of *E. deglupta* tended to split along the grain, forming thin, needle-like flakes. The lower bending strength in the boards containing *E. deglupta* flakes was therefore attributed to flake geometry rather than the chemical properties of the wood. Similarly, Semple et al. (2000) found that chipped wood residues from several mallee eucalypt species grown in Western Australia were as compatible with cement as particleboard flakes produced from radiata pine (*Pinus radiata*). However, CBPs made from these residues were of low bending strength (<5 MPa) compared to CBPs made from the radiata pine flakes. Therefore, studies of eucalypt species in the manufacture of cement-bonded composites should test flake or strand geometry as well as compatibility with cement.

## Conclusion

Wood from 15-year-old trees of eight species of temperate eucalypts was found to have moderate compatibility with Portland cement. Compatibility was significantly affected by species: *E. badgensis* and *E. smithii* had the highest compatibility. The proportion of sapwood was significantly higher in the smaller trees growing at Kowen, and these were significantly less compatible with cement, on average. The sapwood is therefore likely to have contained inhibitory water-soluble and/or alkali-soluble polysaccharides that adversely affected cement hydration reactions. The sapwood was much less deleterious to cement hydration after the water-soluble inhibitory extractive material had been removed by soaking at ambient temperature. Such a pre-treatment would be simple to execute and is recommended before cement-bonded composites are manufactured from these eucalypts. A wider range of temperate species of eucalypts and acacias is currently being screened for their compatibility with Portland cement.

## Acknowledgements

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# Cement-bonded Composites from Wood and Agricultural Residues

# The Use and Processing of Rice Straw in the Manufacture of Cement-bonded Fibreboard

**Elvira C. Fernandez[1] and Vanessa P. Taja-on[1]**

*Abstract*

The total land area planted to rice in the Philippines is 3 144 400 ha, and 1.5 t of rice straw is generated for every tonne of rice harvested. Rice straw can be used in the manufacture of products such as cement-bonded fibreboard, to help alleviate the problem of its disposal, but the processing conditions to optimise the properties of cement-bonded rice straw fibreboards have not been determined. In this study, rice straw was soaked in tap water for 48 h and defibrated in a refiner with an opening of 0.2–0.4 cm. Cement:rice-straw ratios of 60:40 and 50:50 were used. Calcium chloride, aluminium sulphate or sodium silicate were added to accelerate curing and hardening. The average fibre lengths of rice straw were 1.43 mm and 1.32 mm for the first and second disintegration processes, respectively, and average diameters were 0.017 mm and 0.151 mm, respectively. The average densities of the 60:40 and 50:50 boards were 1.67 g $cm^{-3}$ and 1.43 g $cm^{-3}$, respectively. The 60:40 boards with both calcium chloride and sodium silicate as chemical additives exhibited the lowest thickness swelling while the 50:50 boards with no chemical additive exhibited the highest thickness swelling. In general, 60:40 boards absorbed less water than 50:50 boards. The 60:40 board with sodium silicate and calcium chloride had the highest modulus of rupture and modulus of elasticity, while 50:50 boards with calcium chloride had the lowest. The capacity of boards to hold fasteners and nails was evaluated using a nail-head pull through test. Results showed that the 60:40 board with sodium silicate and calcium chloride had the highest nail-head pull through strength. The study clearly showed that rice straw could be used as feedstock for the manufacture of cement-bonded fibreboards. The physical and mechanical properties of cement-bonded fibreboards made from rice straw were comparable with those of other boards available in the market.

In the Philippines, the total land area planted to rice is 3 144 400 ha. For every tonne of palay (rice grains) harvested, 1.5 t of rice straw is generated and requires disposal. Currently farmers burn the rice straw, but this causes air pollution, loss of natural vegetation and low productivity of crops. It would be better if the waste could be converted into a high value product such as cement-bonded fibreboard. Cement-bonded fibreboard technology uses wood waste or agricultural residues for board manufacture, thereby conserving the limited supply of commercial wood species in the Philippines (Mallari et al. 1995).

Chemicals such as calcium chloride, sodium silicate and aluminium sulphate are added to accelerate the curing of cement. These chemical additives minimise the inhibiting effects of organic compounds in rice straw on cement hydration. The most effective additive is calcium

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chloride because it reduces the hydration time of wood–cement boards to just 3 h compared to around 9 h for boards containing no additive (Eusebio and Cabangon 1997a,b). However, according to recent studies, the presence of $CaCl_2$ does not guarantee good board properties (Eusebio and Cabangon 1997a,b). Factors such as board density, cement:rice-straw ratio and fibre quality also strongly influence board properties. It has also been found that not all agricultural residues can be used as the fibre reinforcing material for cement (Peñamora 1993). According to Lee et al. (1987), it is vital to develop appropriate pre-treatments that will increase the compatibility between the residues and cement. The strength of cement boards therefore depends on the raw materials, treatments and additives being combined in the mixture. In making cement-bonded fibreboard it is also important to know the optimum cement:rice-straw ratio.

This study was undertaken with the following objectives: 1) to determine the optimum cement-to-rice-straw ratio and chemical additives to produce rigid and functional fibreboards, and 2) to determine the physical and mechanical properties of cement boards manufactured from rice straw.

## Materials and Methods

### Materials

Rice straw (50 kg) was obtained from the International Rice Research Institute (IRRI) at UP Los Baños. Portland cement was used as binding agent. Technical grade calcium chloride, sodium silicate and aluminium sulphate were used as accelerators. The mixture was shaped in 15 mm × 300 mm × 300 mm moulds and was pressed using a cold press to form the boards and attain the desired thickness and density.

### Methods

*Board formation*

The processes involved in the manufacture of cement-bonded fibreboard from rice straw are shown in Fig. 1.

Rice straw was soaked in water for 48 h. It was then put into a refiner (Kumagai Rikki Kogyo Company Limited, SN 844907, RPM = 3017) with an opening of 0.4–0.2 cm and drained. Disintegrated rice straw was mixed with Portland cement and chemical additives, namely sodium silicate, calcium chloride and aluminium sulphate according to the ratio of cement:rice-straw, which was either 60:40 or 50:50 (Table 1).

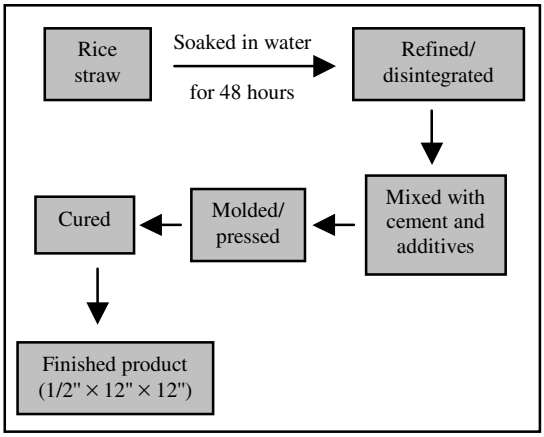


**Figure 1.** Cement-bonded fibreboard process flow diagram

**Table 1.** Materials used in each board formulation

| Materials | Weight (g) | |
|---|---|---|
| | 60:40 | 50:50 |
| **A** | | |
| Cement | 1750 | 1500 |
| Rice straw | 1250 | 1500 |
| Water (mL) | 950 | 850 |
| **B** | | |
| Cement | 1750 | 1500 |
| Rice straw | 1250 | 1500 |
| Calcium chloride (1%) | 27.5 | 15 |
| Water (mL) | 950 | 850 |
| **C** | | |
| Cement | 1750 | 1500 |
| Rice straw | 1250 | 1500 |
| Calcium chloride (1%) | 27.5 | 15 |
| Aluminium sulfate (1.8%) | 39.5 | 27 |
| Water (mL) | 950 | 850 |
| **D** | | |
| Cement | 1750 | 1500 |
| Rice straw | 1250 | 1500 |
| Calcium chloride (1%) | 27.5 | 15 |
| Sodium silicate (2%) | 55 | 30 |
| Water (mL) | 950 | 850 |

*Testing methods*

The physical and mechanical properties of the cement boards were examined and evaluated in accord with ASTM Japanese industrial standard JIS A 5404, 1979.

Samples of fibres from the refined rice straw were randomly collected and their lengths and diameters were determined using optical microscopy.

## Results and Discussion

It is important to know the dimensions of the rice straw fibres, particularly their length and diameter, because most of the board properties depend on them. In this study, after a second pass through the refiner the rice straw fibres had an average diameter of 0.0151 mm and an average length of 1.32 mm.

Fibre length is known to affect many strength properties of paper made from wood fibres. The same applies to rice straw. Rice straw has a long fibre and this coupled with its intrinsic strength distributes the external tension to surrounding matrix material and adjacent fibres. Much work is needed to pull out long fibres, with a consequent wide area of stress concentration, resulting in high tear strength (Hegborn 1990).

### Physical properties

*Board density*

The density of cement-bonded wood composite boards greatly affects their strength properties. At constant moisture content, the higher the density of the board, the greater its strength (Pulido 1993; Fernandez 1996). Table 2 presents the boards' weight, volume and density (i.e. weight/volume). The density of the 60:40 board containing calcium chloride and sodium silicate (1.723 g $cm^{-3}$) was highest, while the board 50:50 control had the lowest density, 1.277 g $cm^{-3}$.

*Thickness swelling*

The percentage thickness swelling for each board was measured after 24 h soaking in water (Table 3). The average thickness swelling of 60:40 boards was 3.93%, compared to 4.09% for 50:50 boards. The higher percentage of rice straw in 50:50 boards contributed to their higher per cent thickness swelling. For both ratios, boards containing calcium chloride and sodium silicates exhibited the lowest thickness swelling.

**Table 2.** The physical measurements of the boards

| Samples | Weight (g) | Volume ($cm^3$) | Density* (g $cm^{-3}$) |
|---|---|---|---|
| **50:50** | | | |
| A | 51.08 | 40 | 1.277 |
| B | 52.98 | 35 | 1.548 |
| C | 58.15 | 45 | 1.292 |
| D | 80.67 | 50 | 1.614 |
| **60:40** | | | |
| A | 79.50 | 50 | 1.590 |
| B | 89.55 | 55 | 1.626 |
| C | 60.52 | 40 | 1.513 |
| D | 86.13 | 50 | 1.723 |

* Average of two samples

**Table 3.** Thickness swelling and water absorption for each board after 24 h soaking in water

| Samples | Thickness swelling (%) | Water absorption (%) |
|---|---|---|
| **50:50** | | |
| A | 5.28 | 42.04 |
| B | 4.95 | 42.48 |
| C | 5.02 | 35.39 |
| D | 1.11 | 39.11 |
| average | **4.09** | |
| **60:40** | | |
| A | 4.38 | 35.72 |
| B | 2.9 | 24.61 |
| C | 5.58 | 37.54 |
| D | 2.84 | 24.81 |
| average | **3.93** | |

*Water absorption*

The test for water absorption determined the amount of water each board absorbed when immersed in water for 24 h at room temperature. The per cent water absorption for each board is shown in Table 3. The data show that boards with cement:rice-straw ratio 60:40 generally had lower per cent water absorption than the 50:50

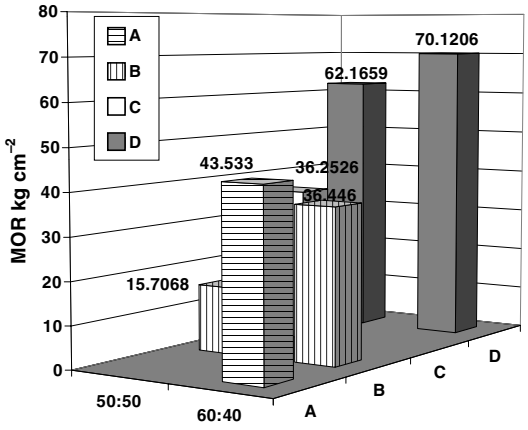


**Figure 2.** Modulus of rupture (kg cm$^{-2}$) for each board

boards. High cement content makes the cement crystals grow and develop from the cement particles during the hydration process so that they push themselves against the fibre surfaces and penetrate into the available void spaces for anchorage. Therefore, the greater the amount of cement present, the stronger the interlocking between the cement crystals and fibres, resulting in a strong fibre–cement composite product.

## Mechanical properties

### *Modulus of rupture*

The mechanical properties of any construction material describe its capacity to resist the application of load. The modulus of rupture (MOR) is a property that is used to approximate the bending strength of various construction materials including cement-bonded boards. The test involves measuring the maximum load that can be sustained by the material before it ruptures.

Figure 2 summarises the MOR values for the different boards, and shows that, on average, 60:40 boards were stronger than 50:50 boards. The 60:40 boards with sodium silicate and calcium chloride as additives had the highest MOR values while boards containing calcium chloride had the lowest.

The MOR of cement-bonded board manufactured with rice straw as the reinforcing material was comparable to the MOR of boards specified in different standards and with wood-wool cement boards (WWCB) manufactured in the Philippines (FPRDI, compare Fig. 2 with values in Table 4) (Pablo 1988).

### *Modulus of elasticity*

Modulus of elasticity (MOE) is another parameter obtained when testing the mechanical properties of boards. The testing procedure is the same as for MOR except that the loads taken into account are those occurring at the proportional limit. On average, the 60:40 boards with calcium chloride and sodium silicate (D) had the highest MOE. Both 50:50 and 60:40 boards with calcium chloride had the lowest MOE.

### *Nail-head pull through*

Another factor to be considered when evaluating the suitability of a panel product for building construction is its ability to hold nails, especially when they are subjected to load. A nail-head pull through test is commonly used to assess this

**Table 4.** Strength values (modulus of rupture (MOR), kg cm$^{-2}$) of FPRDI wood-wool cement board (WWCB) standard values (Pablo 1988)

| Thickness (mm) | DIN 1101 1981 | JIS 1504 | JIS 5417 | FPRDI WWCB | Remarks |
|---|---|---|---|---|---|
| 12 | — | — | — | 33.3 | passed |
| 15 | 17 | 20.4 | 11.6 | 30.2 | passed |
| 25 | 10 | 19.2 | 10.5 | — | passed |
| 30 | 9 | 16.7 | 10.0 | 29.1 | passed |
| 35 | 7 | 16.8 | 8.1 | 28.6 | passed |
| 40 | 6 | 16.9 | 6.2 | 26.4 | passed |
| 50 | 5 | 15.0 | 5.0 | 23.2 | passed |
| 75 | 4 | 12.6 | 7.8 | 18.9 | passed |
| 100 | 4 | 10.1 | 7.0 | 15.6 | passed |

**Table 5.** Nail-head pull through test (kg) for each board

| Samples | I | II | Mean |
|---|---|---|---|
| **50:50** | | | |
| A | 2.5 | 3 | 2.75 |
| B | 2.5 | 1 | 1.75 |
| C | 10.0 | 12 | 11.00 |
| D | 23.3 | 27 | 25.00 |
| **60:40** | | | |
| A | 9.5 | 7 | 8.50 |
| B | 10.0 | 8 | 9.00 |
| C | 1.5 | 0.5 | 1.00 |
| D | | | |

property. In this test, 2-inch (5 cm) common nails were nailed into sample boards measuring 5 cm × 10 cm. The specimens did not break when nailed except for boards manufactured with a 60:40 ratio using formulation D which had to be pre-bored to avoid fracture. Table 5 summarises the load that a particular sample could hold before breaking. Results show that 50:50 boards with sodium silicate and calcium chloride had the highest capacity to resist breakage.

## Conclusion and Recommendations

Cement-bonded boards have proved to be durable and to have low production cost. The use of agricultural waste such as rice straw for the manufacture of such boards not only reduces the production cost of the board but also helps farmers with their problem of disposing of solid wastes, and eventually helps promote a clean environment.

This study has shown that cement board manufactured with rice straw as the reinforcing material has mechanical and physical properties comparable to those of other cement-bonded composites. Its lignocellulosic constituents appear to adhere well to hydrated cement judging from the mechanical properties of the boards.

Based on the analysis of the physical properties of the boards, both 60:40 and 50:50 boards generally gave satisfactory results. However, the 60:40 board was more stable because it had lower percent thickness swelling and water absorption than the 50:50 board.

A series of tests of the mechanical properties of the boards found that boards with a cement:rice-straw ratio of 60:40 were stronger than boards with a ratio of 50:50. This finding accords with previous studies that have shown that increasing cement:wood ratio has a beneficial effect on the mechanical properties of agric-based cement composites (Tuico 1994; Mallari et al. 1995). The chemical additives in formulation D conferred better strength to the boards than the chemical additives used in other formulations. There was a positive correlation between board density and mechanical properties.

Further studies should examine the effect of other variables that may influence board properties; for example, the concentration of chemical additives, soaking pre-treatments and moisture content of the fibres. Further research is needed to study the effect of rice straw on the hydration of cement. Better manufacturing techniques and board properties could stimulate the wood composite industry to adopt the production of cement-bonded fibreboard from rice straw.

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# Fibre-cement Composites from Brazilian Agricultural and Industrial Waste Materials

**P.E.G. Warden[1], H. Savastano Jr[2] and R.S.P. Coutts[3]**

*Abstract*

Fibre-cement composites in which either the reinforcement or the matrix or both were derived from Brazilian waste materials were produced using a slurry vacuum de-watering technique followed by air-curing. Ground iron blast furnace slag (BFS), activated by mixtures of gypsum and lime, was examined as a lower-cost alternative to ordinary Portland cement (OPC) as a matrix material. The BFS-based composites reinforced with chemically pulped *Pinus radiata* fibre were generally weaker and less stiff than corresponding OPC-based materials, but possessed comparable toughness. Permeable void volume and hence water absorption values were greater than those of the OPC-based composites, with water absorption exceeding 30% w/w at a fibre content of 12% w/w. Reject *Eucalyptus grandis* fibre from a kraft pulp mill and laboratory prepared chemi-thermomechanical pulps of sisal and banana crop residues were tested as reinforcements in the BFS matrix. Optimum strength and toughness values were obtained at fibre contents in the range 8% to 12% by mass. At these fibre levels, strengths of approximately 18 MPa and toughness values in the range 0.51–1.25 kJ $m^{-2}$ were obtained. The performance of the waste-derived materials may be acceptable for their use in applications such as low-cost housing construction.

Fibre-cement composites are widely used in building construction throughout the world. Although wood-fibre reinforced cement composites produced using the Hatschek (or wet) process are well known and accepted in most developed countries, almost 70% of global fibre–cement composite production is based on asbestos reinforcement. In developing regions such as South America and parts of Asia, asbestos–cement composites can represent up to 95% of consumption (Anon. 2000). Rapidly increasing urbanisation has produced acute and worsening housing shortages in these regions, prompting efforts to find cheaper alternatives to established asbestos and wood-fibre-reinforced cement products.

There are significant opportunities in tropical countries to use fibres obtained from abundant agricultural residues (e.g. cordage and fruit) or pulp mill wastes as reinforcement in bio-based composites. Research in Brazil has examined the use of fibrous strands from sisal and coir as reinforcement for cement. The length and stiffness of the fibre strands, however, leads to difficulties in mixing and compaction that restricts the level of reinforcement. Moreover, lignin and hemicelluloses in plant fibres may be readily dissolved in the highly alkaline environment of ordinary Portland cement (OPC), leading

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to eventual degradation of the reinforcement and embrittlement of the composite. The relatively poor mechanical performance and uncertain durability of strand-reinforced cement composites has led to them being largely ignored by industry. As a consequence, annual production of asbestos–cement composites in Brazil has remained in the order of 2 million tonnes, mainly in the form of corrugated roofing elements. A recent commitment by the Brazilian Government to ban chrysotile asbestos, similar to the ban to be imposed by the European Union, has added impetus to the search for alternative reinforcing materials (see also Coutts, these Proceedings).

A collaborative study undertaken by CSIRO Forestry and Forest Products in Australia and the University of São Paulo, Brazil, investigated the suitability of several Brazilian waste materials for use in the production of fibre–cements by the Hatschek process with an emphasis on the development of materials for low-cost housing. Ground iron blast furnace slag (BFS), available in large quantities as a by-product of Brazil's steel industry, was examined as a low-cost alternative binder to OPC. Potential fibre resources were subjected to a range of chemical and mechanical pulping processes and the resulting pulps were examined as reinforcement in matrices based on both OPC and BFS. This paper presents an overview of the performances of gypsum- and lime-activated BFS as a matrix material, and waste *Eucalyptus grandis* kraft pulp and chemi-thermomechanical pulps (CTMPs) of sisal and banana pseudo-stem fibre as reinforcing media.

## Materials and Methods

### Materials

Companhia Siderúrgica Tubarão (CST), Brazil, provided alkaline granulated iron blast furnace slag with the composition shown in Table 1. The BFS was ground to an average Blaine fineness of 500 $m^2 kg^{-1}$ and stored in sealed plastic bags prior to use. Chemical or thermal activation, either alone or in combination, is required to promote acceptable hydration rates in BFS (Richardson et al. 1989). This study used chemical activation with mixtures of gypsum and lime, as proposed by John et al. (1990). Five combinations of natural gypsum (6–10% of matrix mass) and hydrated lime (2–8% of matrix mass) were examined. The choice of combinations was based on proportions previously shown to produce acceptable activation in similar slag cements (John et al. 1990; Oliveira et al. 1999). The various activated BFS matrix formulations are hereafter referred to in shorthand form as BFS *x*G*y*L, where *x* and *y* are the respective percentages of total matrix mass that the gypsum and lime additions represent. The costs of preparing the various BFS-based matrix formulations in Brazil were estimated to range from US$25 to US$28 $t^{-1}$ in 1999, at which time the cost of OPC was approximately US$87 (Savastano Jr et al. 2001).

**Table 1.** Chemical composition of granulated blast furnace slag (BFS) (% by mass) (Oliveira et al. 1999)

| | | | |
|---|---|---|---|
| Loss on ignition | 1.67 | $SO_3$ | 0.15 |
| $SiO_2$ | 33.78 | $Na_2O$ | 0.16 |
| $Al_2O_3$ | 13.11 | $K_2O$ | 0.32 |
| $Fe_2O_3$ | 0.51 | $S^{2-}$ | 1.14 |
| CaO | 42.47 | Free CaO | 0.1 |
| MgO | 7.46 | Insoluble residue | 0.53 |

Sisal (*Agave sisalana*) field by-product was provided by the Associação dos Pequenos Agricultores do Município de Valente (Apaeb), Bahia state; banana (*Musa cavendishii*) pseudo-stem strand fibre was provided by Magãrio Plantations – Registro, São Paulo state, Brazil. Waste *E. grandis* fibre, diverted from the cooking and bleaching stage effluents of a kraft pulp mill, was provided by Aracruz Celulose, Espírito Santo, Brazil. All three fibrous residues are produced in large quantities and are currently of little or no commercial value.

Adelaide Brighton brand ordinary Portland cement (Australian Standard AS 3972 1991, Type GP) and commercial New Zealand *Pinus radiata* kraft lap pulp were used as reference matrix and reinforcing materials, respectively.

### Pulp preparation

Sisal and banana pseudo-stem strand fibres were cut to approximately 30 mm lengths and soaked in water overnight before being subjected to chemi-thermomechanical pulping. The chemical pre-treatment step of the CTMP process consisted of boiling the strands in a 10% lime (on strand

**Table 2.** Pulp and fibre physical properties

| Fibre | Freeness (mL) | Fines (%)[a] | Length (mm)[b] | Width (μm) | Aspect ratio |
|---|---|---|---|---|---|
| Sisal | 280 | 5.61 | 1.61 | 10.9 | 148 |
| Banana | 630 | 2.70 | 1.99 | 20.1 | 99 |
| *E. grandis* waste | 685 | 7.01 | 0.66 | 10.9 | 61 |
| *P. radiata* | 650 | 10.4 | 1.71 | 32.4 | 53 |

[a] fines content, arithmetic basis; [b] length-weighted

mass) liquor, at a liquor:strand ratio of 34:1, for a period of 1 h. Defibration was performed using an Asplund type D laboratory defibrator using conditions in accord with those noted by Higgins et al. (1978) as generating a good degree of fibrillation in softwood fibres. Pre-steaming, for 120 s, and subsequent defibration, for 90 s, of each batch of strands were carried out in saturated steam at 121ºC. The pulps were post-refined by being passed several times through a 20 cm Bauer laboratory disc refiner fitted with straight-patterned 'rubbing' plates, final passes being made at a plate gap of 0.076 mm. The refined pulps were passed through a 0.23 mm slotted Packer screen to remove shives. A Sommerville screen (0.18 mm) was subsequently used to reduce the large quantity of apparent fines in the banana CTMP. The pulps were vacuum de-watered, pressed, crumbed and stored in sealed bags under refrigeration until used.

The waste *E. grandis* kraft pulp was disintegrated in hot water (90ºC), but otherwise was used 'as received'. The *P. radiata* reference pulp was prepared by refining disintegrated lap to a Canadian Standard Freeness (CSF) of 650 mL. Selected properties of the prepared pulps and fibres are given in Table 2.

## Composite preparation

Fibre–cement composites with fibre mass fractions of 4%, 8% and 12% were prepared in the laboratory using a slurry vacuum de-watering technique loosely modelled on the Hatschek process. Neat matrices were produced as controls using the same procedure. In the case of formulations incorporating 8% and 12% of fibre, matrix materials were added to the appropriate amount of moist fibres, pre-dispersed in water, to form a slurry of approximately 20% (by mass) solids. For formulations with 0% and 4% fibre content, slurries of about 65% and 30% solids respectively were employed to minimise material segregation during de-watering. After the slurry had been stirred for 5 min it was rapidly transferred to an evacuable 125 mm × 125 mm casting box. An initial vacuum of between 60 kPa and 80 kPa (gauge) was applied until the bulk of the excess water had been removed and a solid surface had formed. The moist pad was tamped flat and vacuum was reapplied for 2 min. The consolidated pad was then removed from the casting box and transferred to an oiled steel plate, and a fine wire mesh was placed on top. Three pads per composite formulation were prepared in this manner, stacked on top of each other and pressed simultaneously at 3.2 MPa for 5 min. On completion of press consolidation, the plates and meshes were removed and the pads were sealed in a plastic bag to cure in saturated air at room temperature. After 7 days the pads were removed from the bags and three 125 mm × 40 mm flexural test specimens were wet-diamond-sawn from each pad. Test specimen depth was the thickness of the pad, which was in the region of 6 mm. The samples were then allowed to air cure in an environment of 23 ± 2°C and 50 ± 5% relative humidity to a total age of 28 days at which time mechanical tests were conducted in the same environment.

## Test methods

Nine flexural specimens were tested for each composite formulation. A three-point bending configuration was used in the determination of modulus of rupture (MOR), flexural modulus of elasticity (MOE) and fracture toughness (FT). A span of 100 mm, corresponding to a span-to-depth ratio of approximately 16, and a deflection rate of 0.5 mm $min^{-1}$ were used for all tests which were carried out using an Instron model 1185

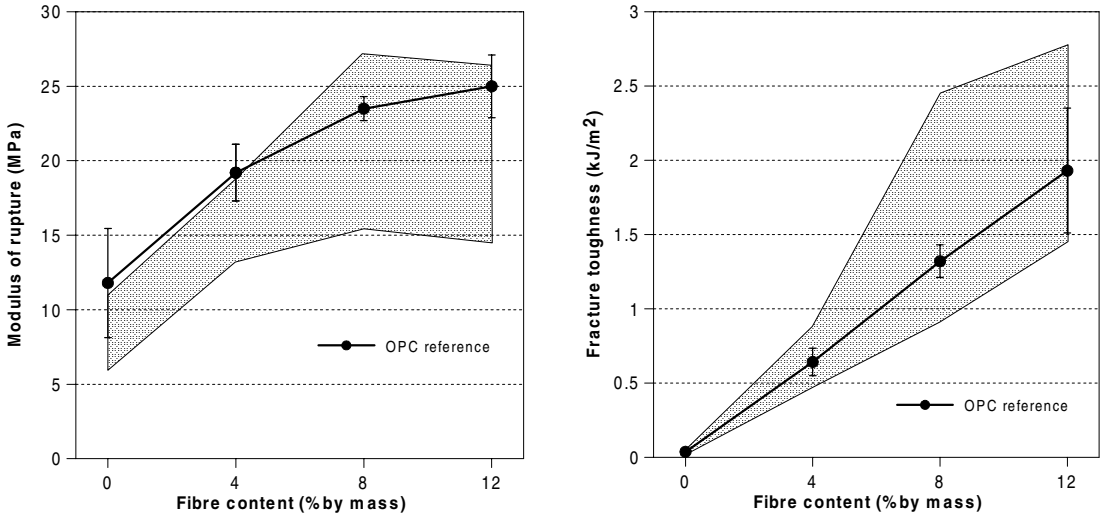


**Figure 1.** Variation in (a) MOR and (b) fracture toughness with matrix formulation and content of *P. radiata* fibre. The vertical spread of the enclosed/shaded areas represents the range of means and standard deviations observed. Error bars indicate single standard deviations of the reference material means.

universal testing machine. The FT was defined as the fracture energy divided by the specimen cross-sectional area. Fracture energy was calculated by integration of the load-deflection curve to the point corresponding to a reduction in load-carrying capacity to 50% of the maximum observed. Water absorption, bulk density and void volume values were obtained from tested flexural specimens following the procedures specified in ASTM C 948-8 (2000). Six specimens were used in the determination of each of these physical properties.

Property data were subjected to one-way analysis of variance using Tukey's multiple comparison method to determine the significance of differences in sample means at the 95% confidence level ($P = 0.05$).

## Results and Discussion

### Blast furnace slag as a matrix material

The processing behaviour of BFS-based matrices during the production of slurry de-watered composite was similar to that of OPC. The strength and toughness properties of the BFS-based matrices were enhanced like those of OPC when reinforced with the *P. radiata* fibre (Fig. 1). The addition of 4% and 8% fibre provided significant incremental improvements in flexural strengths which were doubled at the higher loading (Fig. 1a). The best performance of BFS-based composites in terms of flexural strength was achieved with the BFS 10G4L matrix formulation and *P. radiata* fibre loadings of 8% and 12%. These materials possessed strengths of approximately 24 MPa, similar to those of the corresponding OPC reference composites. At the same fibre loadings, composites based on BFS 6G2L exhibited relatively low strengths, in the region of 16.5 MPa. The poor performance of composites based on this formulation was probably a result of the lower total activator content failing to promote sufficient matrix strength development to allow effective stress transfer to the reinforcement. The remaining binder formulations, all with total activator contents between 12% and 14%, provided intermediate MOR values which in most instances were not significantly lower than those of the BFS 10G4L or OPC-based composites. The strengths of the various BFS-based materials with lower levels of fibre reinforcement were similar to and lower than those of the corresponding OPC reference materials.

As has been previously observed in the case of wood-fibre-reinforced OPC (Coutts 1983, 1988), fracture toughness was the property most

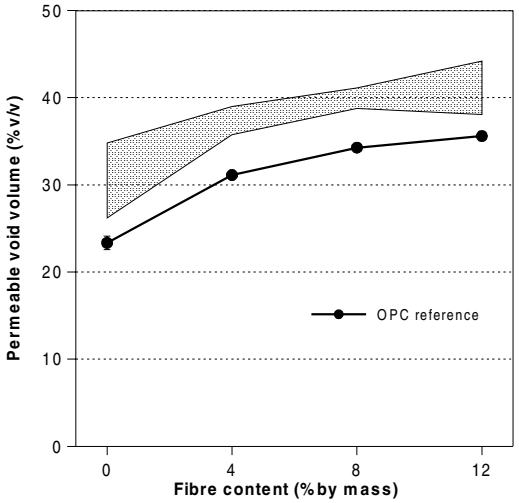


**Figure 2.** Variation in permeable void volume with matrix formulation and content of *P. radiata* fibre

enhanced by reinforcement. At a *P. radiata* fibre content of 12%, toughness values ranged from 1.72 to 2.36 kJ $m^{-2}$, representing at least 40-fold improvements in corresponding neat matrix values (Fig. 1b). The BFS 6G2L-based composites had the greatest toughness at 8% and 12% fibre contents, with values significantly exceeding those of the reference composites. It is thought that the lowered strength of the matrix relative to the strength of the fibre–matrix bond may have helped dissipate energy by permitting microcracking in the vicinity of fibre surfaces. Values for fracture toughness among the remaining BFS-based formulations were similar to each other and similar to the fracture toughness values of the OPC reference composites at each fibre content.

Although the results for elastic moduli are not shown here, it was found that elastic moduli of the BFS composites fell with increasing fibre content, in accord with previous observations for OPC-based materials (e.g. Coutts 1983, 1988). Elastic moduli were in the range 4.3–6.2 GPa at a fibre content of 12% and were consistently lower than the elastic moduli of the corresponding reference composites — a drawback to their use in practical applications.

The BFS-based materials possessed significantly higher void volumes (Fig. 2) and hence higher water absorption and lower density values than the OPC-based reference materials at each fibre loading. At fibre contents of 8% and 12%, the water absorption values of BFS-based materials were approximately 28% and 32% by mass, respectively, whereas those of the reference composites were considerably lower at approximately 22% and 24%, respectively. The higher water absorption values, especially in conjunction with relatively low elastic moduli, would represent a significant disadvantage to the use of these materials in applications such as roofing elements.

A more detailed discussion of the properties of matrices and composites based on gypsum- and lime-activated BFS, and the influence of activator proportions, is provided in Savastano Jr et al. (2001). Mixtures of gypsum and lime were added to BFS because of their low cost cost, abundance and reported effectiveness as activators for BFS matrices (John et al. 1990; Oliveira et al. 1999). A number of previous studies employing different activators have reportedly found BFS-based mortars and concretes to have lower permeable void volumes than OPC-based equivalents (Wang et al. 1995; Bijen 1996). Alternative means of activation, and the effects of variations in production parameters such as compaction pressure (Coutts and Warden 1990) and curing environment (Swamy 1997), warrant investigation in an effort to reduce the permeable void volumes of BFS-based fibre-cements thereby increasing their attractiveness as building materials. Composites based on a BFS 10G2L matrix formulation appeared to display the best balance of properties and this matrix was chosen for reinforcement with the waste-derived fibres.

## Waste fibres as reinforcement

Kraft pulps of softwoods such as *P. radiata* are the preferred reinforcement in commercial fibre-cement composites produced using the Hatschek process. The chemical pulping process substantially reduces the amount of lignin and extractives in the fibres. This is important for the use of the fibres in autoclaved products, since these materials can disrupt matrix cure under autoclave conditions. The long, low-lignin content fibres are also readily refined to increase their compliance, which aids compaction, and they also fibrillate which assists in web formation.

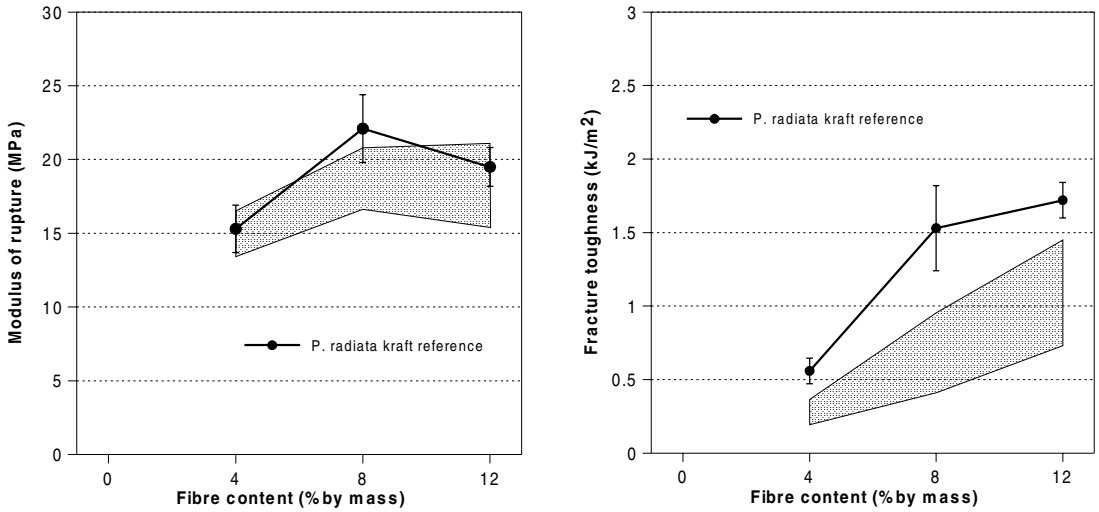


**Figure 3.** Variation in (a) MOR and (b) fracture toughness with fibre type and content

However, chemical pulps are expensive and mills are capital intensive. Mechanical pulps, in which most of the original lignin is retained, can provide adequate reinforcement in air-cured wood fibre–cement products (Coutts 1986). These pulps are cheaper to produce and mills can be operated viably at lower outputs and with fewer effluent problems.

The range of strength and fracture toughness values exhibited by BFS 10G2L-based composites, reinforced with chemi-thermomechanical pulps of sisal and banana and waste *E. grandis* kraft pulp, are shown in Fig. 3. As fibre content increased, trends in the measured mechanical and physical properties followed patterns similar to those described above for *P. radiata*-reinforced BFS and OPC-based composites. The mean strengths of composites reinforced with the waste-derived fibres did not differ significantly between fibre contents in the range 4–12%, and tended to converge as the fibre level increased. Mean strengths at the higher fibre contents lay in the region of 18 MPa. This figure compares favourably with strengths obtained for air-cured OPC reinforced with *P. radiata* CTMP (Coutts 1986) and kraft pulped banana fibre (Zhu et al. 1994; Savastano Jr et al. 2000). The kraft *P. radiata* reference fibre conferred greater strength than the waste fibres at a loading of 8%, although not at loadings of 4% and 12% (Fig. 3a).

Fracture toughness values were significantly lower than those of the reference composites. Values exhibited by composites incorporating sisal CTMP and waste *E. grandis* kraft fibre were similar, reaching 1.25 kJ $m^{-2}$ at a fibre content of 12%. The longer and well-fibrillated banana CTMP fibres produced inferior toughness values, possibly as a consequence of increased fibre-matrix bonding leading to a higher incidence of fibre fracture.

Moduli of elasticity and the physical properties of composites containing the three types of waste fibre were similar at the higher fibre loadings. At 4% fibre content the *E. grandis* reinforced material was denser and stiffer, probably due to the smaller fibre dimensions that allowed better consolidation at this loading. Greater fibre compliance might also be expected as a result of the removal of lignin during chemical pulping. This is also thought to be the reason for slightly lower void volumes for the reference composites.

The properties of the composites manufactured here are superior to those in a previous study (Savastano Jr et al. 1998) in which a dough-mixing process was used to prepare the composites. In the earlier study MOR values of less than 5 MPa were reported for BFS 10G2L-based mortars reinforced with waste *E. grandis* pulp whereas strengths for comparable composites here averaged approximately 18 MPa.

## Conclusions

Ground iron blast furnace slag was found to be suitable for use as a matrix material in the production of fibre–cement composites by a slurry vacuum de-watering method. Composites had strength and toughness values comparable to those achieved with OPC. Increased permeable void volume gave rise to water absorption values that significantly exceeded those of corresponding OPC-based materials when mixtures of gypsum and lime were employed as activators. However, the overall properties of air-cured wood fibre–cements based on gypsum- and lime-activated BFS appear sufficient for their use in low-cost housing applications, particularly when lower projected material costs are taken into consideration. Waste *E. grandis* kraft fibre and chemi-thermomechanical pulps of sisal and banana strand fibre imparted adequate flexural strength to BFS matrices but only relatively low toughness. It may be possible to significantly improve both BFS matrix and composite properties by optimising formulation and processing parameters.

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# Resistance of Wood– and Bamboo–Cement Boards to Subterranean Termite *Coptotermes gestroi* Wasmann (Isoptera: Rhinotermitidae)

**P. Sukartana[1], R. Rushelia[1] and I.M. Sulastiningsih[1]**

*Abstract*

Wood– and bamboo–cement composites were manufactured (in the laboratory) from Portland cement and sengon wood (*Paraserianthes falcataria*) and betung bamboo (*Dendrocalamus asper*), respectively. Magnesium chloride was added to the composites, in the range 1–10% to accelerate the curing of cement. Small samples were cut from boards and subjected to a termite bioassay using the subterranean termite *Coptotermes gestroi*. Samples of the parent wood or bamboo species and rubberwood (*Hevea brasiliensis*) acted as controls. After four weeks exposure, the composites and controls were examined for evidence of termite attack. Termite mortality in individual bioassay containers was also quantified. Both the wood– and bamboo–cement composites were less heavily attacked by termites than the controls. Termite mortality was also higher when feeding had occurred on the wood/bamboo–cement composites. There was no difference in termite resistance between the wood– and bamboo–cement composites. There was a small, positive, effect of magnesium chloride content of boards on their resistance to termite attack. Cement composites manufactured from sengon wood and betung bamboo were clearly resistant to termites. However, they are not immune from attack as there was evidence of termite feeding on boards, particularly at board surfaces.

THE development of industrial-scale forest industries in Indonesia has led to increases in the quantities of wood-waste generated by industry, including logging residues (defective logs and branches) and products of sawmilling such as sawdust and shavings. Certain industries are capable of utilising such waste materials for the production of wood composite products and pulp and paper. These industries, however, are not fully developed in all regions of Indonesia, mainly because of their capital intensive nature and lack of suitable markets. Hence large quantities of wood-waste is simply used for fuel or dumped. There is therefore an urgent need to develop industries that can profitably utilise forest and sawmill residues.

Cement-bonded board is a promising product that uses wood-wastes as its main raw material. Manufacture does not require sophisticated equipment and hence the board can be made in small, rural-based plants using simple technology. It can also be manufactured in industrial areas using the by-products of forest industries. Manufactured boards find a ready market for housing and construction, but they need to meet certain standards governing their physical and mechanical properties. Furthermore, since there are many deteriorating agents in Indonesia, boards need to possess resistance to decay and attack by termites.

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**Table 1.** Raw materials and processing conditions used to manufacture cement-bonded boards

| | |
|---|---|
| *Wood–cement boards* | |
| Wood particle size (from shavings) | pass through a screen of 2.5 cm × 2.5 cm (inside mesh) |
| Wood : cement : water ratio | 1 : 2.5 : 2 |
| $MgCl_2$ as % of cement weight | 0, 2.5%, 5%, 7.5% and 10% |
| Board size, cm | 30 × 30 × 1 |
| Board density, g $cm^{-3}$ | 1.2 |
| *Bamboo–cement boards* | |
| Bamboo particle size (from strands) | about 40 mm × 4 mm × 4 mm (length, width, thickness) |
| Bamboo : cement : water ratio | 1 : 2.5 : 2 (A) and 1 : 2.4 : 2 (B) |
| Mineral content, board size and density | as for wood–cement boards |

This paper examines the resistance of wood– and bamboo–cement boards to the subterranean termite *Coptotermes gestroi* (Wasmann). Sengon wood (*Paraserianthes falcataria* (L.) Nielsen) and betung bamboo (*Dendrocalamus asper* (Schult. f.) Backer) were the main raw materials used in the manufacture of boards.

## Materials and Methods

The wood– and bamboo–cement boards were obtained from experimental products at the Forest Products Research Centre (FPRC), Bogor. The boards were prepared using the raw materials and experimental conditions outlined in Table 1.

The boards were cut into small blocks 2 cm × 1 cm × 1cm in size. Solid test blocks of the parent wood and bamboo species, together with rubber wood (*Hevea brasiliensis* Muell. Arg.), were used as controls. The rubber wood was included in the test because it is very susceptible to termite attack. Five replicates were used for each board or wood type.

Sand was sieved so it would pass through mosquito screen with a mesh size of 2 mm × 2 mm. The sand was moistened with distilled water according to the method described by Sornuwat et al. (1995) and then put into small plastic containers to a depth of about 0.5 cm. The test blocks were placed onto the sand surface.

Subterranean termites, *Coptotermes gestroi* Wasmann, were taken from laboratory stock at the FPRC in Bogor. Fifty termite workers and five soldiers were introduced into each container. The containers were loosely capped and then arranged in a rectangular plastic bowl which already contained wet sand to a depth of 1 cm. The bowl was covered with plastic sheet to keep the air within the bowl humid. The test assembly was incubated in a dark and humid room at approximately 28°C and 80% RH for four weeks. This method was adapted from a test procedure developed by Sukartana (1998).

After four weeks, the test containers were opened and the termite attack of the test blocks was assessed. Degradation of blocks was evaluated according to the ASTM Standard (1995). Termite survival data were subjected to an analysis of variance (ANOVA), and Tukey's test was used to evaluate differences between individual means (Steel and Torrie 1980).

## Results and Discussion

Wood– and bamboo–cement boards were significantly more resistant to termite attack than the solid parent wood species (Table 2). Thus, such boards are able to resist not only the decay caused by wood-destroying fungi (Maloney 1977) but also termite attack. There was a small positive effect of the mineral ($MgCl_2$) content of boards on termite resistance.

The solid test blocks of sengon wood, rubber wood and bamboo were more severely attacked, as shown by the degradation rate of the test blocks and percentage termite survival at the end of the bioassay. However, cement-bonded boards were not immune from attack and surface wood or bamboo particles were often subject to termite attack.

In addition, termites constructed tunnels along the wood or bamboo particles embedded in the

**Table 2.** Means of deterioriation rates of boards, and mean termite survival. Means followed by the same letter do not differ significantly by Tukey's *w* procedure ($P < 0.05$)

| Wood / bamboo : cement : water | $MgCl_2$ content (%) | Degradation rate* | Termite survival (%) |
|---|---|---|---|
| Sengon wood composite | 0 | 7.5 | 0.5a |
| 1 : 2.5 : 2 | 2.5 | 7 | 13.5bc |
| | 5.0 | 8.5 | 0a |
| | 7.5 | 9 | 3a |
| | 10.0 | 9.5 | 0a |
| Bamboo composite | 0 | 9.25 | 0a |
| 1 : 2.5 : 2 | 2.5 | 8.5 | 3.5a |
| | 5.0 | 8.5 | 0a |
| | 7.5 | 9.5 | 0a |
| | 10.0 | 9.25 | 7.5ab |
| Bamboo composite | 0 | 8.5 | 0a |
| 1 : 2.4 : 2 | 2.5 | 9.25 | 0a |
| | 5.0 | 8.75 | 0a |
| | 7.5 | 9.5 | 0a |
| | 10.0 | 10 | 0a |
| Sengon wood | 0 | 7.5 | 19.5c |
| Bamboo | 0 | 7 | 22.5 c |
| Rubberwood | 0 | 7 | 23.5c |

*Deterioration value according to the ASTM (1995): 10 = sound, surface nibbles permitted; 9 = light attack; 7 = moderate attack, penetration; 4 = heavy attack; 0 = perish or failure.

cement matrix. It is possible that termites may create longer tunnels if the wood or bamboo particles are interconnected within boards. Termites could also excavate through cement if they were able to determine the presence of cellulosic material inside the block. However, in general it appears that the physical barrier provided by the cement surrounding the wood or bamboo greatly inhibits termite attack. Termites are wood-destroyers and use wood as nourishment. Hence, using cement as a matrix for wood composites will reduce access to their source of nutrition. Therefore, it is reasonable to predict that the use of higher proportions of cement will increase the boards' resistance to termite attack.

It is also possible that cement impregnates the wood or bamboo particles, providing further resistance to termite attack. Further research is needed to determine the effect of cement impregnation on wood's resistance to wood-destroying insects.

## Conclusions

Wood– and bamboo–cement boards made with sengon wood or betung bamboo were more resistant to attack by the subterranean termite *C. gestroi* than solid blocks of the parent wood and bamboo species. There was no difference between the wood– and bamboo–cement boards in their ability to resist termite attack. The addition of $MgCl_2$ during board manufacture had a slight positive effect on the resistance of the boards to termite attack.

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# The Effects of Bamboo:Cement Ratio and Magnesium Chloride ($MgCl_2$) Content on the Properties of Bamboo–Cement Boards

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*Abstract*

Laboratory-scale bamboo–cement boards were made from strand-like particles of betung bamboo (*Dendrocalamus asper* Backer). The effects of two bamboo:cement ratios (1:2.4 and 1:2.5) and five levels of magnesium chloride ($MgCl_2$) content (0, 2.5, 5, 7.5 and 10% of cement weight) on the properties of bamboo–cement boards were examined. The results showed that the bamboo strands could not be used in their native form for the manufacture of cement-bonded boards; they must be soaked first in cold water for 24 h prior to board fabrication. The average density of the boards produced was 1.19 g $cm^{-3}$. The bamboo:cement ratio significantly affected the thickness swelling, water absorption, modulus of rupture and screw-holding power of bamboo–cement boards. The $MgCl_2$ content greatly affected all the boards' properties except density and linear expansion. The dimensional stability and mechanical properties of bamboo–cement boards increased as the $MgCl_2$ content increased up to a level of 5%. At higher $MgCl_2$ contents, board properties decreased slightly. The board produced at a bamboo:cement ratio of 1:2.5 and $MgCl_2$ content of 5% had the best dimensional stability and mechanical properties.

Bamboo can be used as an alternative source of raw materials for wood-based industries because it can grow in various soils, is fast growing, can grow in short rotation, and has desirable properties. Bamboo has long been recognised as a multi-purpose plant (Dransfield and Widjaja 1995; Sattar 1996).

Bamboos in Indonesia are planted on the edges of home gardens called pekarangan and intermixed with other wood-producing and food-producing plants. Bamboo is also used to mark village boundaries and to control erosion along riverbanks. There are 35 bamboo species growing in Indonesia belonging to 13 genera, but only 13 species are economically valuable. Some of these species have been cultivated for hundreds of years; one of them is *Dendrocalamus asper* Backer (Yudodibroto 1985). People, especially those who live in villages, use bamboo in their daily lives for construction materials (village houses), furniture, household utensils and handicrafts. However, the shape and the hollow form of the bamboo culm limits the use of bamboo as a building material. Furthermore, bamboo is readily attacked by insects. One alternative that overcomes the low natural durability of bamboo is to use it for the manufacture of cement-bonded boards.

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Cement-bonded board, as its name suggests, is a composite product that uses cement as binder. It has better durability than other composite products glued with organic binders, since the cement improves the resistance of the board to fungi, heat and fire (Maloney 1977). Furthermore, researchers (Blankenhorn et al. 1994) have found that wood–cement composites also have good dimensional stability, insulation, nailing, and machining properties. Bamboo–cement boards can also be produced in a wide range of dimensions. However, the setting time of cement is often prolonged by substances in the bamboo, especially simple sugars. These inhibiting substances can sometimes be removed by soaking the bamboo in cold or hot water.

Alternatively, researchers have explored the use of chemical additives in wood–cement–water systems as a means of enhancing cement setting (Moslemi et al. 1983). Additives such as calcium chloride ($CaCl_2$), ferric chloride ($FeCl_3$), ferric sulphate ($Fe_2(SO_4)_3$), magnesium chloride ($MgCl_2$) and calcium hydroxide ($Ca(OH)_2$) have been reported to reduce the inhibitory effects of wood on the setting of Portland cement. Another factor which significantly affects the properties of cement-bonded board is the wood:cement ratio.

Research examining the effect of some Indonesian bamboos (*Dendrocalamus asper*, *Gigantochloa apus*, *G. pseudoarundinacea* and *G. levis*) on the hydration of cement was carried out by Sulastiningsih et al. (1998). Their results showed that the compatibility of bamboos with cement varied both from the bottom to the upper part of the bamboo culm and among species. Untreated *Dendrocalamus asper* had poor compatibility with cement. The $C_A$ values (Hachmi et al. 1990) ranged from 7.7 to 27%. The addition of $MgCl_2$ and $CaCl_2$ to the cement paste at levels of 2.5% and 5% based on cement weight greatly improved the compatibility of *Dendrocalamus asper* with cement.

A study of the manufacture of bamboo–cement composites has been carried out by Ma et al. (1996) using *Phyllostachys heterocycla* Mitf. var. *pubescens* Ohwi. Their results also showed that the compatibility of untreated bamboo with cement was poor. Pretreatments such as cold water, hot water and 1% NaOH extraction of the bamboo improved its compatibility with cement. Treatment with fungi and fermentation can also ameliorate or even eliminate the inhibitory effect of bamboo on cement hydration.

Ma et al. (1998) have developed a new method of producing bamboo–cement composites using the bamboo species *Phyllostachys heterocycla* Mitf. var. *pubescens* Ohwi. Composite boards were produced from particles by cold pressing, steam-injection pressing or hot pressing. Composites manufactured from untreated whole or inner layers of bamboo or particles exposed to fungi for three days had poor properties. Thirty days fermentation improved board properties. The optimum bamboo:cement ratio was estimated to be 2.6 at a water:cement ratio of 0.6 when the steam injection pressing method was employed. Hot pressing time affected the hydration of cement. In the range 3–21 min, pressing time improved the properties of boards.

Previously we showed that the addition of $MgCl_2$ to cement paste at a level of 2.5% of the cement weight greatly improved the compatibility of *Dendrocalamus asper* with cement (Sulastiningsih et al. 1998). In this study, *Dendrocalamus asper* was used as raw material for producing bamboo–cement boards by cold pressing. The objectives of the study were to determine the effects of bamboo:cement ratio and $MgCl_2$ content on the properties of bamboo–cement boards and to establish optimum conditions for the manufacture of bamboo–cement boards.

## Materials and Methods

### Preparation of bamboo particles

Four culms of four-year-old *Dendrocalamus asper* Backer (betung bamboo) were collected from Bogor, West Java. The bamboo culms, which had a minimum diameter of 10 cm, were cross cut into bolts 40 cm long. Each bolt was split into two parts, and grooves, 4 cm long, were cut into the bamboo. The bamboo was then converted into strands approximately 4 cm long, 4 mm wide and 0.4 mm thick using a wood-wool machine. The strands were placed in a concrete container (internal dimensions 100 cm × 50 cm × 50 cm) and cold water (25°C) was added to the container. The bamboo strands were left to soak for 24 h,

**Table 1.** The experimental conditions for the manufacture of bamboo–cement boards

| Experimental conditions | Specifications |
|---|---|
| Bamboo:cement:water ratio | 1 : 2.4 : 2; 1 : 2.5 : 2 |
| $MgCl_2$, % of cement weight | 0 ; 2.5 ; 5 ; 7.5 ; 10 |
| Board size, cm | 30 × 30 × 1 |
| Board density target, g $cm^{-3}$ | 1.2 |

and were then air dried for 3 days to attain a moisture content of approximately 15%.

## Board manufacture

The experimental design is shown in Table 1. In total, 40 boards were manufactured, at two bamboo:cement ratios × five $MgCl_2$ contents × four replications.

The accelerator ($MgCl_2$) was first dissolved in water. Bamboo–cement board samples were prepared by wetting the bamboo strands with the $MgCl_2$ solution. Cement was then mixed thoroughly with the wet bamboo strands. The mixture was then hand-formed into a loose mat in a wooden deckle box (30 cm × 30 cm internal dimensions). The wooden deckle box was removed and wooden sticks (10 mm thick) were placed on the sides of the mat. The mat was then pressed to thickness and left clamped for 20 h at room temperature. The boards produced were left to cure at room temperature for one month prior to testing.

## Testing

The boards were cut to produce the specimens required to determine the following properties: density, moisture content, thickness swelling, water absorption, linear expansion, bending strength, internal bond strength and screw-holding power. The tests were performed to American Standard ASTM D 1037-93 (Anon. 1995) with some modifications being necessary for evaluating the properties of bamboo–cement boards.

The experiment was a randomised block design in which bamboo:cement ratio (BCR) and $MgCl_2$

**Table 2.** Physical and mechanical properties of bamboo–cement board

| No. | Properties | Bamboo:cement ratio | Magnesium chloride ($MgCl_2$) content (%) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 0 | 2.5 | 5 | 7.5 | 10 |
| 1 | Moisture content, % | 1:2.4 | 6.80 | 8.85 | 9.07 | 9.24 | 10.55 |
| | | 1:2.5 | 6.55 | 9.32 | 9.47 | 10 | 11.42 |
| 2 | Density, g $cm^{-3}$ | 1:2.4 | 1.18 | 1.19 | 1.20 | 1.17 | 1.19 |
| | | 1:2.5 | 1.18 | 1.17 | 1.19 | 1.20 | 1.21 |
| 3 | Thickness swelling (24 h), % | 1:2.4 | 4.97 | 3.64 | 3.21 | 3.27 | 3.27 |
| | | 1:2.5 | 3.50 | 2.45 | 2.14 | 2.47 | 2.59 |
| 4 | Linear expansion (24 h), % | 1:2.4 | 0.36 | 0.28 | 0.30 | 0.28 | 0.21 |
| | | 1:2.5 | 0.26 | 0.21 | 0.13 | 0.20 | 0.22 |
| 5 | Water absorption (24 h), % | 1:2.4 | 35.73 | 22.26 | 22.60 | 24.71 | 24.44 |
| | | 1:2.5 | 32.49 | 22.88 | 21.84 | 23.12 | 23.48 |
| 6 | MOR, kg $cm^{-2}$ | 1:2.4 | 139.45 | 174.14 | 184.70 | 181.05 | 177.81 |
| | | 1:2.5 | 157.31 | 178.78 | 189.29 | 188.29 | 187.81 |
| 7 | MOE, kg $cm^{-2}$ | 1:2.4 | 22 381 | 30 118 | 34 480 | 30 166 | 30 948 |
| | | 1:2.5 | 24 722 | 32 657 | 36 515 | 34 519 | 31 547 |
| 8 | Internal bond, kg $cm^{-2}$ | 1:2.4 | 1.72 | 2.28 | 2.94 | 2.59 | 2.50 |
| | | 1:2.5 | 2.01 | 2.36 | 3.03 | 2.78 | 2.77 |
| 9 | Screw holding power, kg | 1:2.4 | 23 | 26 | 30 | 24 | 25 |
| | | 1:2.5 | 26 | 30 | 32 | 29 | 27 |

**Table 3.** Results of analysis of variance on physical and mechanical properties of bamboo–cement boards

| No. | Properties | F calculated | | |
|---|---|---|---|---|
| | | Bamboo:cement ratio | $MgCl_2$ content | Interaction |
| 1 | Moisture content | NS | ** | NS |
| 2 | Density | NS | NS | NS |
| 3 | Thickness swelling (24 h) | ** | ** | NS |
| 4 | Linear expansion (24 h) | NS | NS | NS |
| 5 | Water absorption (24 h) | * | ** | NS |
| 6 | MOR | ** | ** | NS |
| 7 | MOE | NS | ** | NS |
| 8 | Internal bond | NS | ** | NS |
| 9 | Screw-holding power | ** | ** | NS |

* = significant; ** = highly significant; NS = not significant

content were treatment factors. Four replications were made for each treatment combination.

## Results and Discussion

Bamboo strands (*Dendrocalamus asper* Backer) could not be used directly as raw materials for cement-bonded board, and therefore they had to be immersed in cold water for 24 h prior to board manufacture. This result is in agreement with our previous findings (Sulastiningsih et al. 1998) and those of Ma et al. (1996, 1998). Table 2 shows the physical and mechanical properties of the bamboo–cement boards. Analysis of variance of the data revealed that the BCR had a significant effect on thickness swelling, water absorption, modulus of rupture and screw-holding power, whereas $MgCl_2$ content had a significant effect on all properties except density and linear expansion (Table 3).

The density of bamboo–cement boards varied from 1.17 g $cm^{-3}$ to 1.21 g $cm^{-3}$ with an average of 1.19 g $cm^{-3}$. According to BISON (Anon. 1975), the maximum density of cement-bonded board is 1.25 g $cm^{-3}$ which corresponds to a wood:cement ratio of approximately 1:2.75. Lower densities are possible but involve reducing the proportion of cement. A density of 1 g $cm^{-3}$ and a wood:cement ratio of approximately 1:1.18 can be accepted. Therefore, the reason the average density of the boards produced here (1.19 g $cm^{-3}$) is lower than that of the BISON product (1.25 g $cm^{-3}$) is probably because the wood:cement ratios were relatively low, i.e. 1:2.4 and 1:2.5. Nevertheless, the densities of all boards met the International Standard (ISO) requirement of not less than 1 g $cm^{-3}$ (Anon. 1987). In addition, it was observed that the BCR and $MgCl_2$ contents had no significant effect on board density (Table 3).

The moisture content of bamboo–cement boards varied from 6.5% to 11.4% with an average of 9.1%. Analysis of variance showed that the moisture content of the boards was affected by $MgCl_2$ content. Increases in the $MgCl_2$ content resulted in increases in moisture content of the boards. Moisture content values, however, were still in the range (6–12%) required by ISO (Anon. 1987).

Thickness swelling values after 24 h soaking in cold water were affected by BCR and $MgCl_2$ content (Table 3). The thickness swelling decreased as BCR and $MgCl_2$ content increased. At a BCR of approximately 1:2.4, the average thickness swelling was 3.7%, and this decreased to 2.6% when the BCR increased to 1:2.5. When the BCR remained constant at 1:2.4, for instance, the thickness swelling of the board without $MgCl_2$ (0%) was 5%, whereas when the $MgCl_2$ content increased to 2.5% the thickness swelling decreased to 3.6%. A similar trend was observed with other BCRs. Despite the positive effect of increasing the cement and $MgCl_2$ content of boards on thickness swelling, none of the boards met the standard required by ISO 8335 of <2% thickness swelling.

The BCRs and the $MgCl_2$ contents did not affect the linear expansion of bamboo–cement boards

(Table 3). The average linear expansion of boards produced at a BCR of 1:2.4 was 0.28%, while that of boards produced at a BCR of 1:2.5 was 0.20%. The linear expansion of all boards met the BISON requirements.

Water absorption of bamboo–cement boards was lower at the higher BCR and decreased as the $MgCl_2$ content of boards increased up to a level of 5%. At higher $MgCl_2$ contents water absorption increased slightly. At a BCR of 1:2.4, the average amount of water absorbed was 25.9%, and this decreased to 24.7% when the BCR was increased to 1:2.5, a reduction of 4.6%. When the BCR was constant at 1:2.5 the water absorption of boards without $MgCl_2$ (0%) was 32.5%, and when the $MgCl_2$ content was increased to 2.5% the amount of water absorbed was reduced to 22.9%. Water absorption is not specified in the International Standard for cement-bonded particleboards.

As shown in Table 3, the modulus of rupture (MOR) of bamboo–cement boards was affected by both bamboo:cement ratio and $MgCl_2$ content. The MOR of bamboo–cement boards increased as the BCR increased (Table 2). Values of MOR increased as the $MgCl_2$ content increased from 0% to 5%, then decreased slightly as $MgCl_2$ content increased further. The MOR of all boards produced met the BISON and International Standard requirements.

The results of a previous study (Ma et al. 1998) on the effects of various additives on the properties of cold-pressed bamboo–cement composites differ slightly from those found here. Ma et al. (1998) observed that the addition of 10% $MgCl_2$ resulted in the highest MOR value (138 kgf $cm^{-2}$). Further increases in $MgCl_2$ content up to 15% of cement weight, however, decreased the MOR value (87.2 kgf $cm^{-2}$). In that study, bamboo particles were directly used (without pretreatment) to produce bamboo–cement composites, and the bamboo:cement:water ratio applied in the experiment was 1.0:2.2:1.32, which may explain the differences between their results and those here.

The modulus of elasticity (MOE) of bamboo–cement boards was greatly affected by BCR and $MgCl_2$ content. The MOE of boards produced at a BCR of 1:2.4 varied from 22 381 kg $cm^{-2}$ to 34 480 kg $cm^{-2}$ with an average of 29 618 kg $cm^{-2}$. Those produced at a BCR of 1:2.5 varied from 24 722 kg $cm^{-2}$ to 36 515 kg $cm^{-2}$ with an average of 31 992 kg $cm^{-2}$. If the data for MOE in Table 2 are compared with the ISO 8355 and BISON requirements, all boards except those with 0% $MgCl_2$ had adequate MOE. The addition of $MgCl_2$ improved MOE with the optimum level being 5% by cement weight.

The $MgCl_2$ content was a major factor affecting internal bond strength of bamboo–cement boards, which increased as $MgCl_2$ content increased up to a level of 5% and then decreased slightly at higher $MgCl_2$ contents. The internal bond strengths of boards produced at a BCR of 1:2.4 varied from 1.72 kg $cm^{-2}$ to 2.94 kg $cm^{-2}$ with an average of 2.40 kg $cm^{-2}$, while those produced at a BCR of 1:2.5 varied from 2.01 kg $cm^{-2}$ to 3.03 kg $cm^{-2}$ with an average of 2.59 kg $cm^{-2}$. However, the internal bond strengths of the boards did not meet BISON requirements. In the International Standard the internal bond strength requirement of cement bonded boards is not specified.

A previous publication on bamboo–cement composites manufactured using the bamboo *Phyllostachys heterocycla* Mitf. var. *pubescens* Ohwi (Ma et al. 1998) did not give internal bond strength data for bamboo–cement composites manufactured with the addition of $MgCl_2$ at 5% of cement weight. However, bamboo–cement composites made with $MgCl_2$ at 10% and 15% of cement weight had internal bond strengths of 4.4 kg $cm^{-2}$ and 2.6 kg $cm^{-2}$ respectively, the former being much higher than that obtained here.

The results of the present study reveal that BCR and $MgCl_2$ contents affect the screw-holding power values of boards (Table 3). The screw-holding power of bamboo–cement boards increased as the BCR and $MgCl_2$ content increased up to 5% (Table 2). The screw-holding power of boards produced at a BCR of 1:2.4 varied from 23 kg to 30 kg with an average of 25.60 kg. When bamboo–cement boards were produced at a BCR of 1:2.5 the screw-holding power varied from 26 kg to 32 kg with an average of 28.8 kg. The screw-holding power requirement is not specified in the International Standard for cement-bonded particleboards.

## Conclusions

Bamboo strands of *Dendrocalamus asper* Backer could not be used in their native form as raw

material for cement-bonded board; they had to be soaked first in cold water for 24 h. The average density of bamboo–cement boards was 1.19 g $cm^{-3}$ and it was not affected by bamboo:cement ratio or $MgCl_2$ content.

The bamboo:cement ratio significantly affected the thickness swelling, water absorption, modulus of rupture and screw-holding power of the boards. Both the thickness swelling and water absorption decreased as the bamboo:cement ratio increased, while the modulus of rupture and screw-holding power increased as the bamboo:cement ratio increased.

All bamboo–cement board properties except density and linear expansion were greatly affected by $MgCl_2$ content. The dimensional stability and mechanical properties of bamboo–cement boards increased as the $MgCl_2$ content increased up to a level of 5%. At higher $MgCl_2$ contents (7.5% and 10%), board properties decreased slightly.

The optimum combination of raw materials for the manufacture of the bamboo–cement boards was a bamboo:cement ratio of 1:2.5 and $MgCl_2$ content of 5%. This resulted in the best board properties. Apart from internal bond strength, all board properties met the BISON and International Standard requirements.

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# Comparative Resistance of Cement-bonded Rubberwood Particleboard, Rubberwood Medium Density Fibreboard, Rubberwood and Radiata Pine to Microfungi and Subterranean Termite Attack

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COMMERCIALLY produced cement-bonded rubberwood particleboard from peninsular Malaysia was subjected to a laboratory evaluation of its resistance to attack by the aggressive subterranean termite *Coptotermes curvignathus*. The cement-bonded particleboards were also subjected to bioassays to test their resistance to colonisation by pure strains of *Botryodiplodia theobromae* (typical blue-stainer), *Paecilomyces variotii* (mould species), *Trichoderma* spp. and *Aspergillus* spp. (mould species). The resistance of boards to colonisation by naturally occurring microfungi was also tested by exposing samples out-of-doors for four weeks. The biological resistance of these particleboards was compared with that of representative samples of commercial low-formaldehyde-emission-quality rubberwood medium-density fibreboard (for microfungal tests only), Malaysian rubberwood and New Zealand radiata pine. Results of all tests consistently revealed that cement-bonded particleboard was highly resistant to attack by the subterranean termite species *C. curvignathus* and colonisation by microfungi. In contrast, rubberwood and medium-density fibreboard samples sustained severe mould and stain infection after only one week's exposure to pure cultures of mould and staining fungi, respectively. Both rubberwood and radiata pine were susceptible to termite attack. These results accord with previous findings that have shown that cement-bonded wood composites are far more resistant to biodeterioration than their resin-bonded counterparts.

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# Cement-bonded Boards From Wastewater Treatment Sludge of a Recycled Paper Mill

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*Abstract*

Paper mills in the Philippines generate large volumes of fibrous sludge each day and options for disposing of it are limited. The use of fibrous sludge as a reinforcement for cement-bonded fibreboard is one option that could help alleviate the paper industry's problems in disposing of the sludge, which is recovered after treatment of process water. Research was undertaken to determine the technical feasibility of using these waste fibres for the production of fibre-reinforced cement bonded boards. Cement and sludge were mixed in the ratios 60:40 and 50:50 and used to manufacture boards. Calcium chloride, sodium silicate and aluminium sulphate were added to accelerate curing and hardening of boards. Morphological characteristics of fibrous components of sludge such as fibre length, cell wall and cell lumen dimensions were determined. The percent thickness swelling and water absorption and mechanical properties of boards were measured. The average length of fibres in the sludge was 1.424 mm. The average dimensions of the cell wall and lumen were 0.006 mm and 0.0153 mm, respectively. The average densities of the boards were 1.232 g $cm^{-3}$ for the 60:40 boards and 1.177 g $cm^{-3}$ for the 50:50 boards. The 60:40 board containing aluminium sulphate exhibited the lowest thickness swelling while the 50:50 board with both sodium silicate and aluminium sulphate had the highest thickness swelling. In general, 60:40 boards absorbed less water than 50:50 boards. The 60:40 board with sodium silicate and aluminium sulphate had the highest modulus of rupture and modulus of elasticity, while the 50:50 board with sodium silicate had the lowest. The boards were also evaluated for their nail-head pull through strength. Results showed that the 60:40 board containing aluminium sulphate had the highest strength. Our findings suggest that cement boards manufactured with sludge as reinforcement have mechanical and physical properties comparable to those of other cement-bonded boards manufactured in the Philippines. The fibres bond well together and the sludge does not greatly inhibit the setting of cement. The results are sufficiently encouraging to suggest that the management of paper mills should consider using sludge for the production of cement-bonded boards.

RECOVERED paper is of growing importance to the paper industry in the Philippines because of the decreased availability of wood from native forests. Trust International Paper Company (TIPCO) in the Philippines has started to produce good quality paper grades from recycled fibres. One unwanted by-product of the use of recycled fibres, however, is the sludge that contains waste fibres and fines.

Sludge is the final solid waste recovered after treatment of process water in the paper mill. TIPCO is producing 100–120 t (bone dry weight) of sludge per day. In some paperboard mills it is possible to reuse primary sludge in the

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**Table 1.** Amounts of materials in each of the boards (Wo = oven dry weight of sample)

| | Weight (g) | |
|---|---|---|
| **A** | **60:40** | **50:50** |
| Cement | 849.51 | 707.92 |
| Sludge (Wo) | 566.34 | 707.92 |
| Calcium chloride (1%) | 8.50 | 7.08 |
| Sodium silicate (2.2%) | 18.69 | 15.57 |
| Aluminum sulphate (1.8%) | 15.29 | 12.74 |
| Water (mL) | 500.00 | 400.00 |
| **B** | | |
| Cement | 849.51 | 707.92 |
| Sludge (Wo) | 566.34 | 707.92 |
| Calcium chloride (1%) | 8.50 | 7.08 |
| Sodium silicate (2.2%) | 18.69 | 15.57 |
| Water (mL) | 500.00 | 400.00 |
| **C** | | |
| Cement | 849.51 | 707.92 |
| Sludge (Wo) | 566.34 | 707.92 |
| Calcium chloride (1%) | 8.50 | 7.08 |
| Aluminum sulphate (1.8%) | 15.29 | 12.74 |
| Water (mL) | 500.00 | 400.00 |

manufacturing process, but the high biological activity of secondary sludge prevents its reuse. In most cases secondary sludge must be disposed of externally, usually after dewatering to reduce its volume and weight (McKinney 1995). Because of the relatively large volume of sludge produced each day, disposal at landfill is uneconomic. It would therefore be highly desirable to find uses for sludge. The use of sludge as a component in the manufacture of cement-bonded fibreboard is one option.

In the Philippines, there has been an active program of research to examine the feasibility of manufacturing cement-bonded composites, including fibreboards from a variety of lignocellulosic materials (Mallari 1994, 1995; Mallari et al. 1995; Pamplona and Mari 1998; Velayo 1998). In some industrialised countries, cement-bonded boards are widely accepted as a construction material and are being used as roofing, exterior and interior-type panels, and ceilings.

It is often necessary, when manufacturing wood–cement composites, to add chemicals that accelerate the dehydration time of cements, including sodium silicate, calcium hydroxide, aluminium sulphate, magnesium chloride and calcium chloride (Lee et al. 1987; Chew et al. 1992). Such chemicals ameliorate the inhibitory effect that lignocellulosic residues have on the setting of cement. The use of a higher cement: wood ratio can achieve a similar effect and it is important to know the appropriate cement:wood ratio when manufacturing wood–cement composites from an unfamiliar lignocellulosic residue. The amount of cement should complement the fibre content of the board (Chew et al. 1992; Mallari 1994, 1995; Velayo 1998).

The main objective of this study was to evaluate the suitability of sludge as reinforcement for cement-bonded board. Specifically, the study was undertaken to: 1) determine the optimum cement: sludge ratio, the best types and amounts of chemical additives, and the amount of water needed to produce rigid and functional boards; 2) determine the physical and mechanical properties of cement-bonded boards manufactured from the sludge; and 3) determine the effect of cement:sludge ratio on the physical and mechanical properties of cement-bonded boards.

## Materials and Methods

### Materials

Two sacks of sludge were collected from TIPCO, Pampanga. The dewatered sludge was air dried for two weeks to remove the volatile gases that cause foul odour. Portland cement was used as a binding agent. Technical grade calcium chloride, sodium silicate and aluminium sulphate were used as cement setting accelerators.

### Methods

*Board formation*

The sludge was soaked in water for 24 h and fibrous clumps were disentangled using a disintegrator running at 3012 rpm. The disintegrated sludge was mixed with cement, accelerator and chemical additives. The cement:sludge ratios were 60:40 or 50:50 and the quantity of accelerator added was 1–2% (based on cement weight). The amounts of materials needed to make the various boards are shown in Table 1.

To form boards, the mixtures were placed in a 15 mm × 300 mm × 300 mm mould and pressed at 1500 psi at room temperature to form boards with the desired thicknesses and densities. Boards

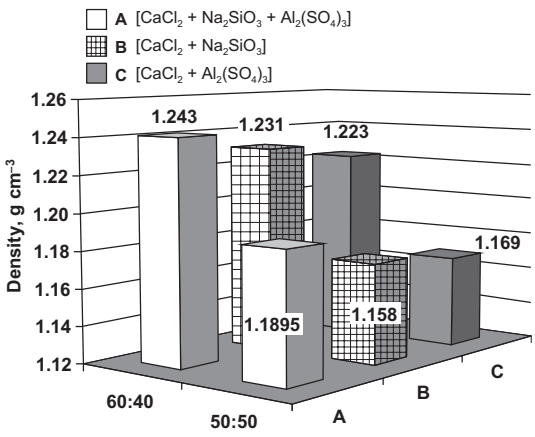


**Figure 1.** The densities of the various boards

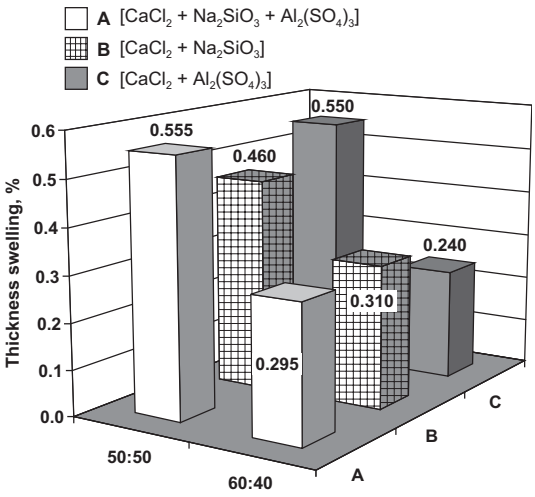


**Figure 2.** Percentage thickness swelling of the various boards

were kept under compression for 24 h, then removed from the press and cured at room temperature for 28 days prior to testing.

*Testing methods*

The physical and mechanical properties of the cement boards were examined and evaluated according to the relevant Japanese standard (JISA 5404, 1979).

Fifty samples of fibres from the sludge were collected and their length and diameter were measured using optical microscopy. Duncan's Multiple Range Test and analysis of variance (ANOVA) were used for the statistical analysis (Table 3).

## Results and Discussion

### Fibre dimensions

The morphology of wood fibres has a significant influence on the mechanical properties of fibreboards. Thus it was vital to quantify the dimensions of the fibres in the sludge, particularly their length, cell wall thickness and cell lumen width. On average, fibres obtained from the sludge were 1.424 mm in length and their cell wall diameter and cell lumen width were 0.0060 mm and 0.0153 mm, respectively. The average Runkel ratio of the fibres was 0.783. However, in pulp and paper, it has been suggested that the Runkel ratio of fibres should be greater than 1.0 to have good conformability during mat formation.

### Physical properties

*Board density*

Figure 1 shows the densities of the different boards. The 60:40 board, containing all three accelerators, had the highest density, 1.243 g $cm^{-3}$, while the 50:50 board, containing calcium chloride and sodium silicate, had the lowest density, 1.158 g $cm^{-3}$. These results are due to the fact that the 60:40 board contained more cement which is much denser than wood fibres. Both these density values are within the standard range, 0.8–1.4 g $cm^{-3}$ specified for the density of compressed wood-wool cement board manufactured by the Forest Products Research and Development Institute (FPRDI) in the Philippines.

*Thickness swelling*

Figure 2 shows the percentage thickness swelling of boards. Boards with a cement:sludge ratio of 60:40 had less tendency to swell than boards that had a cement:sludge ratio of 50:50. The effect of chemical additives on swelling was not significant, but there was a significant interaction of cement:sludge ratio and the chemical accelerator on thickness swelling (Table 2).

**Table 2.** Analysis of variance (ANOVA) of the results of tests on thickness swelling (TS)

| Source of variation | df | Sum of squares | Mean square | F-value | Tabular F | |
|---|---|---|---|---|---|---|
| | | | | | 5% | 1% |
| Repetition | 5 | 0.57 | 0.114 | | | |
| Ratio | 1 | 0.52 | 0.52 | 18.57** | 4.24 | 7.77 |
| Chemical additives | 2 | 0.009983 | 0.00499 | $0.178^{ns}$ | 3.38 | 5.57 |
| Ratio & Chemicals | 2 | 0.242648 | 0.121342 | 4.333* | 3.38 | 5.57 |
| Error | 25 | 0.7112 | 0.028 | | | |
| **Total** | 36 | | | | | |

**highly significant; *significant; $^{ns}$not significant

**Table 3.** Comparison of the effects of various treatment levels on thickness swelling (TS) of the boards

| Treatment | Mean (%) | Duncan grouping |
|---|---|---|
| a) Ratio | | |
| 60:40 | 0.28 | b |
| 50:50 | 0.52 | a |
| b) Chemical additives | | |
| A | 0.43 | a |
| B | 0.39 | a |
| C | 0.40 | a |
| c) Interaction | | |
| A 60:40 | 0.30 | c |
| A 50:50 | 0.56 | a |
| B 60:40 | 0.31 | c |
| B 50:50 | 0.46 | b |
| C 60:40 | 0.24 | c |
| C 50:50 | 0.55 | a |

Boards with 50:50 fibre:cement ratio and with chemical accelerators A and C did not differ significantly from each other. The board with 50:50 ratio containing all three accelerators showed the highest percent thickness swelling. On the other hand, boards with a ratio of 60:40 and chemicals A, B and C did not differ significantly from each other in terms of thickness swelling, and the values obtained were low (Table 3).

*Water absorption*

Table 4 and Figure 3 compare the water absorption by the various boards. The result of the ANOVA for water absorption is presented in Table 5. Both cement:sludge ratio and its interaction with chemical accelerator had highly significant effects on water absorption. The type of chemical accelerator added to boards had no significant effect on water absorption.

Table 6 shows that boards with cement:sludge ratio of 60:40 absorbed less water than boards with a 50:50 ratio. Water absorption appeared to

**Table 4.** Per cent thickness swelling for each board after 24 h of soaking in water

| | Thickness swelling | Water absorption |
|---|---|---|
| | 60:40 | |
| A | 0.30 | 22.79 |
| B | 0.31 | 28.22 |
| C | 0.24 | 23.08 |
| | 50:50 | |
| A | 0.56 | 29.53 |
| B | 0.46 | 24.24 |
| C | 0.55 | 25.07 |

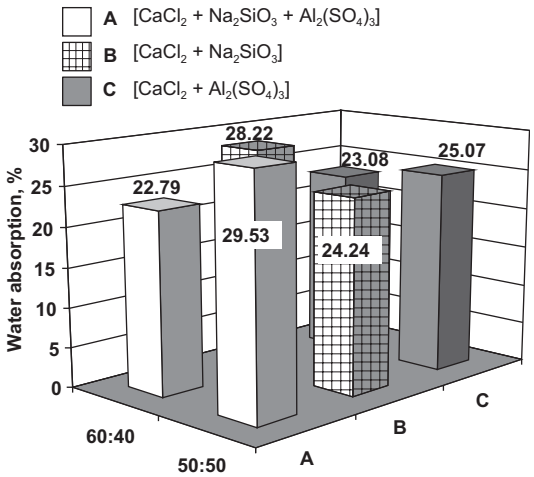


**Figure 3.** Percentage water absorption of the boards

**Table 5.** Analysis of variance (ANOVA) of the results of tests on water absorption

| Source of variation | df | Sum of squares | Mean square | F-value | Tabular F | |
|---|---|---|---|---|---|---|
| | | | | | 5% | 1% |
| Repetition | 2 | 3.158 | 1.579 | | | |
| Ratio | 1 | 12.28 | 12.28 | 10.78** | 4.96 | 10.04 |
| Chemical additives | 2 | 16.99 | 8.495 | 7.46* | 4.10 | 7.56 |
| Ratio & Chemicals | 2 | 86.562 | 43.281 | 38.00** | 4.10 | 7.56 |
| Error | 10 | 11.39 | 1.139 | | | |
| **Total** | 18 | | | | | |

**highly significant; *significant; $^{ns}$not significant

**Table 6.** Comparison of the effects of various experimental variables on water absorption of boards

| Treatment | Mean (%) | Duncan grouping |
|---|---|---|
| a) Ratio | | |
| 60:40 | 24.697 | b |
| 50:50 | 26.280 | a |
| b) Chemical additives | | |
| A | 26.160 | a |
| B | 26.230 | a |
| C | 24.075 | b |
| c) Interaction | | |
| A 60:40 | 22.79 | d |
| A 50:50 | 29.53 | a |
| B 60:40 | 28.22 | b |
| B 50:50 | 24.24 | c |
| C 60:40 | 23.08 | d |
| C 50:50 | 25.07 | c |

be proportional to the amount of sludge present in boards. This result agrees with the findings of Tuico (1994). She found that boards with a higher cement:coconut coir dust ratio absorbed less water than boards with a lower ratio. Similar findings were also obtained by Mallari (1994) for wood-wool cement boards manufactured from Moluccan sau (*Paraserianthes falcataria* Nielsen).

Boards containing the accelerators A or B absorbed similar quantities of water but there was a significant interaction of cement:sludge ratios and accelerator on water absorption. The 60:40 boards with A and C chemicals did not differ significantly from each other. The same results were obtained for 50:50 boards containing B and C.

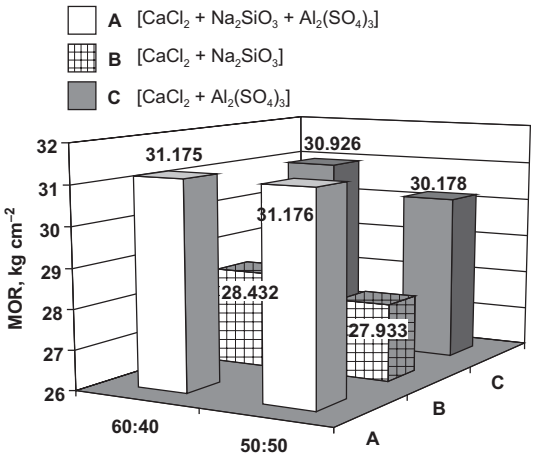


**Figure 4.** Modulus of rupture (kg cm$^{-2}$) of the boards

High cement content enhances the growth and development of cement crystals from the cement particles during the hydration process, resulting in greater bonding between wood and cement (Ahn and Moslemi 1980). Therefore, the larger the amount of cement present, the stronger is the interlocking between cement crystals and wood, resulting in a less porous material that absorbs less water.

## Mechanical properties

### *MOR and MOE*

The modulus of rupture (MOR) values in Fig. 4 indicate that, on average, 60:40 boards were stronger than 50:50 boards. ANOVA showed that cement:sludge ratio had a highly significant effect on MOR (Table 7). The addition of chemical accelerator also had a significant effect.

Table 8 shows that a cement:fibre ratio of 60:40 ratio resulted in a significantly higher MOR than a ratio of 50:50. In other words, the higher the

**Table 7.** Analysis of variance (ANOVA) of the results of tests on modulus of rupture (MOR)

| Source of variation | df | Sum of squares | Mean square | F-value | Tabular F 5% | Tabular F 1% |
|---|---|---|---|---|---|---|
| Repetition | 5 | 1.007 | 0.2014 | 9.90** | | |
| Ratio | 1 | 9.513 | 9.513 | 5.01* | 4.124 | 7.77 |
| Chemical additives | 2 | 9.63 | 4.815 | | 3.38 | 5.57 |
| Ratio & Chemicals | 2 | 12.718 | 6.359 | 6.617** | 3.38 | 5.57 |
| Error | 25 | 24.023 | 0.061 | | | |
| **Total** | 36 | | | | | |

**highly significant; *significant; $^{ns}$not significant

**Table 8.** Comparison of the effects of different experimental variables on modulus of rupture (MOR) of the boards

| Treatment | Mean (%) | Duncan grouping |
|---|---|---|
| a) Ratio | | |
| 60:40 | 6.08 | a |
| 50:50 | 6.02 | b |
| b) Chemical additives | | |
| A | 6.25 | a |
| B | 5.72 | b |
| C | 6.18 | ab |
| c) Interaction | | |
| A 60:40 | 6.27 | a |
| A 50:50 | 6.23 | a |
| B 60:40 | 5.75 | ab |
| B 50:50 | 5.70 | b |
| C 60:40 | 6.23 | a |
| C 50:50 | 6.13 | a |

cement content of boards the greater the force needed before the boards fail, i.e. the strength properties of the board increase as the sludge content decreases.

Table 8 shows that chemical accelerator and additives A and C are not significantly different from each other; and the interaction of ratio, chemical accelerator and additive for 60:40 boards was not significant. The results for modulus of elasticity (MOE) were similar to those of MOR.

*Nail-head pull through*

Another factor to consider when testing the mechanical properties of panel products is their ability to hold nails, especially when subjected to load. Table 9 and Fig. 5 give the nail-head pull through strength for the various boards. On average, 60:40 boards had higher nail-head pull through strength than 50:50 boards.

Table 10 shows that only the cement:sludge ratio had a highly significant effect on nail-head

**Table 9.** Nail-head pull through strength (kg) for the boards

| | I | II | III | IV | V | VI | Mean |
|---|---|---|---|---|---|---|---|
| | | | | 60:40 | | | |
| A | 74 | 93 | 99 | 101 | 110 | 94 | 95.17 |
| B | 50 | 74 | 92 | 100 | 95 | 91 | 83.67 |
| C | 91 | 95 | 106 | 104 | 100 | 103 | 99.83 |
| | | | | 50:50 | | | |
| A | 56 | 74 | 90 | 97 | 88 | 72 | 79.50 |
| B | 74 | 98 | 97 | 104 | 67 | 66 | 84.33 |
| C | 76 | 100 | 99 | 67 | 71 | 64 | 79.50 |

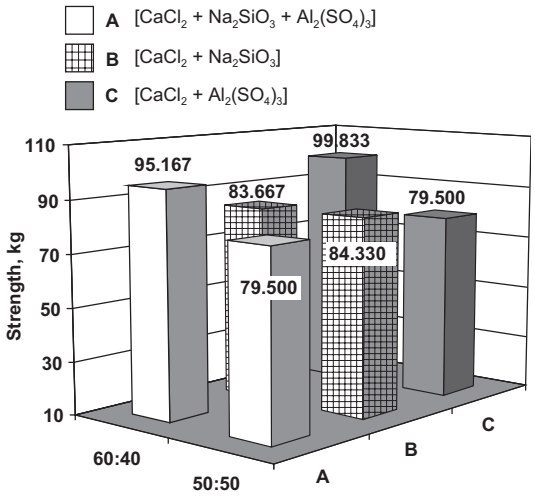


**Figure 5.** Nail-head pull through strength for the boards

**Table 10.** Analysis of variance (ANOVA) of the results of the nail-head pull through test

| Source of variation | df | Sum of squares | Mean of squares | F-value | Tabular F 5% | Tabular F 1% |
|---|---|---|---|---|---|---|
| Repetition | 5 | 2965.132 | 593.0264 | | | |
| Ratio | 1 | 2358.7036 | 2358.7036 | 7.80** | 4.24 | 7.77 |
| Chemical additives | 2 | 2547.217 | 1273.608 | 4.21* | 3.38 | 5.57 |
| Ratio & Chemicals | 2 | 3303.516 | 1651.758 | 5.46* | 3.38 | 5.57 |
| Error | 25 | 7562.995 | 302.5198 | | | |
| **Total** | 36 | | | | | |

**highly significant; *significant; $^{ns}$not significant

**Table 11.** Comparison of the effects of various treatment levels on nail-head pull through of the boards

| Treatment | Mean (%) | Duncan grouping |
|---|---|---|
| a) Ratio | | |
| 60:40 | 92.889 | a |
| 50:50 | 81.11 | b |
| b) Chemical additives | | |
| A | | |
| B | 87.33 | a |
| C | 84.00 | b |
| | 89.67 | a |
| c) Interaction | | |
| A 60:40 | 95.17 | a |
| A 50:50 | 79.50 | c |
| B 60:40 | 83.67 | b |
| B 50:50 | 84.33 | b |
| C 60:40 | 99.83 | a |
| C 50:50 | 79.50 | c |

pull through strength. According to the Duncan groupings (Table 11) the 60:40 boards were significantly stronger than the 50:50 board. Boards containing chemical accelerators A and C were not significantly different from each other.

## Conclusions and Recommendations

Cement-bonded fibreboard containing pulp-mill sludge fibres as reinforcement has mechanical and physical properties comparable to those of other cement-bonded boards manufactured in the Philippines. The fibres bond well with cement and fit into the interlocked crystals of hardened cement. The sludges are largely free of extractives such as phenolics and sugars, which are known inhibitors of cement hydration, and hence they have no adverse effects on hardening of boards.

Boards with cement:sludge ratios of 60:40 and 50:50 have acceptable mechanical properties but boards with the higher cement content show lower thickness-swelling and water absorption. The 60:40 boards are also stronger than 50:50 boards. The addition of calcium chloride, sodium silicate or aluminium sulphate (Additive A) improved properties to a greater extent than the other additives tested.

Due to the preliminary nature of this study, the authors recommend testing of other properties that are important to the use of panels in building construction. Higher density boards are recommended for use in load-bearing situations.

The management of the various paper mills should consider the potential of sludge as an aggregate in cement-bonded board production.

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# Modified Formaldehyde-based Resin Adhesives for Rice Hull–Wood Particleboard

**Chung-yun Hse[1] and Elvin T. Choong[2]**

*Abstract*

A study was conducted to develop an effective and economical resin system to improve the physical and mechanical properties of rice hull–wood composites. Boards 0.5 inch (12.5 mm) thick were made from a mixture of rice hulls and pine particles with three main resin types: urea formaldehyde (UF), phenol formaldehyde (PF), and polyisocyanate (ISO), in various adhesive formulations. Results indicated that conventional UF and PF resins did not perform well with rice hull–wood composites. However, a modified resin system with ISO as minor component significantly improved the boards' strength properties and dimensional stability. Resin content had a significant effect on the quality of the boards, with the higher resin content resulting in stronger boards. The boards bonded with the 1%ISO / 6%UF resin system had higher internal bond strength, and attained the best dimensional stability and the highest bending strength (MOR) and stiffness (MOE).

As global population increases and developing countries increase their use of wood and paper products, there is new interest in producing and conducting research on composite board from agricultural fibres. Rice hull is quite fibrous by nature and requires little energy input to prepare, so its suitability for the manufacture of particleboards has been assessed in a number of studies (Vasishth 1971; Hancock and Chandramouli 1974; Mahanta et al. 1980; Viswanathan et al. 1987). However, particleboards made from rice hulls have not found commercial acceptance because substantially more adhesive is needed for rice hulls than for wood flakes to yield boards with acceptable properties (Vasishth 1971; Chen 1979).

The reason for the higher resin requirement for bonding rice hulls is not completely understood, but a comparison between wood and rice hull showed that rice hull has less holocellulose and a much higher ash content (Houston 1972). The predominant component of its ash is silica (Luh 1991). The silica covers almost the entire outer layer of the rice hull surface which also contains the water repellent cuticle (Juliano 1985). This silica layer and the partially hydrophobic surface of rice hull are incompatible with aqueous urea formaldehyde (UF) or phenol formaldehyde (PF) resins and prevent the formation of a good bond between rice hull surfaces. Thus, a new and improved resin adhesive system is needed to produce high quality rice hull particleboards.

Urea formaldehyde resins are often fortified with melamine to increase the bond strength and water resistance of particleboard. More recently, highly reactive polyisocyanate (ISO) has been used to modify UF resins (Deppe and Ernst 1971; Deppe 1977; Pizzi 1981; Liu and Binglye 1992) and PF resins (Hse 1978, 1980) for board products. ISO modified adhesives improve the bond strength and performance of wood particleboards, so they might have similar beneficial effects on the bonding of rice hulls. Therefore,

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**Table 1.** Summary of resin type and resin application levels used in the study

| Resin type | Resin application level | |
|---|---|---|
| | Low | High |
| ISO/UF | (5%): 1%ISO/4%UF | (7%): 1%ISO/6%UF |
| ISO/PF | (5%): 1%ISO/4%PF | (7%): 1%ISO/6%PF |
| ISO/PF/UF | (5%): 1%ISO/1%PF/3%UF | (7%): 1%ISO/1%PF/5%UF |
| UF | 5%UF | 7%UF |
| PF | 5%PF | 7%PF |
| ISO | 2.5%ISO | 5%ISO |

the objective of this study was to investigate the feasibility of developing multi-polymer adhesive systems that could take advantage of the durability of phenol formaldehyde, the low cost of urea formaldehyde, and the reactivity of polyisocyanate for manufacturing rice hull–wood composite products. This paper reports preliminary findings and discusses further developments necessary to improve the properties of rice hull–wood particleboard bonded with modified ISO/UF adhesives.

## Materials and Methods

### Experimental variables

The resin types used in this study are polyisocyanate/urea formaldehyde (ISO/UF), polyisocyanate/phenol fomaldehyde (ISO/PF), polyisocyanate/phenol formaldehyde/urea formaldehyde (ISO/PF/UF), UF, PF, and ISO resin adhesives. The ISO/UF, ISO/PF, and ISO/PF/UF adhesive systems were obtained by the alloying process described in a previous study (Hse 1978). The process involves applying minor amounts of polyisocyanate before adding major amounts of either UF or PF resin to the furnish, then letting the combined adhesive react in situ to obtain an improved thermosetting adhesive resin. The UF-, PF-, and ISO-bonded boards acted as controls. There were two resin application levels, based on percentage oven dry weight of rice hull furnish: high (7%) and low (5%), except for ISO which was applied at 2.5% and 5%. The various resin formulations are summarised in Table 1.

### Board manufacture

All boards were prepared in the laboratory with equal weight (50:50) mixtures of rice hulls and wood particles. The rice hulls were brought to the laboratory from a local rice mill, passed through a Sears chipper to break the boat-shape hull particles, sieved to remove fines, and then dried at 105°C to an average moisture content of 4%. The dry southern pine (*Pinus* sp.) wood particles were obtained from a local particleboard plant and used without further treatment.

To prepare each board, a pre-weighed mixture of rice hulls and wood particles was placed in a rotating drum-type blender. The resin was weighed and applied to the mixture using air-atomising nozzles. After blending, the rice hull–wood furnishes were carefully felted into a 19 × 20 inch (475 mm × 500 mm) box to form a mat. The mat was transferred immediately to a 40 × 40 inch (1 m × 1 m) single-opening hot press with the platen temperature regulated at 370°F (188°C). Sufficient pressure (about 550 psi / 3790 kPa) was applied so that the platen, closed to ½-inch thickness, stopped in 45 s. The press time was 255 s.

### Sampling and testing

All boards were conditioned in an environmental chamber at 50% RH and 80°F (40.6°C) ambient temperature to obtain an average equilibrium moisture content of 5.8%. After conditioning, each board was cut to yield ten 2 × 2 inch (50 mm × 50 mm) specimens for tensile strength perpendicular to the face (internal bond strength), five 2 × 14 inch (50 mm × 350 mm) static-bending specimens, and two 6 × 6 inch (150 mm × 150 mm) specimens for dimensional stability tests.

The mechanical tests were performed in accordance with ASTM standard D-1037-99 (ASTM 1999) using an Instron universal testing

**Table 2.** Summary of resin type and resin application levels used in the study

| Resin type | Resin content | Density (psi) | MOR (psi) | MOE ($10^2$ psi) | IB (psi) | TS (%) |
|---|---|---|---|---|---|---|
| PF | 5.0 | 53.61 | 1735.5 | 387.2 | 29.2 | 33.7 |
| PF | 7.0 | 55.69 | 1663.1 | 408.2 | 43.0 | 23.7 |
| UF | 5.0 | 56.47 | 1434.5 | 399.2 | 22.2 | 57.0 |
| UF | 7.0 | 60.54 | 1769.7 | 470.9 | 44.3 | 46.6 |
| ISO* | 2.5 | 51.00 | 1645.6 | 321.0 | 25.5 | 28.3 |
| ISO* | 5.0 | 51.62 | 3022.1 | 464.3 | 59.5 | 12.6 |
| ISO/PF | 1/4 | 53.01 | 2285.8 | 410.9 | 60.5 | 21.1 |
| ISO/PF | 1/6 | 54.60 | 2521.6 | 461.5 | 78.0 | 18.5 |
| ISO/UF | 1/4 | 57.86 | 2252.8 | 400.4 | 85.9 | 23.7 |
| ISO/UF | 1/6 | 54.61 | 3162.4 | 494.1 | 97.6 | 12.3 |
| I/P/U | 1/1/3 | 54.20 | 2570.5 | 451.4 | 60.1 | 25.5 |
| I/P/U | 1/1/5 | 50.97 | 2412.2 | 447.2 | 73.8 | 13.5 |

*The average moisture content of particles was 11.2 and 9.25% for rice hull and pine, respectively.

machine. The dimensional stability test measured changes in thickness and weight after the specimens had been submerged in water at room temperature for 24 h.

## Results

The average physical and mechanical properties of the particleboards are summarised in Table 2. The effects of resin types and resin contents were evaluated by analysis of variance at the 5% significance level ($P < 0.05$), and all differences discussed below were significant at that level.

### Internal bond strength

The average internal bond strength ranged from 22.2 psi (153.1 kPa) for UF resin content at 5%, to 97.6 psi (672.9 kPa) for ISO/UF resin content at 1% / 6%. The analysis of variance showed that the internal bond strengths differed significantly among resin types and resin contents. Figure 1 shows that boards bonded with PF and UF resins had very low internal bond strength. The average values of 43.0 psi (296.5 kPa) (PF) and 44.3 psi (305.4 kPa) (UF) at high (7%) resin content levels are far lower than the 130 psi (896.3 kPa) required by the American National Standard of Mat-Formed Wood Particleboard. The results suggest that the inclusion of 50% rice hull in a wood particleboard substantially reduces internal bond strength. As expected, the internal bond strength of rice hull–wood particleboard increased as resin content increased. The internal bond strength of 5% PF-bonded board was 29.2 psi (201.3 kPa), and that of 7% PF-bonded board was 43 psi (296.5 kPa), an increase of 47%. When UF was used, comparable internal bond strength figures at 5 and 7% were 22.2 psi (153.1 kPa) and 44.3 psi (305.4 kPa), respectively, an increase of 99%. These trends and values are similar to those reported by Chen (1980).

The internal bond strengths of boards that were bonded with ISO were only slightly higher than the internal bond strengths of PF- or UF-bonded boards because the ISO resin content was substantially lower than the PF or UF controls. Note, however, that the internal bond strengths

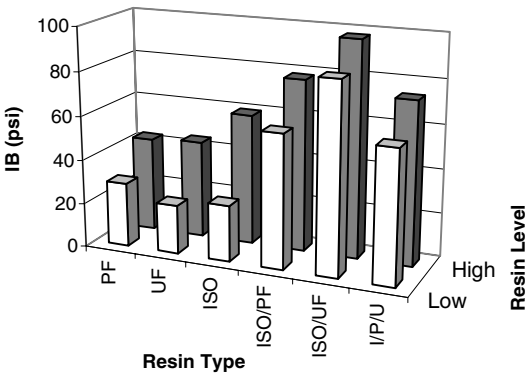


**Figure 1.** Effect of resin type and resin content on the internal bond strength of rice hull–wood composites

of ISO-bonded boards at 5% resin content level were 104% and 168% higher than those of PF- and UF-bonded boards at the same resin contents, respectively. The significant effect of ISO on bonding strength also resulted in significantly higher internal bond strength for all boards bonded with ISO-modified resin systems. For example, the internal bond strengths of 1/4 ISO/PF and 1/4 ISO/UF were 107% and 287% greater than those of 5% PF and UF, respectively.

Substantially higher bonding strength was found in boards bonded with the ISO/UF resin system than in those bonded with ISO/PF. The internal bond strengths of 1/4 ISO/UF and 1/6 ISO/UF were 42% and 25% higher than those boards bonded with the ISO/PF system. The low cost of UF resins suggests that there is merit in further investigation of the use of ISO/UF resin systems for the bonding of rice hull–wood composites.

Note, however, that the ISO/PF/UF resin system yielded the lowest internal bond strength of the three ISO-modified resin systems. This may be due to the basic incompatibility of the curing properties of PF and UF resins (i.e. PF resin cures at alkaline pH; UF resin cures at acidic pH).

## Bending strength (MOR)

The relationships between modulus of rupture (MOR) and resin type for the two resin content levels are shown in Fig. 2. Boards bonded with polyisocyanate had the highest bending strength. The significant effect of ISO in increasing bending strength also occurred with the mixed ISO resin

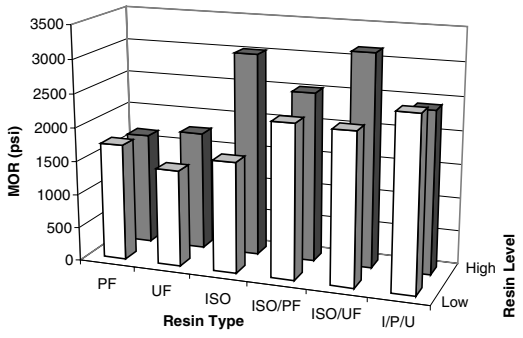


**Figure 2.** Effects of resin type and resin content on the MOR of rice hull–wood composites

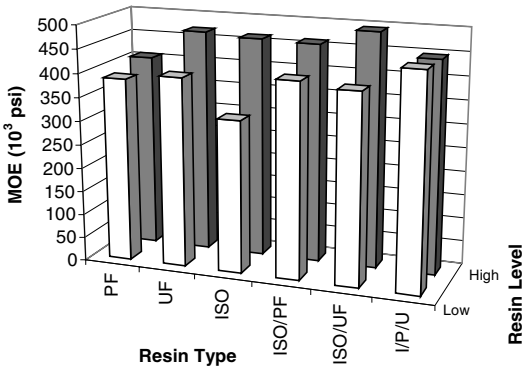


**Figure 3.** Effects of resin type and resin content on the MOE of rice hull–wood composites

adhesive system, i.e. ISO/PF, ISO/UF and ISO/PF/UF, even though the ISO content was only 1% in the resin systems. The MORs of boards bonded with 5% ISO, 1/6 ISO/PF, 1/6 ISO/UF, 1/1/3 ISO/PF/UF and 1/1/5 ISO/PF/UF met the American National Standard of Mat-Formed Particleboard standard of 2400 psi (16.5 MPa).

## Stiffness (MOE)

The relationships between modulus of elasticity (MOE) and resin type for the two resin content levels are shown in Fig. 3. The MOEs of most boards exceeded the 350 000 psi (2.4 GPa) minimum requirement of the American National Standard. The exceptions were boards that were bonded with 2.5% ISO. The significant effect of ISO on MOE was again evident. Boards bonded with 5% ISO had the highest MOE when compared to boards with the same resin content levels, and exceeded even the MOE of boards bonded with PF and ISO/PF/UF resins at the higher resin content. As with MOR, boards bonded with ISO/UF had the highest MOE of all boards.

## Thickness swelling

Figure 4 shows the relationships between thickness swelling and resin type for the two resin contents. Thickness swelling was greatly affected by resin content. Increasing the resin content from 5% to 7% reduced thickness swelling by 18.0% and 23.7% for boards bonded with UF and PF, respectively. All ISO-based resin formulations exhibited excellent dimensional stability. Boards

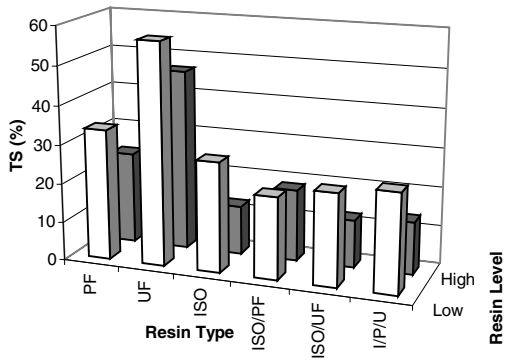


**Figure 4.** Effects of resin type and resin content on the thickness swelling of rice hull–wood composites

bonded with 1/6 ISO/UF had the lowest thickness swelling. The improvement in thickness swelling was more noticeable with increased resin contents. The reduction in thickness swelling was 55%, 48%, and 47% for ISO, ISO/UF and ISO/PF/UF, respectively, as resin content increased from low to high levels. These values show that an ISO-modified resin system can effectively enhance moisture resistance of rice hull–wood particleboards.

## Discussion and Conclusion

Modified resin systems with ISO as a minor component significantly improved the strength properties and dimensional stability of rice hull–wood particleboards. As expected, resin content had an appreciable effect on board performance. In most cases, the higher the resin content, the better the performance of the boards, in terms of both strength properties and dimensional stability. The superiority of the resin system containing ISO is apparent for all resin levels in the test. Conventional UF and PF resins by comparison did not perform well with rice hull–wood composites.

The most interesting result in the study was the overall improved performance of the ISO/UF resin system. The boards bonded with 1% ISO/6% UF resin had the highest internal bond strength, the lowest thickness swelling and the highest MOE and MOR. Since the cost of UF (US$0.17 $lb^{-1}$) is much lower than the cost of ISO (US$0.85 $lb^{-1}$), there could be substantial economic gains by using UF resin as the major component in an ISO/UF system.

The internal bond strength was the only board property evaluated in the study that did not meet the requirements of the American Standard of Mat-Formed Particleboard. The study showed that the internal bond strength could be increased most appreciably by raising the resin content level, and the ISO/UF resin system would be expected to provide the greatest potential for further improvement on an internal bond strength per unit cost basis. Note, however, that to maintain optimum internal bond strength : cost ratio, the increase in resin content would have to be obtained from an increase in UF resin level and not from the ISO content. Without the increase in the ISO content, the application efficiency of ISO in the resin could be critically important in further improving the performance of the ISO/UF resin system. The recent development of emulsifiable PMDI (polymeric methyl diisocyanate) for the medium-density fibreboard industry (Moriarty 1999) provides an additional avenue for efficiency improvements. A study is in progress, based on emulsifiable isocyanate adhesives in conjunction with a solvent-extended isocyanate resin system, to improve the efficiency of ISO application. It is anticipated that satisfactory internal bond strength will be achieved by improving the ISO efficiency and by increasing the UF content in the resin system.

## Acknowledgement

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# Rice Hulls, A Unique Material for the Manufacture of Extruded Biocomposites

**Peter Klatt and Simon B. Spiers[1]**

*Abstract*

Rice hulls are a waste material that is well known in all rice-growing countries. This paper describes the Husk-I-Bond process, a recently patented development that uses rice hulls for the manufacture of hollow-core load-bearing building panels. The panels, which have potential for use in earthquake or cyclone-prone areas, have excellent load-bearing capability, sound absorption and fire resistance. For this product to be useful as a building material its strength attributes must be consistent. To achieve this, fibres can be added as reinforcement. Sisal fibre confers appropriate tensile strength characteristics at a suitable price. It can also increase the strength of compressive dunnage blocks made of rice hull composite.

RICEGROWERS' Co-operative Ltd (RCL) is the major miller and marketer of rice in Australia, producing $1.2 \times 10^6$ t of paddy rice each year. Milling this rice produces 240 000 t of rice hulls annually, of which approximately 100 000 t is already gainfully used in processes previously developed by RCL's research and development group. The balance is currently disposed of by being incorporated into the soil on our own farms. Most rice-producing nations have a similar need to dispose of rice hulls: world-wide the rice industry produces in excess of $100 \times 10^6$ t of rice hulls per year. Many of these rice-growing countries require cheap housing. A process, hereafter referred to as the Husk-I-Bond process, has the potential to solve both these problems simultaneously in an environmentally friendly way.

Rice hulls are composed of 20% silica and 30% lignin (Beagle 1981), making this by-product one of the most intractable agricultural wastes known. The Husk-I-Bond process uses a patented Unistaltic Extruder to combine rice hulls and thermo-setting resins. Products can be produced that resemble particleboard in consistency.

Three product lines were identified and tested during initial research:

- hollow-core load-bearing building panels that can be used to build low-cost houses in cyclone- and earthquake-prone areas;
- roadside guide posts that are car-friendly and naturally durable;
- high density load-bearing blocks to replace timber dunnage (load spacers) used in export shipping.

These products represent a range of commodities that can be used in many applications in all countries to replace products usually derived from timber. Other agricultural residues such as coir, sisal and African veld grass have also been successfully tested. This paper describes the main features of the Husk-I-bond process, the products produced by it and the use of fibre reinforcement to improve the mechanical properties of building panels made using it.

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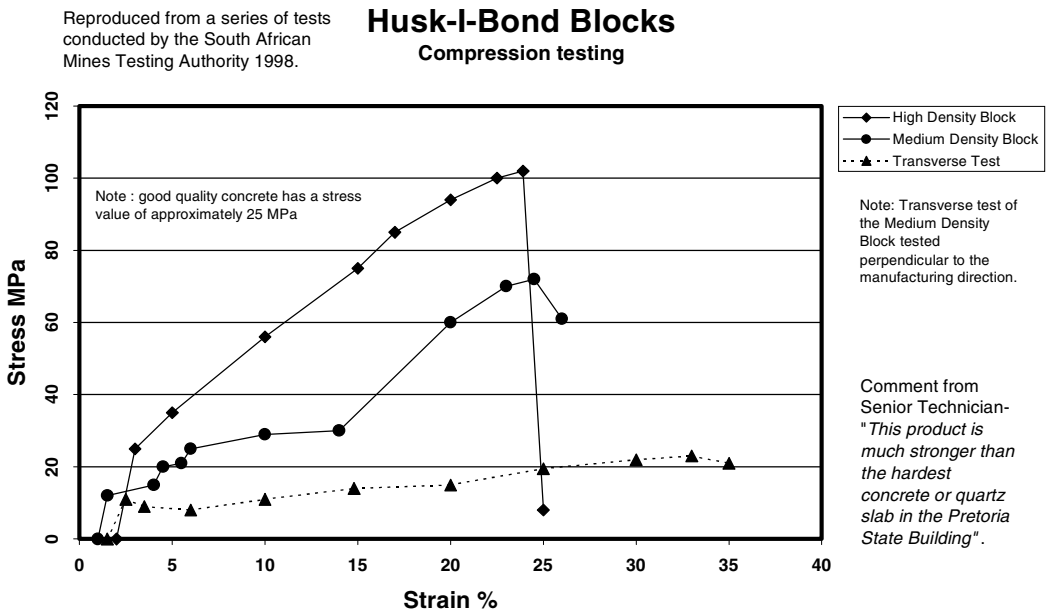


**Figure 1.** Stress–strain relationships for Husk-I-Bond blocks, reproduced from a series of tests conducted by the South African Mines Testing Authority (1998)

### The Husk-I-Bond Process

The Husk-I-Bond process uses hydraulic technology, which allows for continuous extrusion. In conjunction with this, the hydraulics allow for variations in extrusion pressures and thus a control on the density of the product being extruded. As density increases so does the strength, as illustrated by in-house testing and experiments conducted by Royal Melbourne Institute of Technology. Any increase in density results in increased cost as more raw products are included in the same volume.

The raw product is extruded through a heated die, which first gels the resin and then cures it to full strength. Die temperatures are critical to the success of the extruder. A die temperature that is too hot burns the product and a die temperature that is too cold prevents the product from being extruded. This translates back to another critical element, the die length. Currently, dies are manufactured to a length depending on a residence time and the cross-section of the product being extruded. Typically for a 75 mm × 75 mm cross-section, the die is 1400 mm long.

The Husk-I-Bond process itself imparts some special properties to the end products. The blocks, for example, have demonstrated great strength under compression as shown in Fig. 1. The hollow core extruded wall panel has been selected for further development because of its commercial potential. The panels are intended for load-bearing in single-storey building systems for low-cost homes. Later the panel will be refined for use in high-rise building applications in Australia and elsewhere.

The Husk-I-Bond process was acquired in 1998 from the original inventor, Mr Ken Pagden of Leeton, for development and commercialisation. A pilot plant has been built, to bring the prototype products to full commercial status. For the sake of clarity, only the Hollow-core Panel process is described next, but the processes for the other products are similar and/or share some of the development stages of the panel.

The surface properties and high resilience of rice hulls have proved to be a technical challenge to researchers trying to develop composite panels from rice hulls. Previously it has been difficult to bond the silica coating with conventional resins, and large additions of resin have usually been needed to achieve bond strengths similar to those of conventional boards. The extrusion of

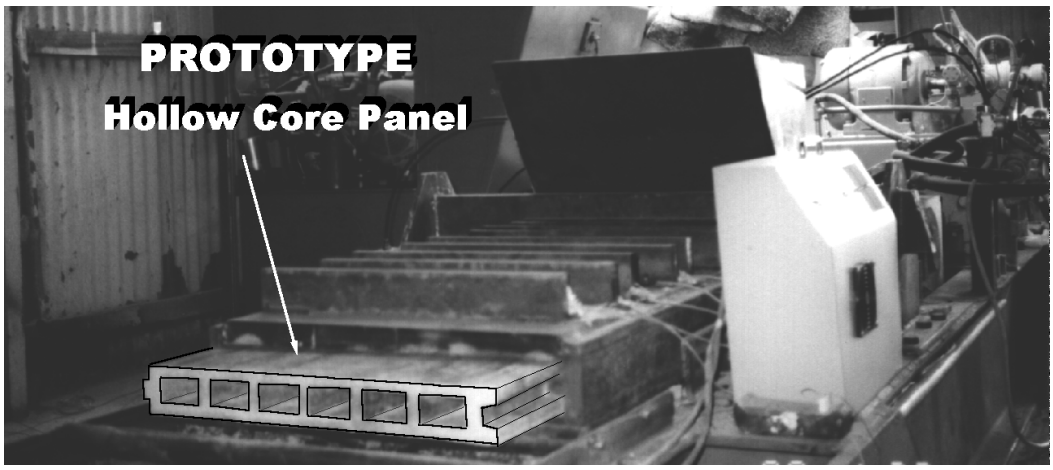


**Figure 2.** A rice-hull hollow-core load-bearing panel being extruded

rice hull mixtures also involves high power requirements and die wear.

### Hollow-core Building Panels

In most countries, supply of adequate housing for the population poses continuing problems. Many house construction methods now employ pre-fabricated panels of one sort or another, but these pre-fabricated panels rarely fit exactly. The Husk-I-Bond panels are fully extruded (see Fig. 2), are true and square in all planes, and are forced to slot together using a proven tongue and groove system.

Framing is unnecessary, as the panels have been extensively tested by the Australian CSIRO for use as a load-bearing structure, with surprising results. Typically a single-storey house panel of 1200 mm width must bear a load of 2200 kg on an axial offset of 5°. The Husk-I-Bond panel is only 400 mm wide and supports over 4000 kg. It has frequently been tested at up to 6000 kg without rupture, and has then snapped back to its original form. This latter feature has excited many people involved in developing low-cost housing for earthquake-prone areas.

Termites find rice hulls indigestible, as has been demonstrated by many groups previously (QFRI 2001). The Husk-I-Bond process merely builds on this desirable property. Generally the product is composed of 85% rice hulls with resins and other ingredients making up the balance. The high concentration of rice hulls ensures that termites will avoid the product. Rice hulls naturally resist decomposition by having very high silica and lignin contents. This natural feature ensures that fungal or mould attack is reduced, and only minor amounts of fungicides need be added for critical applications.

### Modular units

Two distinct manufacturing units are under development: a modular Unistaltic Extruder, suitable for inclusion in a multi-stand factory; and a self-contained module capable of being trucked to any suitable location. A typical modern particleboard plant needs 100 000 t of material and an investment of A$100 million to be viable. By contrast one Unistaltic Extruder module typically uses 2000 t of rice hulls per annum. If more production is needed then it is simple to add a new module. The process is capable of many modes of operation, from manual operation, needing three people per unit, to full automation needing three people for six extruders.

The self-contained module is intended for use by small rice milling applications where it would be appropriate to move the module to the rice hull source, manufacture panels for housing, and then move on to the next town. The estimated construction price of one module is $US40 000.

## Other Products

The success of the other products will rely heavily on their ability to perform better than hardwood products in similar applications. Typically in Australia the supply of good hardwood for dunnage is declining. There is also an increasing need for such timber to be fumigated when used in export shipping, and sometimes all timber is prohibited. The Husk-I-Bond process can make pre-shaped dunnage blocks to meet a variety of applications with some identifiable advantages:

- the blocks are completely stable, and will not dry out or shrink during voyages;
- the blocks have a higher coefficient of friction than dry hardwood;
- the material does not harbour any insect pests;
- the blocks can be reused many times.

One stevedoring company has stated that it could potentially save one day in port by using the blocks. Other niche markets for special blocks will be pursued as the project evolves.

Similarly the project to develop guide-posts is driven by the need for a cost-effective and technically superior alternative to timber posts. Alternatives such as steel are costly, while plastic posts seem to have technical problems (QFRI 2001). For example, they become loose and can be blown from the vertical position by the wind. One of the major drawbacks of timber posts is that a jagged spike is often left after a collision. The Husk-I-Guide post has exhibited the following advantages: it breaks off cleanly; it is price competitive to timber; and it is resistant to termites and rot.

## Fibre as a Strengthening Agent

Like concrete and many other ceramic building products the Husk-I-Bond product has a high compressive modulus (see Fig. 1). Although the Husk-I-Bond block has a high yield point, similar to concrete, the broadness of the chart is low, indicating that a small energy input will cause failure. Figure 3 shows that this product can rapidly deteriorate as soon as its elastic limit has been reached. It therefore has poor ductile properties.

At higher resin content, as shown in Fig. 3, the peak yield force of a Husk-I-Bond block increases. However, there is also an increase in its brittleness. The block for batch number 10052 containing 23% resin has a much more abrupt peak than the other blocks that had lower resin contents (10058, 19% resin; and 10061, 15% resin). Batch 10058 (19% resin) has a steeper peak than Batch 10061 (15% resin). This suggests that the

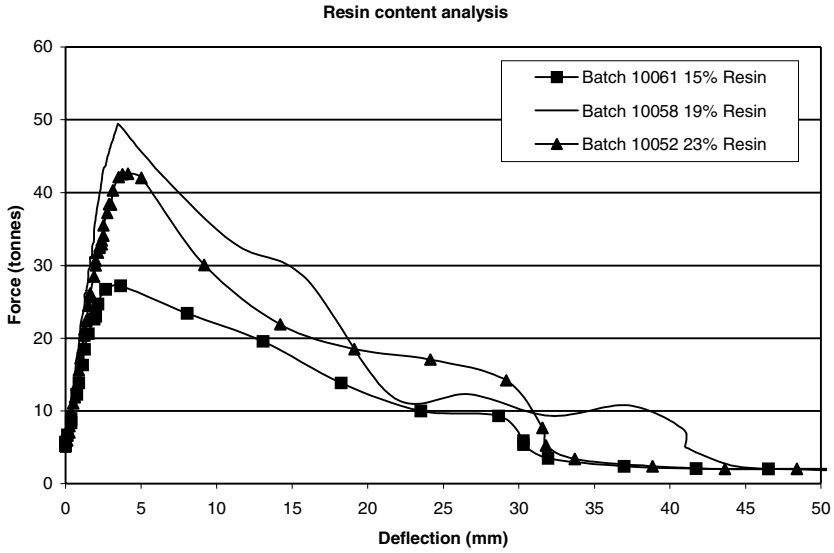


**Figure 3.** Correlation between force and deflection for several resin concentrations

increase in resin content increases the brittleness of the block, even though it also increases its overall strength. These results accord with the known properties of phenolic resins which have a tendency to be very brittle (Woebcken 1995).

A building product that is to be used in cyclonic areas and possible earthquake sites must be able to flex and bow, absorbing large amounts of energy before the product fails. To achieve this in concrete, steel reinforcement is used, but on exposure to the weather the steel rusts causing 'concrete cancer' and other deformities in the product. Although it is possible to extrude steel wires into the Husk-I-Bond panel it is costly and technically difficult. A much more uniform and consistent method of increasing the strength of Husk-I-Bond is to incorporate a fibre as a reinforcing agent before the product is extruded.

## Selecting the fibre

Sisal is a fibrous plant material that is often used for weaving ropes, carpets and mats. There are many reasons why sisal has been selected as the preferred fibre source for these applications. Richardson and Lokensgard (1997) indicate that there are six general variables that influence the properties of reinforced composite materials and structures.

1. *Interfacial bond between matrix and fibre*

   As with most phenolic resins, Novolak resins have a good affinity with natural fibres. As well, this resin can be powdered, allowing it to be used in existing ribbon blender mixing equipment (Woebcken 1995). Therefore sisal should bond well with phenolic resin using the standard processing equipment.

2. *Properties of the reinforcement*

   Richardson and Lokensgard (1997) suggest that sisal fibres have good moisture resistance, impact strength and tensile strength, and are dimensionally stable — all properties that are essential to a building product. Bolton (1994) further suggests that plant fibres can have a specific tensile strength in the range 1.60–2.95 GPa and a specific tensile modulus of 10–130 GPa.

   An advantage of sisal fibre is that it has lower specific gravity than glass fibre. Plant fibres typically have a specific gravity of 0.6–1.2 whereas glass fibre has a specific gravity of 2.6 (water being 1.0 at 25°C at sea level) (Perry et al. 1984). Having a slightly lower specific gravity allows for a lighter product which is critical when the product needs to be exported and there is an increase in cost for any increase in weight.

3. *Size and shape of the reinforcement*

   The desired length of fibre for reinforcement is in the range 10–20 mm. The fibres can be longer, but this results in problems in feeding and blending of fibres with matrix. Long fibres have a tendency to clump together and agglomerate rather than blending thoroughly through the mix. Also, because fibres are gravity fed in the process, long fibres can 'bridge-out' which also causes problems with consistency of the end product.

4. *Loading of the reinforcement*

   Naturally the greater the amount of reinforcement the greater the strength of the product (Woebcken 1995). As implied above the Husk-I-Bond process requires the mixture to be fluidised to flow under the force of gravity. If too much sisal is added, again, 'bridging out' occurs and the mixture cannot be gravity-fed. This constraint has resulted in a maximum of 10% (by weight) of sisal being added in the Husk-I-Bond system.

5. *Processing technique*

   The processing technique encourages a random orientation of the reinforcement. This is a result of a series of factors including the mixing, the gravity feed and the compression stage of the process. There is no possibility of altering the process to allow the fibres to be directed in a continuous (anisotropic) or a fabric (bi-directional) orientation. In either case, the strength of the composite material, though greater, would be in a particular plane and not random as required by the building panel.

6. *Alignment or distribution of the reinforcement*

   Having a random matrix or pseudo-isotropic reinforcement orientation does not give the best reinforcement properties. It does, however, allow the reinforcement to be relatively consistent in all planes of the applied

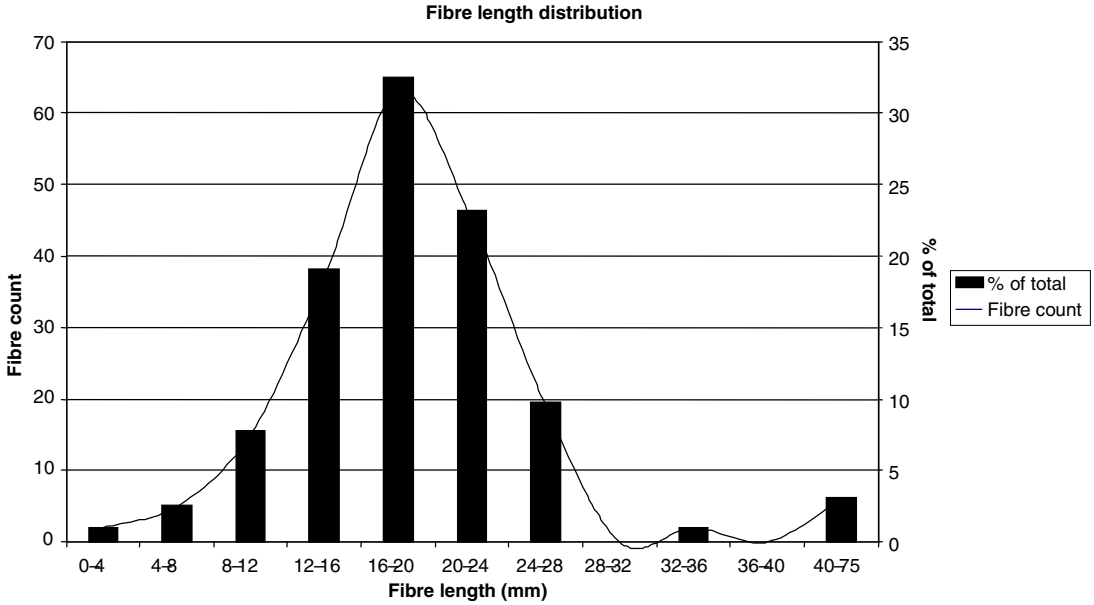


**Figure 4.** Length distribution of sisal fibres after manual sorting

force (Richardson and Lokensgard 1997). To some degree the rice hulls do line-up in one direction, in particular on the surface of the product where the friction between the die and product helps to orientate the rice hulls in the direction of extrusion. This is not experienced with the sisal fibres because they have a much higher aspect ratio and so there is more intertwining between particles.

In conjunction with these six variables the Husk-I-Bond process must take into consideration the availability, the cost and the environmental impact of the fibre.

The fibre is generally supplied in 1–1.5 m lengths and generally sells for US$300–400 $t^{-1}$ (Textile Fibre Space 2000), which is relatively cheap considering synthetic fibres such as glass and Kevlar cost US$7500 $t^{-1}$ and US$8000 $t^{-1}$, respectively (Bolton 1994). Sisal fibre is considered to be an environmentally acceptable fibre. Bolton (1995) suggests that the energy content in plant fibres is about 4 GJ $t^{-1}$, as compared to carbon fibre which contains 130 GJ $t^{-1}$, where the energy content is calculated as the amount of energy required to produce the product, and the energy stored in the product after manufacture.

The disadvantage of using a natural fibre as a reinforcing agent is that there is no uniformity from one fibre to the next. Unlike man-made fibres, which are extruded to very accurate dimensions in controlled conditions, natural fibres can have deformities and inconsistencies in width, strength and length. Since rice hulls make up the bulk of the raw material, about 80%, this should not greatly affect the overall performance of the composite.

## Fibre preparation

First, the sisal is dried at 50°C for 24 h and separated into clumps of about 250 g. This part of the process is completed manually (although a more automated system is being designed) and poor control over the sizing of fibres can result in them having a range of lengths (Fig. 4). There is a small skew to longer fibres, because of the cutter not being fed properly and the fibres being torn rather than cut.

## Using the fibre

In a trial, two batches of boards were made. One contained fibres and the other, with no fibres, acted as a control. This enabled the effect of sisal

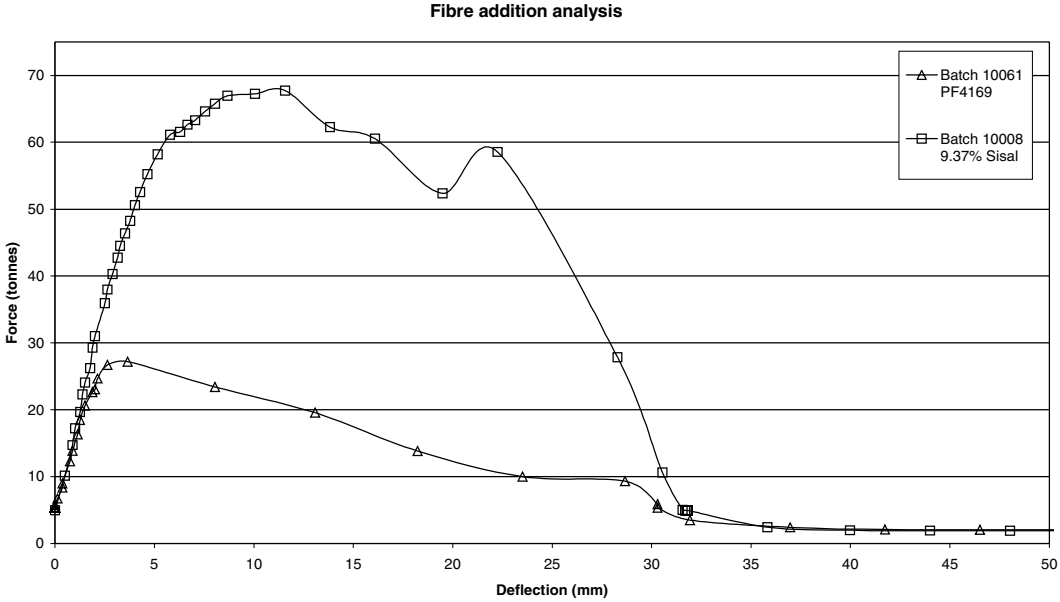


**Figure 5.** Effect of sisal reinforcement on the yield point and toughness of sisal blocks

fibre reinforcement on the properties of blocks to be estimated.

The fibre was added at a rate of 10% (w/w) of the total ground rice hulls added. The resin content was maintained at the same level in both boards, as a percentage of the rice hulls added. Both mixtures were mixed for twenty minutes. The extruder produced approximately 120 blocks for each batch. All parameters were held constant during extrusion, including temperature, pressure and extrusion rate. The blocks produced were 100 mm long.

Figure 5 illustrates the results obtained. For Batch 10008, 9.37% (w/w) of sisal fibres were added. Batch 10061 (also shown in Fig. 3) had no sisal. Clearly, the fibres have a large effect. First, they make the product much stronger, giving a much higher yield point. Second, they increase the deflection for a given force, making the blocks much more ductile.

## Conclusion

The Husk-I-Bond process, which uses a Unistaltic Extruder to manufacture a plant-fibre-reinforced, PF-bonded rice hull composite, is a major breakthrough in using the intractable rice hull. It has the potential to make a valuable range of products as well as solving the problem of disposing of the large quantities of rice hulls that are produced each year.

To impart sufficient mechanical properties to products, some type of fibre reinforcement is necessary. Of the many options, sisal fibre appears to be not only cost-effective but also environmentally friendly and otherwise suitable. As a result of adding the sisal the strength of the product can be increased by a factor of about 2.5 — a substantial increase in strength for a relatively small addition of fibre.

With timber products becoming more expensive as old growth forests become less available, the alternative is to look at agricultural waste as a source of materials to manufacture building materials. Bio-composites use renewable resources and by-products of the agricultural industry, though they still rely on developing technology to engineer a product that can be used in a variety of applications where timber is both too expensive and not necessarily the right material for the application.

Hollow-core building panels produced by the Husk-I-Bond process are a first step. They will be closely followed by pre-stressed floor panels

and, ultimately, roofing panels that will allow ‘a house to be built entirely from rice hulls’.


## Acknowledgements

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# Cement-bonded Composites from Eucalypts and Acacias

# Effect of Post-harvest Storage on the Suitability of *Acacia mangium* for the Manufacture of Wood-wool Cement Boards

**Rico J. Cabangon[1], Dwight A. Eusebio[1], Florence P. Soriano[1], Ross B. Cunningham[2] Christine Donnelly[2] and Philip D. Evans[3]**

*Abstract*

*Acacia mangium* wood has been found to be incompatible with cement and hence it is regarded as being unsuitable for the manufacture of wood–cement composites. The aim of this study was to determine whether manipulating the time that *A. mangium* billets are stored before processing could improve this species' suitability for the manufacture of wood-wool cement boards (WWCBs). Freshly felled *A. mangium* logs were converted into billets 400 mm long (150 to 250 mm in diameter). Half of the billets were debarked and all billets were then stored outdoors for 0, 6, 12 or 32 weeks. After storage, the billets were shredded and the cold water extractive content of the wood-wool was determined. Wood-wool cement boards were manufactured, and their mechanical properties were measured to assess the effects of storage time, soaking the wood-wool in water and using $CaCl_2$ as a cement setting accelerator. The cold water-soluble extractive content of *A. mangium* decreased continuously during storage. Boards made from unsoaked wood-wool obtained from fresh *A. mangium* billets had inferior board properties. Storage of billets for 6–12 weeks had a positive effect on the stiffness of boards but it was not as effective as water soaking at improving MOR. Billet storage and use of an accelerator improved board MOE and MOR particularly in boards made from unsoaked wood-wool. Storage of billets in the bark-free condition had a greater beneficial effect on the properties of WWCBs than storage of billets with their bark intact.

THE suitability of wood species for the manufacture of wood–cement composites is largely determined by the degree to which their wood inhibits the setting of ordinary Portland cement (OPC). Many wood species are incompatible with cement because they contain low molecular weight compounds that inhibit the normal setting of the cement. In general, hardwoods are less compatible than softwoods with OPC (Weatherwax and Tarkow 1964; Lee et al. 1987; Frick 1989) because they contain more inhibitory substances; for example, phenolics and sugars. Thus, many hardwoods in their natural state are unsuitable for the manufacture of wood–cement composites (Weatherwax and Tarkow 1964).

Softwoods are not readily available in the Philippines, unlike plantation hardwood species such as *Acacia mangium*. This species has been widely planted in Asia. In the Philippines, for example, about 45 000 ha of plantations have been established (Vercoe 1993). As with many other hardwood species, the wood of *A. mangium*

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**Plate 1.** Storage of *A. mangium* billets

inhibits the setting of cement (Rahim and Ong 1983). Tachi et al. (1988) found that cement-bonded particleboards made from nine-year-old *A. mangium* trees had low bending strength, even when calcium chloride ($CaCl_2$) accelerator was added to the cement. They also found that the incompatibility was due to the presence in heartwood of the flavonoid teracacidin which has a 7,8-dihydroxyl group in a leucoantho-cyanidin structure. Rahim and Wan Asma (1990) reported that *A. mangium* has a sugar content of 0.54%, slightly above the level of 0.5% suggested by Solorzano (1989) as being the upper limit for wood to be used for the manufacture of wood–cement composites. Rahim and Wan Asma (1990) recommended natural storage of logs to reduce their wood sugar content before converting them into wood–cement particleboard.

A number of studies have found that storage of logs outdoors for 4 to 20 weeks reduces the wood sugar content and increases the suitability of the wood for the manufacture of wood–cement composites. Schwarz and Simatupang (1984) reported a 75% decrease in the sugar content of temperate wood species such as beech (*Fagus sylvatica*) when the logs were stored outdoors for three months. The authors also found that air drying for 16 weeks increased the suitability of birch (*Betula* sp.) logs for cement-bonded particleboard manufacture. A shorter storage time was sufficient if the chips were either dried or extracted with water before board manufacture. Lee et al. (1987) showed that particleboard made from Southern pine (*Pinus* sp.) and hardwoods stored for two months in summer conditions had higher compressive strength than boards made from the same woods stored at 45°F (7.2°C). This result is relevant to boards with low cement:wood ratios of 4:1 and 5:1. In tropical environments such as Malaysia, the sugar content of rubberwood (*Hevea brasiliensis*) was reduced from 1.67% to 0.23% after 20 weeks of storage. The decrease in sugar content was rapid when the logs were stored without bark (Azizol and Rahim 1989).

The bending strength of cement-bonded particleboard made from rubberwood was best when the billets were stored with and without bark for 4–8 weeks and 12 weeks, respectively (Rahim et al. 1989). It is believed that fungi and other microorganisms colonised the billets, reducing the sugar content by consuming the low molecular weight carbohydrates present in wood (Norhara 1981). An early study showed that colonisation of loblolly pine (*Pinus taeda*) wood by blue stain fungi enhanced the setting of cement (Davis 1966). Brown stain fungi also increased the compatibility of wood with cement (Raczkowski et al. 1983). However, colonisation of wood by cellulolytic micro-organisms can cause wood to

decay, consequently reducing its compatibility with cement. Weatherwax and Tarkow (1967) incorporated decayed southern pine wood into cement and found that the setting time of cement was greatly increased. They attributed this effect to the degraded cellulose fraction of the decayed wood.

Decay can occur when logs are stored outdoors for prolonged periods of time and therefore care needs to be taken when using outdoor storage as a means of reducing the sugar content of wood. For example, Simatupang et al. (1989) found that the strength of cement-bonded particleboard made from beech decreased if the boards were made from logs that had been subject to decay when stored outdoors for 32 weeks. Because of the negative effect of prolonged storage of logs and associated decay on the suitability of wood for wood–cement composites, in Malaysia rubberwood stored outdoors for more than 6 weeks is considered unsuitable for the manufacture of wood–cement particleboard.

There is no information on whether storage of *A. mangium* logs improves the compatibility of this species with cement. Soaking of wood-wool in water and the addition of a cement setting accelerator, usually $CaCl_2$, are the normal means of improving the compatibility of hardwoods for the manufacture of wood-wool cement boards in the Philippines. During times of drought, water pre-treatment cannot be undertaken, which results in lost production. Furthermore, the use of $CaCl_2$ increases the cost of boards. It would therefore be desirable to develop alternative methods of increasing the compatibility of *A. mangium* wood with cement. The aim of this study was to determine whether manipulation of log storage time could be used to increase the compatibility of *A. mangium* wood with cement, and to compare the effects of storage time (if any), soaking in water, and use of a cement setting accelerator.

## Materials and Methods

### Sampling and storage

Eight freshly-felled 10-year-old *A. mangium* logs were obtained from the Provident Tree Farms Inc. (PTFI) plantation on the island of Mindoro, Philippines. The trees were felled during the dry season and were labelled A to H in random order. Each log was cross-cut into eight billets, 400 mm long, with diameters ranging from 150 to 250 mm. The billets were labelled from 1 to 8 from the top to the base representing the position of each billet with respect to the height of the tree. The first four billets from logs labelled A to D were left with their bark intact while the remaining four billets were debarked. The first four billets from trees labelled E to F were debarked while the remaining billets were left with their bark intact. Debarked billets and billets with bark were labelled and assigned at random to specific storage times. The billets were then randomly stacked (Plate 1) in an open area of the Forest Products Research and Development Institute in Laguna, Philippines, and left to season for periods of 0, 6, 12 or 32 weeks. After storage, the water soluble substances in the wood were determined and the wood from the billets was used to manufacture WWCBs.

### Determination of cold water soluble extractives

Shredded wood was taken from each billet after its assigned storage time. The heartwood and sapwood were separately converted into particle form using a Willey mill. Ground wood passing a 425 mm sieve and retained by a 250 mm sieve was used for analysis. Cold water soluble extractive content of ground wood was determined by following the ASTM D1110-84 test method for water solubility of wood (Anon. 1990).

### WWCB manufacture

In total, 64 boards were produced. Sixteen boards were manufactured each day for four days.

First, for each storage period, eight billets from the stack were cut longitudinally into quarters and assigned a label, from ‘a’ to ‘d’, at random (Fig. 1). The quartered billets were converted into wood-wool with dimensions 0.4 mm × 4 mm x 400 mm, using a vertical-type shredding machine. The wood-wool produced from each quarter was placed separately in air-permeable sacks and labelled.

For each billet, two of the sacks containing shredded wood were soaked in tap water for 24 h to leach out low-molecular weight extractives that could interfere with the setting of cement. The soaked and the unsoaked wood-wool were

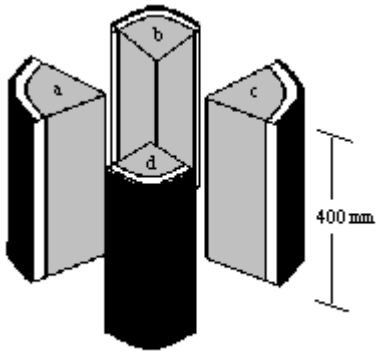


**Figure 1.** Quartering of billets before shredding into wood-wool

air-dried to equilibrium moisture content (EMC) of about 18% for two days.

Shredded wood, ordinary Portland cement (Fortune brand), $CaCl_2$ (for some boards) and water were weighed separately in quantities required to produce boards with the desired density of 650 kg $m^{-3}$. Board thickness was 12 mm, wood:cement ratio was 0.75:1, and water: cement ratio was 1. Wood-wool, water (in some instances containing dissolved $CaCl_2$), and cement were mixed manually in a plastic basin for 5–8 min or until the wood was thoroughly coated with cement paste. $CaCl_2$ was added to the mixture for one of the batches of soaked and unsoaked wood-wool obtained from a billet. The cement-coated wood-wool was uniformly distributed in a detachable forming box (200 mm × 300 mm × 300 mm) placed over a caul plate lined with plastic sheet. The caul plates with the formed mats were placed on top of each other in batches of eight. High density wooden stoppers corresponding to the desired board thickness of 12 mm were placed on the edges of the caul plates and then pressure was applied using a hydraulic press until the caul plates met the stoppers. After 24 h of maintained pressure, the boards were removed from the press. They were conditioned for 28 days in a dry and well-ventilated area, before board property tests.

### Board property tests and statistical analysis

Manufactured boards were tested for their bending strength (MOR), stiffness (MOE), thickness swelling and water absorption properties. The MOR and MOE tests were carried-out on rectangular WWCB specimens (50 mm × 230 mm) using a Shimadzu universal testing machine. The test span was 180 mm and the rate of loading was 5 mm $min^{-1}$. Thickness swelling and water absorption of specimens were determined by measuring specimen thickness and weight before and after soaking in water for 24 h.

**Table 1.** Significant effects of experimental variables, and their interactions, on bending strength (MOR), stiffness (MOE), thickness swelling and water absorption of WWCBs made using *Acacia mangium*

| | Response variable | | | |
|---|---|---|---|---|
| Experimental factor | MOR | MOE | TS | WA |
| Storage time (T) | *** | *** | *** | *** |
| Storage of logs with or without bark (B) | ** | ** | ns | * |
| Soaking (S) | *** | *** | *** | *** |
| Accelerator (A) | *** | *** | *** | *** |
| B × S | *** | ns | ns | ns |
| T × S | *** | *** | ns | ** |
| B × A | ** | * | ns | ns |
| T × A | ** | *** | ns | ns |
| S × A | ns | ns | ns | ns |
| B × T × S | ns | ** | ns | ns |
| B × T × A | ns | ns | ns | ns |
| B × S × A | ** | ns | ns | ns |
| T × S × A | ** | * | ns | ns |
| B × T × S × A | ns | ns | ns | ns |

*$p < 0.05\%$; **$p < 0.01\%$; ***$p < 0.001\%$; ns = not significant

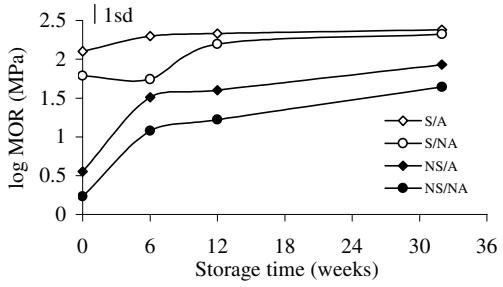


**Figure 2.** Effect of storage time, soaking and cement setting accelerator on the MOR of WWCB made from *A. mangium* (S = soaked, NS = not soaked, A = accelerator, NA = no accelerator)

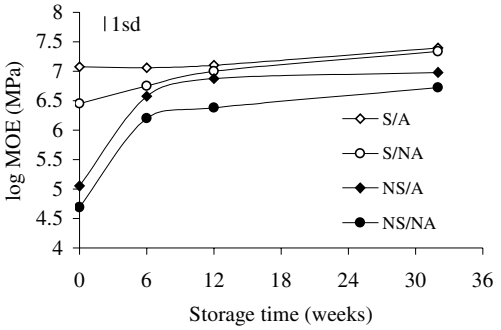


**Figure 3.** Effect of storage time, soaking and cement setting accelerator on the MOE of WWCB made from *A. mangium* (S = soaked, NS = not soaked, A = accelerator, NA = no accelerator)

These specimens had dimensions similar to the bending test specimens. The main effects of and interactions between the fixed factors on board properties were tested for significance using an appropriate multi-factorial analysis of variance model at the 5% significance level. Statistical computation was performed using Genstat 5 (Lawes Agricultural Trust 1994).

## Results and Discussion

Table 1 shows the significant effects on board properties of storage time, soaking, use of an accelerator and storage with or without bark. Figures 2–7 summarise the most important findings. In accord with the factorial design of the experiment, the choice of mean values used in each graph was determined by the most significant interaction term in the analysis (Table 1). Some graphs include a least significant difference (LSD) bar to show significant differences between means.

Storage of billets generally improved the properties of WWCBs, and the positive effect of storage on board properties was generally greater when logs were stored in the bark-free condition. Soaking of wood-wool in water before the manufacture of boards, or the use of a cement setting accelerator, also improved the properties of boards, as expected. Figures 2 and 3 show the effects of storage time, soaking and use of $CaCl_2$ on MOR and MOE, respectively, in WWCBs made from *A. mangium*. The use of wood-wool from fresh billets (not stored) that were not soaked in water before board manufacture and with no added $CaCl_2$ resulted in boards with inferior strength properties, confirming the incompatibility of *A. mangium* with OPC. Storage of billets before their conversion into WWCBs and the use of a cement setting accelerator both had positive effects on MOR, particularly where the wood-wool was not soaked in water before board manufacture. However, when boards were made from logs stored for 12–32 weeks and then soaked in water, the addition of an accelerator resulted in little additional improvement in properties.

Low stiffness (MOE) values were obtained for boards made from unsoaked wood-wool from fresh billets. However, storing the billets before board manufacture and the addition of a cement accelerator significantly increased board MOE. After 12 weeks of storage, the MOE of boards made from unsoaked wood-wool treated with an accelerator was comparable to the MOE of boards made from soaked wood-wool without an accelerator.

Storage of beech logs for 32 weeks has been shown to have a deleterious effect on the properties of wood-cement particleboard (Simatupang et al. 1989). However, storage of *A. mangium* logs for 32 weeks had no apparent deleterious effect on the mechanical properties (MOR and MOE) of WWCBs. This result suggests that *A. mangium* logs may still be suitable for WWCB manufacture even after 32 weeks of natural storage in the Philippines.

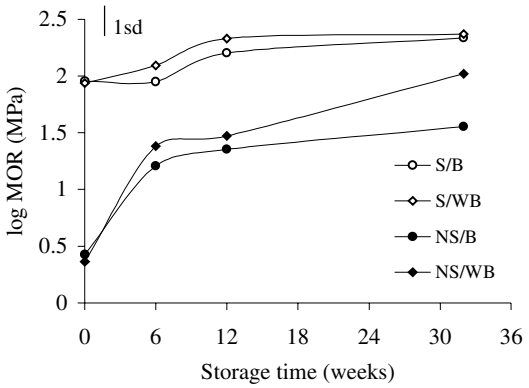


**Figure 4.** Effect of billet storage condition, soaking, and storage time on the MOR of WWCBs made from *A. mangium* (S = soaked, NS = not soaked, WB = billets stored without bark, B = billets stored with bark)

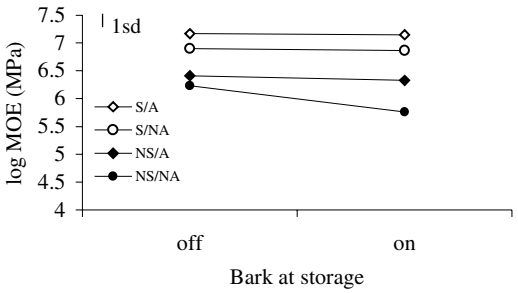


**Figure 5.** Effect of billet storage condition, soaking, and cement setting accelerator on the MOE of WWCBs made from *A. mangium* (S = soaked, NS = not soaked, A = accelerator, NA = no accelerator)

The MOR of boards was affected by the interaction of billet condition during storage (with or without bark), storage time and soaking of wood-wool before board manufacture (Fig. 4). Boards made from unstored fresh billets and unsoaked wood-wool had low MOR. However, if the billets were stored for 6–32 weeks before board manufacture then there was an increase in MOR, regardless of whether the billets had been stored with or without bark. Rahim et al. (1989) found that the maximum bending strength of cement-bonded particleboard was attained by storing rubberwood billets outside for 4–8 weeks in the bark-free condition. Results here show that after 12 weeks of storage, board MOR continued to increase, and after 32 weeks the boards made from billets debarked before storage showed higher bending strength than boards made from billets with bark. On the other hand, there was no significant effect of storage time in boards that were made from soaked wood-wool, irrespective of storage condition.

Board MOE was also affected by the interaction of billet condition during storage, soaking of wood-wool before board manufacture and the addition of an accelerator (Fig. 5). Boards made from unsoaked wood-wool had significantly lower MOE, most notably in those boards that were manufactured without accelerator, and where the wood-wool came from billets that were stored with their bark intact. In contrast, the MOE of boards made from soaked wood-wool did not vary, regardless of whether they contained an accelerator or came from billets that were stored with or without bark.

The storage of *A. mangium* billets before their conversion into WWCBs had a positive effect on both the thickness swelling and water absorption of the boards (Figs 6 and 7). Both these characteristics improved as storage time increased. High thickness swelling and water absorption were observed in boards made from unstored fresh logs, but even 6 weeks of storage caused significant reductions in thickness swelling and water absorption. There was a small decrease in both thickness swelling and water absorption as a result of storing billets for between 6 and 12 weeks. Prolonged storage, for up to 32 weeks, had positive effects on thickness swelling and water absorption.

The water absorption of boards from soaked and unsoaked wood-wool (Fig. 7) showed similar trends. The lowest water absorption values were observed for boards made from soaked wood-wool from billets stored for 32 weeks. Similarly, the lowest water absorption value for boards made from unsoaked wood-wool was observed when the billets had been stored for 32 weeks. However, this value was equivalent only to the water absorption value of boards made from soaked wood-wool obtained from billets that had been stored for 6 or 12 weeks.

Soaking the wood-wool before board manufacture had favourable effects on both the thickness swelling and the water absorption of boards (Table 1). Irrespective of storage time there was a marked reduction in the water absorption of

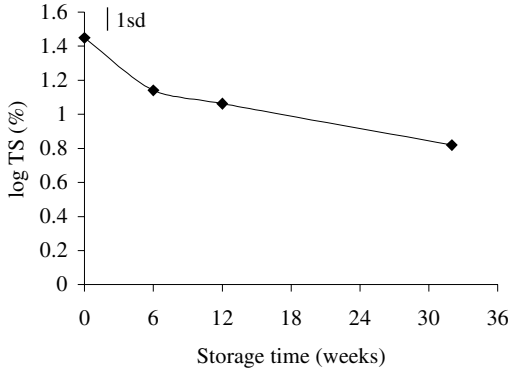


**Figure 6.** Effect of storage time on the thickness swelling of WWCBs made from *A. mangium*

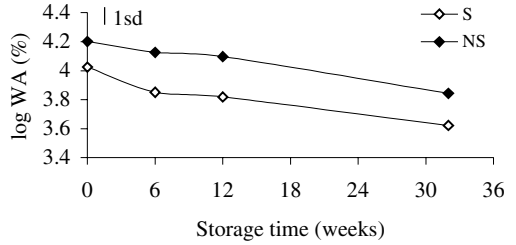


**Figure 7.** Effect of storage time and soaking on the water absorption of WWCBs made from *A. mangium* (S = soaked, NS = not soaked

boards as a result of soaking wood-wool, as expected (Table 1).

The use of $CaCl_2$ during board manufacture also led to significant improvements in thickness swelling and water absorption (Table 1). Enhanced cement setting and consolidation could have been achieved in boards that contained $CaCl_2$ and this may have restricted the absorption of water and swelling of the wood-wool compared to boards manufactured without accelerator. Storage of billets with or without bark affected water absorption but not thickness swelling (Table 1). Storing the logs without bark significantly improved the water absorption of boards, and this may be attributed to the greater reduction of inhibitory substances in *A. mangium*.

### Cold water solubility of *Acacia mangium*

The solubility of wood in cold water gives an indication of the amount of sugars, tannins, gums and colouring matter in the wood (Anon. 1990).

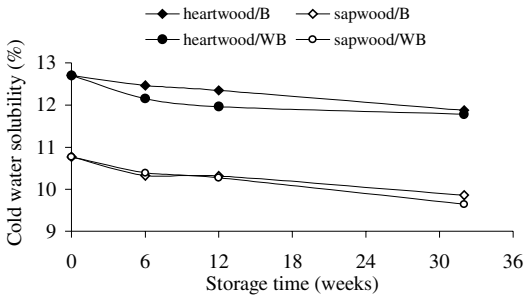


**Figure 8.** Effect of storage time on the cold water solubility of *A. mangium* (WB = billets stored without bark, B = billets stored with bark)

Cold water solubility of *A. mangium* wood was highest in fresh samples (Fig. 8) and continuously decreased as a result of storage of billets outdoors. Since the water-soluble fraction of wood contains polysaccharides and other compounds that inhibit the setting of cement, this probably explains why there was a positive correlation between storage of logs and improvements in WWCB properties. Generally, wood from billets stored without bark had lower solubility in cold water than wood from billets stored with bark, but the effect was not significant. In contrast, a marked difference in solubility in cold water can be clearly observed between sapwood and heartwood (Fig. 8). Heartwood samples had higher solubility than sapwood suggesting greater amounts of substances that could inhibit cement setting.

## Conclusion

*Acacia mangium* in its natural state is highly incompatible with ordinary Portland cement. Post-harvest storage of *A. mangium* for 6–32 weeks improves its compatibility with OPC, although water extraction is more effective than storage. The positive effect of post-harvest storage of logs on the properties of WWCB is more pronounced when unsoaked wood-wool is used and can be correlated to the decrease in the amount of cold-water soluble extractives present in *A. mangium* wood.

The use of $CaCl_2$ as a cement setting accelerator can also improve the suitability of *A. mangium* for the manufacture of WWCBs. An additive such as this is not required, however, if the wood has

been subjected to prolonged storage before it is used for the manufacture of WWCBs.

In general, boards made from billets that are stored without bark show higher bending strength than boards made from billets stored with bark. If the wood-wool is to be soaked in water before board manufacture, or if $CaCl_2$ is to be added to boards, billets can be stored with or without bark. Otherwise, the billets should be stored without bark to increase the boards' MOR. Lower thickness swelling and water absorption of boards are other benefits of storage of billets.

## Acknowledgements

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# Manufacture of Low-cost Wood–Cement Composites in the Philippines Using Plantation-grown Australian Species: I. Eucalypts

**Dwight A. Eusebio[1], Florence P. Soriano[1], Rico J. Cabangon[1] and Philip D. Evans[2]**

*Abstract*

Laboratory size (300 mm × 300 mm) wood-wool cement boards (WWCBs) with a thickness of 12 mm were produced using shredded wood ('excelsior') of *Gmelina arborea*, *Eucalyptus tereticornis* and *E. grandis*. The effects of soaking the excelsior in water prior to board production (0, 6, 12, 24 h), wood–cement ratio (50:50, 40:60, 30:70) and cement setting accelerator (none, $CaCl_2$, $Al_2(SO_4)_3$) on board properties were examined. The highest dry MOR values of the WWCBs were obtained from boards containing $CaCl_2$ as cement setting accelerator and at a wood–cement ratio of 40:60. *Gmelina arborea* excelsior required soaking for at least 6 h before it was suitable for the manufacture of WWCBs, but eucalypt excelsior could be used unsoaked. The MOE of the boards increased as the amount of cement increased, to a wood:cement ratio of 30:70, especially in the case of WWCBs made from *G. arborea.* Both the MOR and MOE of the boards dramatically decreased when boards were soaked in water for 24 h. In general, boards containing unsoaked excelsior exhibited the largest thickness swelling and water absorption irrespective of whether they contained a cement setting accelerator. The properties of certain boards containing eucalypt excelsior were comparable to those of boards made from *G. arborea*. This suggests that eucalypts may be used for the commercial production of WWCBs, which could expand the raw material base for this panel product.

Wood-wool cement board (WWCB) combines the properties of two important construction materials: cement and wood. Its use is of particular interest in countries where climate and environmental conditions make extremely durable products essential. WWCB has outstanding potential as a housing and building component because it resists biological degradation and has excellent insulation capabilities against heat and noise.

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Research in the Philippines has examined the effects of a number of parameters, such as wood species, wood:cement ratio, type of accelerator, amount of water, soaking time and board density, on the properties of WWCB. To date, studies have concentrated on locally available wood species and this has led to the establishment of several WWCB plants that are using mainly indigenous species (Pablo 1989).

*Eucalyptus* is the most important genus of Australian forest trees, and contains over 500 species. Several species are extensively planted in SE Asia; the eucalypts introduced and grown in the Philippines include *E. grandis*, *E. deglupta*, *E. camaldulensis*, *E. tereticornis* and many more. According to various estimates, eucalypt planta-

tions cover probably between 8 and 12 million ha worldwide (SBS 1990; Turnbull 1991).

A number of studies have examined the use of eucalypts for the manufacture of WWCBs. One of the key issues when examining the suitability of wood species for the manufacture of most wood–cement composites is the effect that the wood has on the setting of cement. Measurement of the extent to which wood depresses the maximum hydration temperature ($T_{MAX}$) of cement (usually 60–70°C) has mainly been used to assess the compatibility of eucalypt wood with cement. Using such a system, Sandermann and Kohler (1964) ranked *E. diversicolor* as incompatible with cement ($T_{MAX}$ of 44°C) and unsuitable for the manufacture of wood–cement composites, whereas *E. marginata* was rated as being slightly more compatible ($T_{MAX}$ of 56°C). *Eucalyptus camaldulensis* was rated as compatible and moderately compatible with cement by Jain et al. (1989) and Hachmi and Moslemi (1989), respectively. Hachmi and Sesbou (1991), however, found that provenances of *E. camaldulensis* were incompatible with cement. Both *E. gomphocephala* (Hachmi and Moslemi 1989) and *E. saligna* from 3–4 year old thinnings (Manzanares et al. 1991) have been rated as being moderately compatible with cement. *Eucalyptus grandis* wood was considered unsuitable for the manufacture of cement-bonded composites because of its poor compatibility with cement (Rahim and Ong 1983). The tropical eucalypts *E. pellita* and *E. urophylla* and a variety of Western Australian mallee eucalypts were classed as moderately compatible with cement by Semple et al. (1999, 2000).

A number of studies have manufactured wood–cement composites from eucalypts and then examined the physical and mechanical properties of board samples. Kamil and Ginoga (1975) manufactured WWCBs from untreated *E. deglupta* wood, but were unable to make boards of acceptable quality. In contrast, a later study by Pablo (1989) found that WWCBs with satisfactory mechanical properties could be made from *E. deglupta* provided that the wood-wool was soaked in cold water before being mixed with cement. Paribotro (1978) found that the performance of *E. deglupta* in WWCB was strongly influenced by whether the wood was obtained from different plantation sites in Indonesia, suggesting strong geographic and/or genetic influences on the chemical constituents in the wood that affect cement setting. Hawkes and Robinson (1978) studied the suitability of *E. grandis* and two provenances of *Pinus kesiya* for the manufacture of WWCB and found that boards manufactured from *E. grandis* exhibited small to severe signs of cement inhibition. They concluded that *E. grandis* was unsuitable for the manufacture of WWCB, but they cautioned that inhibition of cement hydration in their boards might have been due to an oil-based preservative that was used to prevent fungal contamination of *E. grandis* logs. Accordingly, they recommended further tests to examine the suitability of *E. grandis* for the manufacture of WWCB. *Eucalyptus deglupta* was found to be only marginally suitable for the manufacture of cement-bonded particleboard by Tachi et al. (1988) although the authors attributed the poor performance of *E. deglupta* compared to other fast-growing tropical hardwood species to poor flake geometry, rather than the presence of inhibitory wood constituents. Wood and bark from 5-year-old *E. camaldulensis* plantations produced cement-bonded particleboard of very poor quality (Yasin and Qureshi 1990). Soaking of *E. camaldulensis* flakes in cold water to remove inhibitory wood constituents, followed by the use of calcium chloride as a cement setting accelerator, did not enable boards with satisfactory bending strength and thickness swelling to be made (Yasin and Qureshi 1990). Soaking flakes for 1 h in hot water produced better results, and following such a treatment cement-bonded particleboards with satisfactory properties could be made from *E. camaldulensis.*

In the Philippines, the most widely used wood species for WWCB manufacture is *Gmelina arborea* which is an industrial tree plantation species. The reasons for its widespread use for the manufacture of WWCB are its rapid rates of growth, its ability to grow on a variety of sites and its ease of conversion into wood-wool. *Gmelina arborea* is not an ideal raw material for the manufacture of WWCB as its wood in its native state is incompatible with cement and has to be pretreated by soaking in water for 24 h to leach out the chemicals that inhibit cement curing and hardening (Cabangon 1997). There is therefore a

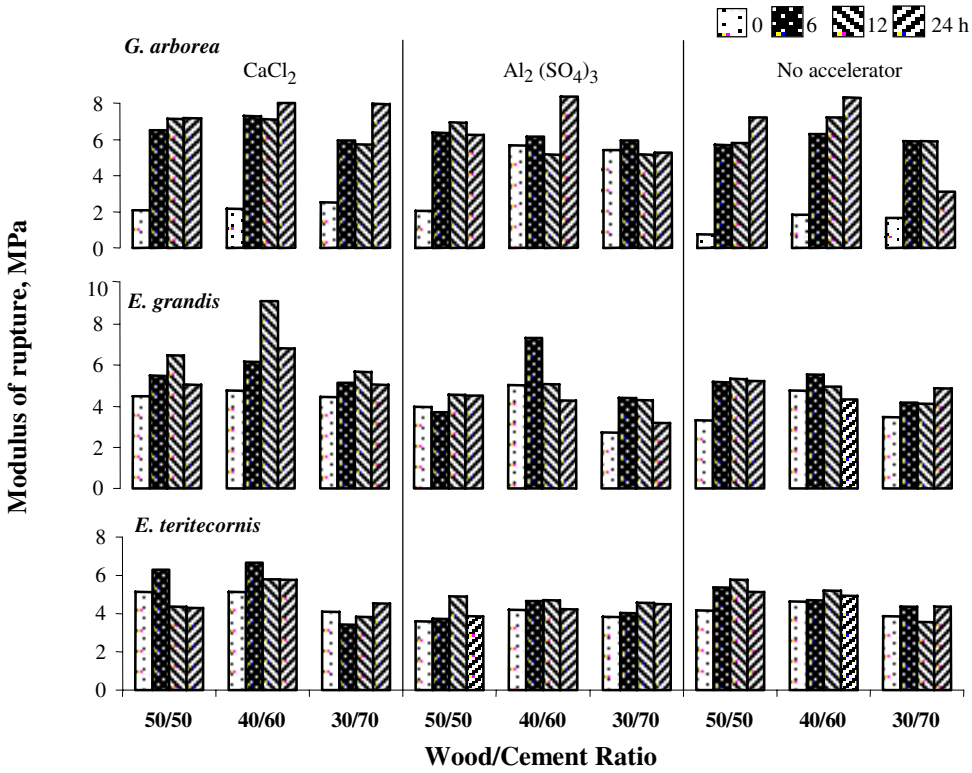


**Figure 1.** Dry modulus of rupture of WWCB containing excelsior of *G. arborea*, *E. grandis* and *E. tereticornis* soaked for 0, 6, 12 or 24 h prior to board production, as affected by wood:cement ratio and choice of chemical accelerator

need to assess the suitability of other industrial tree crops for the manufacture of WWCB.

This study aimed to determine the technical feasibility of using *E. grandis* and *E. tereticornis* for WWCB manufacture, and to assess the properties of the resulting board in comparison to WWCB manufactured from *G. arborea*. Specifically, it measured the effects of soaking time of excelsior (0, 6, 12, 24 h) before it was mixed with cement, and of wood:cement ratio (50:50, 40:60, 30:70) and of cement setting accelerator ($CaCl_2$ and $Al_2(SO_4)_3$) on board properties.

## Materials and Methods

The wood species used in this study were 8–12-year-old *E. grandis*, *E. tereticornis* and *G. arborea* grown in Oriental Mindoro, Philippines. The binder used was Type I ordinary Portland cement (OPC) while calcium chloride ($CaCl_2$) and aluminium sulphate ($Al_2(SO_4)_3$) were used as cement setting accelerators.

Wood-wool cement boards (300 mm × 300 mm), 12 mm thick, with a target density of 0.75 g $cm^{-3}$ were produced. Three wood:cement ratios (50:50, 40:60, 30:70) were used and the percentages of water and accelerator were 80% and 3%, respectively, based on cement weight.

Eucalypt and *G. arborea* logs were cut into billets, 35–40 cm long, that were debarked and made into excelsior 4–5 mm wide using a vertical-type shredding machine. The thicknesses of 200 strands of randomly sampled excelsior were measured using a digital caliper. The average thicknesses of strands of each species were 0.26 mm (*G. arborea*), 0.25 mm (*E. grandis*)

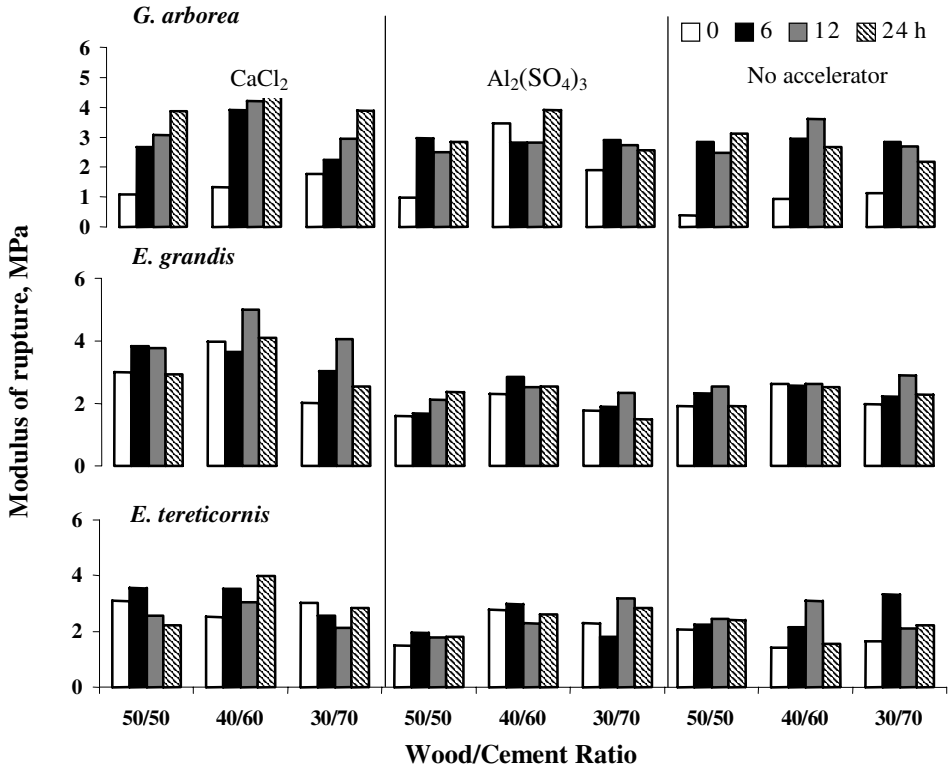


**Figure 2.** Wet modulus of rupture of WWCB containing excelsior of *G. arborea*, *E. grandis* or *E. tereticornis* soaked for 0, 6, 12, 24 h prior to board production, as affected by varying wood:cement ratio and chemical accelerator

and 0.25 mm (*E. tereticornis*), respectively. The excelsior of each wood species was soaked in water for 6, 12 and 24 h in separate tanks. Batches of unsoaked (0 h) excelsior were set aside and also used in board production. Water-soaked excelsior was air-dried to an equilibrium moisture content of 18–20%. Wood-wool, cement and water containing accelerator were mixed by hand until all the wood-wool was thoroughly coated with cement paste. The proportion of materials was adjusted to achieve the target board density.

Sufficient cement-coated wood strands for one board were spread out in a wooden forming box and placed on a plywood caul to form a mat. A polyvinyl sheet was placed between the plywood caul and the mat to prevent the board from sticking during pressing. Several mats were formed and stacked one on top of each other, separated by the plywood cauls.

The mats were compressed to 12 mm thickness using a hydraulic press. The target thickness was achieved by placing wooden stoppers between cauls. After pressing, boards were kept under compression for 24 h. They were then unloaded from the press and conditioned for three weeks before being tested.

## Property testing

The conditioned boards were cut into standard-size bending test specimens (230 mm × 50 mm × 12 mm). Their dry and wet modulus of rupture (MOR) and modulus of elasticity (MOE) were then assessed. Wet MOR and MOE were determined, following immersion of the specimens in tap water for 24 h, using a three-point bending test configuration. A span of 150 mm and a deflection rate of 0.5 mm $min^{-1}$ were used for all tests, which were carried out using a Shimadzu

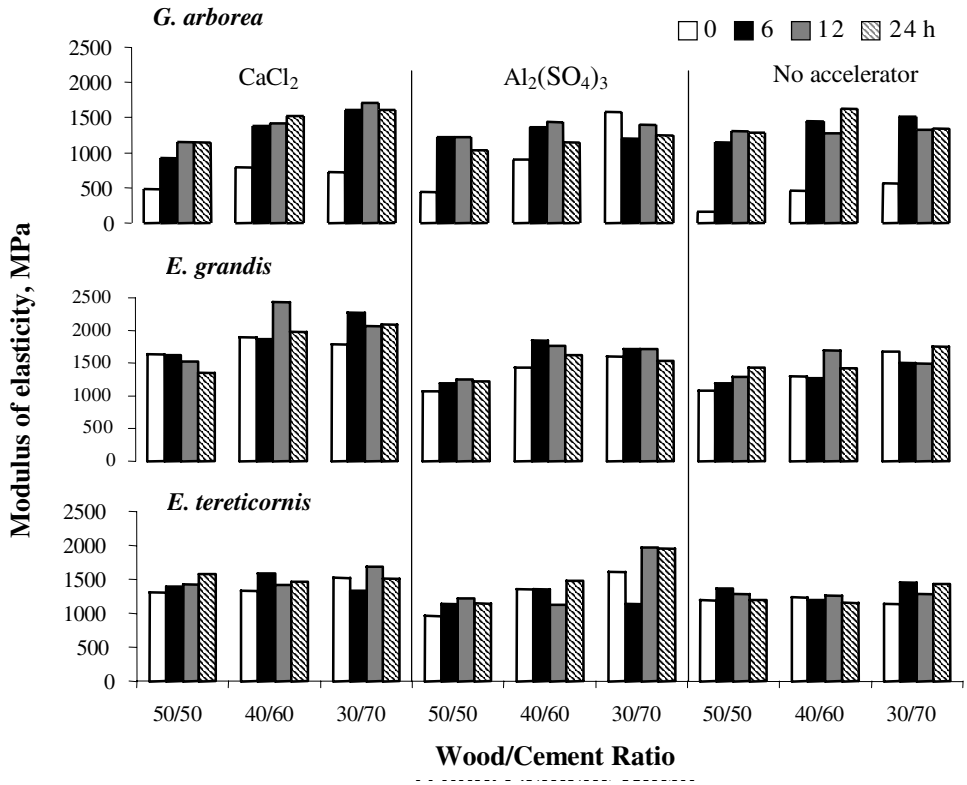


**Figure 3.** Dry modulus of elasticity of WWCB containing excelsior of *G. arborea*, *E. grandis* and *E. tereticornis* soaked for 0, 6, 12, 24 h prior to board production, as affected by varying wood:cement ratio and chemical accelerator

universal testing machine. Thickness swelling and water absorption properties were also measured after the specimens had been immersed in water for 24 h.

## Results and Discussion

### Effect of species

Figure 1 shows the average MOR of wood-wool cement boards. *Eucalyptus tereticornis* excelsior in particular was observed to be more brittle than *G. arborea* excelsior when mixed with cement during board production. This is probably one reason why boards made from this species tended to have lower MOR values than boards made with *G. arborea* excelsior. Interestingly, unsoaked (0 h) excelsior of eucalypts generally gave boards with better MOR values than unsoaked excelsior of *G. arborea*. Pretreatment of *G. arborea* excelsior by soaking for at least 6 h was necessary to produce boards with acceptable properties, but such pretreatment was not necessary for boards made from eucalypts. There was little indication that MOR increased when the soaking time was extended from 6 h to 24 h.

As a cement setting accelerator, $CaCl_2$ seemed more promising than $Al_2(SO_4)_3$. The $Al_2(SO_4)_3$ had a small or adverse affect on the MOR of the boards because higher MOR values were obtained from boards that contained no accelerator. The adverse effect of $Al_2(SO_4)_3$ on MOR was more pronounced for boards containing excelsior soaked for 6–24 h at wood:cement ratios of 50:50 and 40:60. Cabangon et al. (1998) made similar observations when WWCBs were made from *E. pellita*.

As expected, the MOR of the boards was affected by wood:cement ratio. Generally, boards with 40:60 wood:cement ratio had the highest MOR. This was particularly noticeable for boards containing $CaCl_2$ as cement setting accelerator.

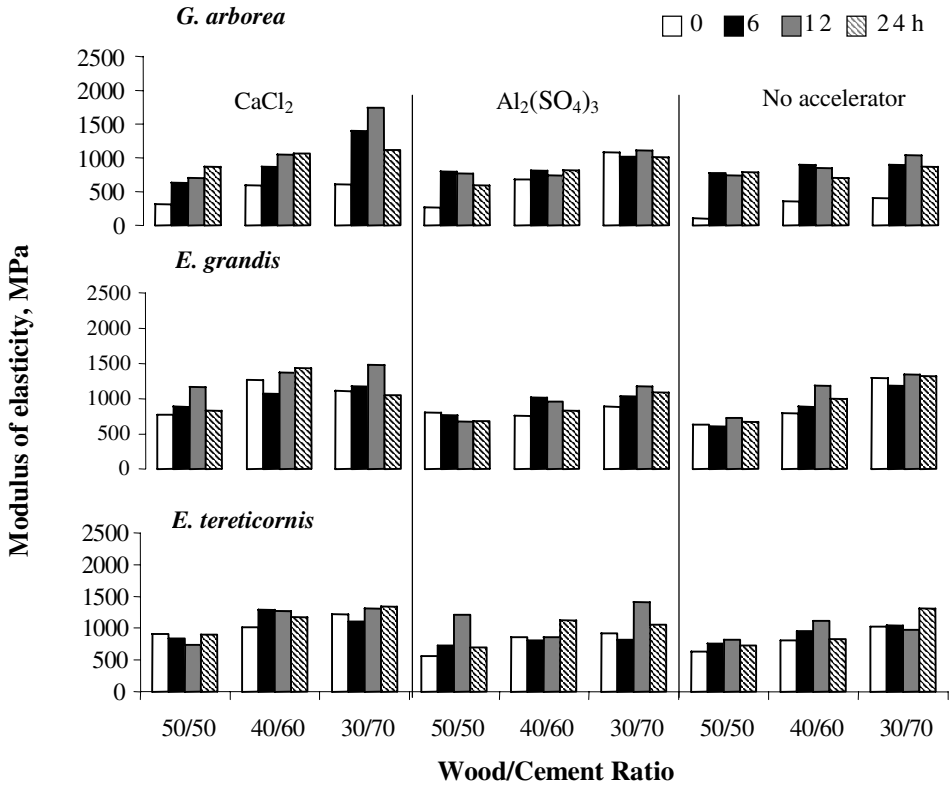


**Figure 4.** Wet modulus of elasticity of WWCB containing excelsior of *G. arborea*, *E. grandis* and *E. tereticornis* soaked for 0, 6, 12, 24 h prior to board production, as affected by varying the wood:cement ratio and chemical accelerator

The wet MOR of boards after 24 h water immersion are shown in Fig. 2. Significant reductions in MOR were observed for all boards as a result of wetting: 30–67% for *G. arborea*, 17–61% for *E. grandis* and 24–69% for *E. tereticornis* WWCBs. There was no indication that strength reductions would be lessened by altering material or manufacturing parameters such as soaking time, wood:cement ratio, or cement-setting accelerators. The smallest loss of MOR, on soaking, for *G. arborea* boards occurred with unsoaked excelsior and a 30:70 wood:cement ratio using $CaCl_2$ as cement setting accelerator. The greatest loss, on the other hand, was in boards containing excelsior soaked for 24 h and a 40:60 wood:cement ratio. In the case of *E. grandis*, the smallest loss of MOR was found with unsoaked excelsior and a wood:cement ratio of 40:60 while the largest loss was in boards containing excelsior soaked for 6 h and wood: cement ratios of 40:60 and 30:70, using $Al_2(SO_4)_3$ as accelerator. In the case of *E. tereticornis*, the smallest loss was in boards containing excelsior soaked for 6 h and a wood:cement ratio of 30:70 but no accelerator. The greatest loss was in boards containing unsoaked excelsior, a 40:60 wood: cement ratio and no accelerator. In general, wet boards containing $CaCl_2$ accelerators were stronger than those with $Al_2(SO_4)_3$ or no accelerator at all.

### Modulus of elasticity

The modulus of elasticity (MOE) values of boards tested in the dry condition are shown in Fig. 3. Of the three wood species tested, *E. grandis* boards had the highest dry MOE with values ranging from 1348 to 2429 MPa for boards containing soaked or unsoaked excelsior and using $CaCl_2$ as cement

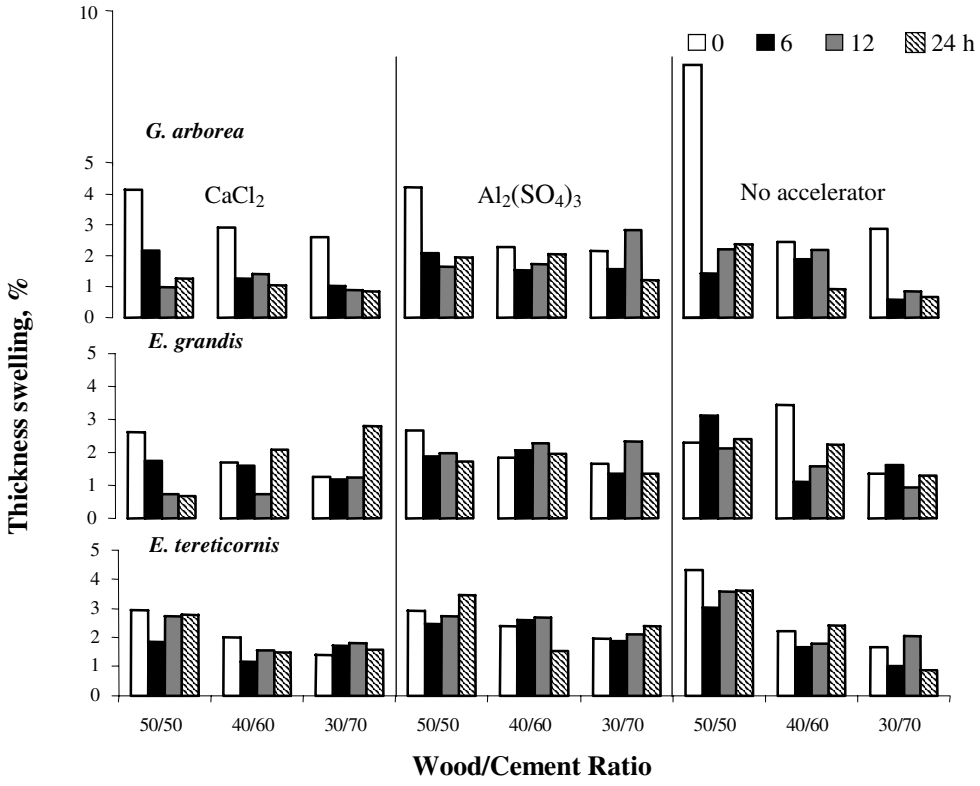


**Figure 5.** Thickness swelling of WWCB containing excelsior of *G. arborea*, *E. grandis* and *E. tereticornis* soaked for 0, 6, 12, 24 h prior to board production, as affected by varying the wood:cement ratio and chemical accelerator

setting accelerator. $CaCl_2$ was more effective than $Al_2(SO_4)_3$ in increasing MOE. Boards with the lowest MOE were those containing unsoaked excelsior of *G. arborea* and containing no accelerator.

The importance of soaking the excelsior even for 6 h was very pronounced in boards containing *G. arborea* excelsior and either $CaCl_2$ or no accelerator. However, a different response was found with $Al_2(SO_4)_3$ where MOE values were higher when unsoaked excelsior was used, particularly at a wood:cement ratio of 30:70.

The effect of wood:cement ratio was equally important for all the boards produced. The greater the proportion of cement (30:70) used, the higher the MOE obtained. Similar findings were observed for wood fibre-reinforced cement composites, in which MOE decreased with increasing fibre content (Eusebio et al. 1998).

The MOE of the boards tested wet after 24 h water immersion are shown in Fig. 4. Immersion of *G. arborea* boards in water reduced MOE by 13–37%, 15–48% and 19–56% when boards contained $CaCl_2$, $Al_2(SO_4)_3$ and no accelerator, respectively. There is little indication that extending the soaking time or increasing the amount of cement or even using soaked excelsior minimises the reduction in strength due to wetting.

A reduction in MOE, due to wetting, was also observed in boards containing *E. grandis* excelsior, with losses of 28–49%, 29–48% and 22–49% for boards containing $CaCl_2$, $Al_2(SO_4)_3$ and no accelerator, respectively. Again, none of the variables, including wood:cement ratio, soaking time and accelerator type, reduced the loss of MOE caused by wetting.

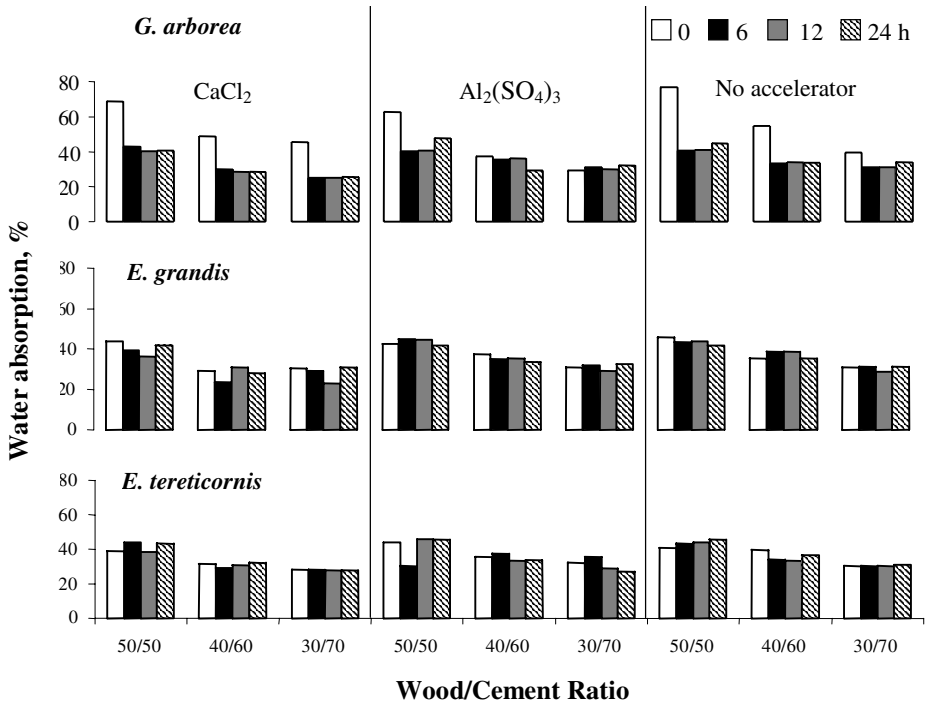


**Figure 6.** Water absorption of WWCB containing excelsior of *G. arborea*, *E. grandis* and *E. tereticornis* soaked for 0, 6, 12, 24 h prior to board production, as affected by varying the wood:cement ratio and chemical accelerator

A similar result was found for boards made from *E. tereticornis*. Although these boards lost less MOE on wetting, there was no indication that the manufacturing variables greatly influenced strength losses caused by wetting. The reductions in MOE were 11–43%, 23–45% and 8–46% for boards containing $CaCl_2$, $Al_2(SO_4)_3$ and no accelerator, respectively.

It can be concluded that none of the manufacturing variables, such as soaking time, wood:cement ratio and chemical accelerator, were effective in minimising losses in MOR and MOE caused by wetting. A similar finding was observed when *E. pellita* was used in the production of WWCB containing $CaCl_2$, $Al_2(SO_4)_3$ and $FeCl_3$ as cement setting accelerators. None of the chemicals enhanced the wet bending strength properties of the boards produced (Cabangon et al. 1998). In general, the decreases of properties following immersion of boards in water were more species-dependent.

### Thickness swelling and water absorption

The results of thickness swelling and water absorption tests of the boards after 24 h water immersion are shown in Figs 5 and 6, respectively. For WWCBs containing *G. arborea*, a minimum thickness swelling of 0.85% was found in boards with 30:70 wood:cement ratio, $CaCl_2$ accelerator and excelsior soaked for 24 h. The largest thickness swelling value, on the other hand, was obtained from boards with unsoaked excelsior, wood:cement ratio of 50:50 and no accelerator. In general, it appears that the greater the cement content of boards, the lower their thickness swelling. More cement coating on the excelsior may have restrained the wood from swelling.

The thickness swelling values of boards containing eucalypt excelsior were improved by using $CaCl_2$ as cement setting accelerator at all wood:cement ratios and soaking times, compared to boards with $Al_2(SO_4)_3$ or those with no accelerator. This suggests that $CaCl_2$ contributed

to better fibre-to-fibre contact as a result of improved bonding ability with cement.

In general, boards containing *G. arborea* excelsior had higher water absorption values than boards with eucalypt excelsior, particularly the boards containing unsoaked excelsior of *G. arborea*. This result may be related to the low density of *G. arborea* excelsior. During board production it was observed that *G. arborea* excelsior was more bulky than eucalypt excelsior, and so more water was absorbed during the 24 h water immersion. The water absorption tended to decrease as the amount of cement was increased from 50:50 to 30:70. Obviously, a higher wood content, as in the case of 50:50 wood:cement ratio, would result in greater water absorption. Also, it has been suggested that the products of cement hydration have a low solubility in water and this may be another reason for the smaller water absorption values observed for boards with a 30:70 wood:cement ratio.

## Conclusions and Recommendations

The WWCBs made from *E. grandis* and *E. tereticornis* performed better than boards made from *G. arborea* when they were made from unsoaked wood-wool.

Remarkable improvements in MOR and MOE were attained when *G. arborea* excelsior was soaked for 6 h. Further soaking does not appear to be necessary.

Among the three wood:cement ratios, boards with 40:60 and 30:70 ratios had the highest MOR and MOE values, respectively, for all the wood species used.

For eucalypts, $CaCl_2$ seemed more promising than $Al_2(SO_4)_3$ as cement setting accelerator, even when unsoaked excelsior was used.

The MOR and MOE significantly decreased when boards were soaked in water, and none of the cement setting accelerators reduced the loss of MOR or MOE.

In general, boards containing unsoaked excelsior exhibited the largest values for thickness swelling and water absorption, with or without cement setting accelerator, indicating that soaking of the excelsior is still necessary to maintain good thickness swelling and water absorption properties.


## Acknowledgements

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# Manufacture of Low-cost Wood–Cement Composites in the Philippines Using Plantation-grown Australian Species: II. Acacias

**Dwight A. Eusebio[1], Florence P. Soriano[1], Rico J. Cabangon[1] and Philip D. Evans[2]**

*Abstract*

*Acacia mangium and A. auriculiformis* were used in the manufacture of wood-wool cement boards (WWCBs). The properties of the boards were compared with those of boards made from *Gmelina arborea*. A series of experiments examined the effects of manufacturing variables such as soaking time (0, 6, 12, 24 h), wood:cement ratio (50:50, 40:60, 30:70) and cement setting accelerator (none, $CaCl_2$, $Al_2(SO_4)_3$) on the properties of boards (MOR, MOE, thickness swelling and water absorption). The WWCBs containing unsoaked *A. mangium* excelsior had the lowest MOR, irrespective of wood:cement ratios. However, remarkable improvements in properties were observed when the excelsior was soaked in water for 6 h, although extending the soaking time to 12 and 24 h did not significantly improve properties except in boards containing $CaCl_2$. The incorporation of $CaCl_2$ and $Al_2(SO_4)_3$ as cement setting accelerators (3% based on cement weight) improved properties, particularly in the case of acacias. Increasing the cement content of boards had favourable effects on MOE, thickness swelling and water absorption, but resulted in lower MOR. It is concluded that acacias require soaking of excelsior (for 12 h) and the use of a cement setting accelerator to produce WWCBs with satisfactory properties.

THE technology for making wood-wool–cement board (WWCB) is well established in the Philippines. Expansion of the raw material base for the WWCB industry has attracted the attention of researchers and WWCB manufacturers alike. A number of studies have shown that a variety of indigenous wood species can be used for board manufacture (Pablo 1989). *Acacia mangium* and *A. auriculiformis* have been planted in the Philippines, but they are not used for the manufacture of WWCB despite the fact that their growth in plantations is often comparable to that of recognised fast-growing species such as *Gmelina arborea*, *Albizia falcataria*, *Anthocephalus chinensis* and *Pinus caribaea* (Ogata 1982). Previous research into the utilisation of *A. mangium* has mainly examined its conversion into sawn timber (Murata et al. 1994), particleboard (Korai and Lim 1998) and medium density fibreboard (Asdar et al. 1998). There has, however, been some research elsewhere in Asia into the utilisation of acacia species for wood–cement composites. Rahim and Ong (1983) rated *A. mangium* as unsuitable for use in wood–cement composites based on the results of experiments that examined the force required to remove test sticks set in cement. The bonding strength of *A. mangium* was improved by preliminary soaking of wood in aqueous solutions of aluminium sulphate or calcium chloride.

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Firmanti and Subiyanto (1998) found that *A. mangium* was less compatible with cement than *Paraserianthes falcataria* and *Agathis alba* on the basis of compression strength tests, but it responded well to 2 h soaking in 1% NaOH, as did the other species tested.

One species of acacia was among the 99 different woods tested for their compatibility with Portland cement by Sandermann and Kohler (1964). In their study both the sapwood and heartwood flour of *A. decurrens* Benth. were found to be highly incompatible with cement and unsuitable for wood–cement composites. Another acacia species, *A. mearnsii*, has also been shown to be highly incompatible with cement (Hachmi and Moslemi 1989; Hachmi et al. 1990; Hachmi and Sesbou 1991).

Only one species of acacia, *A. mearnsii*, has been tested for its suitability for the manufacture of WWCB. Results showed that commercial quality WWCB could be manufactured from *A. mearnsii* provided the excelsior was soaked in a 1% solution of $CaCl_2$ before being mixed with cement; however, a 3% solution was recommended for producing boards of commercial quality (Flawes and Chittenden 1967).

Since *A. mangium* and *A. auriculiformis* are available in the Philippines, they could be used for the manufacture of WWCB. First, however, it would be necessary to develop means of overcoming the inhibitory effect of acacia wood on the setting of cement. This study therefore aimed to determine the technical feasibility of using *A. mangium* and *A. auriculiformis* for WWCB manufacture and to assess whether soaking wood with water or using a cement setting accelerator or higher wood:cement ratios improved the properties of boards. The properties of resulting WWCBs are compared with WWCBs containing *G. arborea* excelsior (wood-wool). *Gmelina arborea* is the most widely used wood species for the manufacture of WWCB in the Philippines because of its abundance and ease of processing.

## Materials and Methods

The wood species used in this study were 8–12 year old *A. mangium*, *A. auriculiformis* and *G. arborea* grown in Oriental Mindoro, Philippines. The binder was Type I ordinary Portland cement (OPC) while calcium chloride ($CaCl_2$) and aluminium sulphate ($Al_2(SO_4)_3$) were used as cement setting accelerators at 3% based on cement weight.

The methods used for board production and testing were the same as those described in part I of this study (Eusebio et al., these Proceedings).

## Results and Discussion

### Modulus of rupture

The dry modulus of rupture values (MOR) of boards manufactured from *G. arborea*, *A. auriculiformis* and *A. mangium* are shown in Fig. 1. The highest MOR values obtained were 8.31, 7.65 and 8.17 MPa for *G. arborea*, *A. auriculiformis* and *A. mangium*, respectively. Boards made from *G. arborea* were generally stronger than those manufactured from the two acacias, but when an accelerator was used differences in strength were quite small. The slightly higher strength of the *G. arborea* boards may be related to the quality of the excelsior (during shredding and board production, acacia excelsior was observed to break easily when pulled apart or when tension was applied). Acacia also has higher density than *G. arborea* (lower density wood excelsior appears to produce a higher compression ratio during pressing). Both accelerators favourably affected the strength of the boards made from the acacias compared to those without accelerator. These findings agree with the results obtained by Cabangon et al. (1998).

Boards made from unsoaked excelsior generally had poor MOR, but the inhibitory effect of wood extractives could be overcome by the use of $CaCl_2$ and $Al_2(SO_4)_3$ particularly at wood:cement ratios of 40:60 and 30:70. As shown in Fig. 1, 6 h soaking time was sufficient to produce boards with satisfactory MOR from *G. arborea* and *A. mangium.* Further soaking for 12 and 24 h had little additional beneficial effect on MOR. For *A. auriculiformis*, 12 h soaking time was required, particularly for boards containing $CaCl_2$ at wood:cement ratios of 50:50 and 40:60. This may imply that the inhibitory extractives are less easily removed from *A. auriculiformis* by soaking.

The effect of varying the wood:cement ratio on MOR was significant. The MOR decreased when

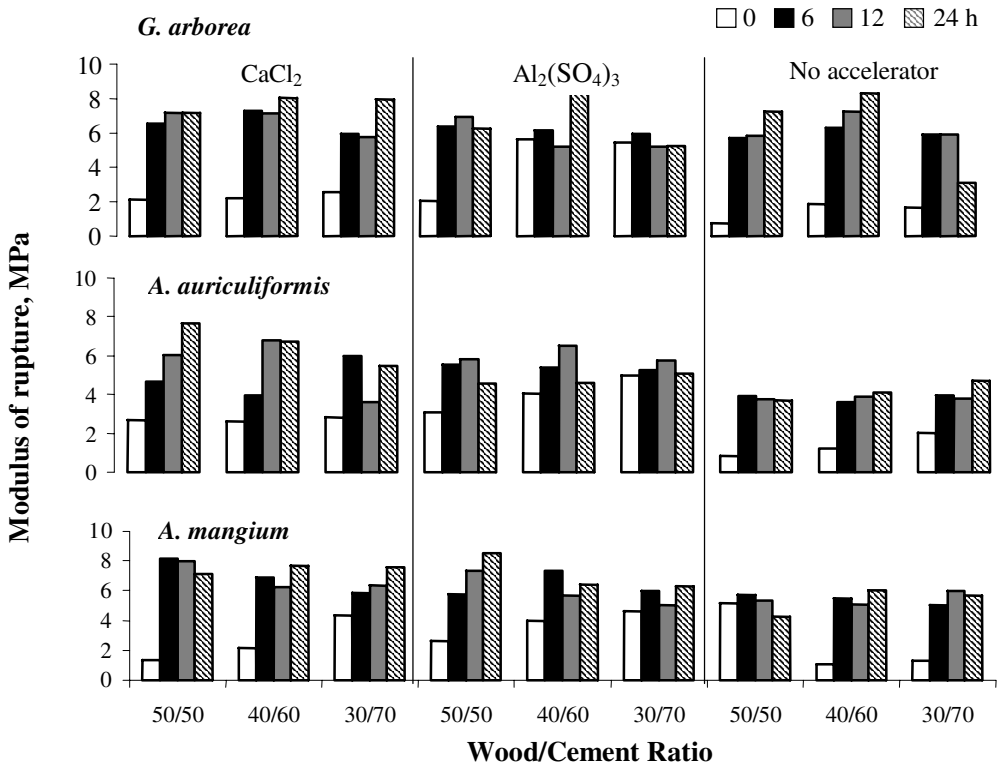


**Figure 1.** Dry modulus of rupture of WWCB containing excelsior of *G. arborea*, *A. auriculiformis* and *A.mangium* soaked for 0, 6, 12 or 24 h prior to board production as affected by wood:cement ratio and chemical accelerator

the amount of cement increased (i.e. wood: cement ratio of 30:70). This effect is due to the capacity of wood, when present in higher proportions, to resist load applied during the bending test (Moslemi and Pfister 1987).

It is interesting to note that satisfactory WWCB can be made from *G. arborea* without the addition of an accelerator, provided that the excelsior is soaked in water for at least 6 h; this result was limited to wood:cement ratios of 50:50 and 40:60. This result suggests that acacias have more chemicals inhibiting the curing and hardening of cement than *G. arborea*. The adverse effects of extractives remaining after soaking may have been altered by the addition of cement setting accelerator. It was observed during soaking that both acacias had more water-soluble extractives than *G. arborea*, as indicated by the degree of discolouration of water used for soaking.

Soaking boards in water for 24 h caused a dramatic reduction in the MOR (Fig. 2) of samples tested in the wet condition. There was no indication that increasing the amount of cement or adding accelerators reduced strength losses caused by wetting. The percentage reductions in MOR of WWCBs containing acacia excelsior were almost the same as the percentage reductions in boards made from *G. arborea* excelsior. In general, boards containing $CaCl_2$ had the highest wet MOR compared to boards containing $Al_2(SO_4)_3$ or no accelerator. It was suggested in an earlier study that $Al_2(SO_4)_3$ was a more effective accelerator than $CaCl_2$ for the manufacture of WWCBs from *A. mangium* (Soriano et al. 1997). In that report, however, the soaking time of the excelsior was 48 h; that length of soaking might have removed a greater proportion of the extractives from *A. mangium* reducing the requirement for an accelerator.

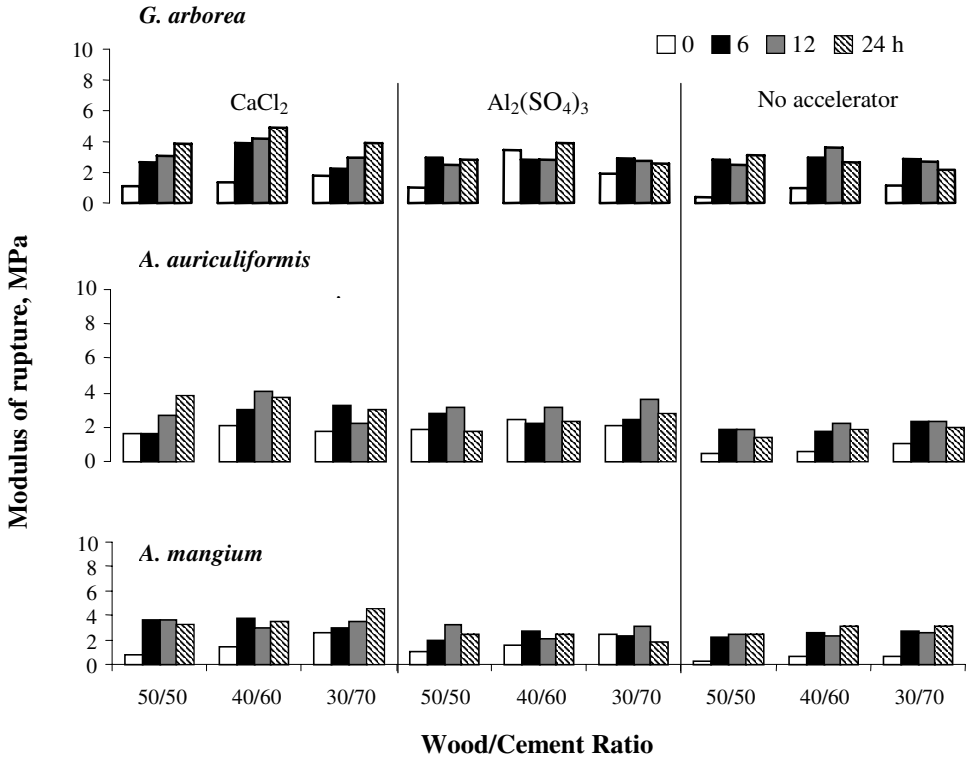


**Figure 2.** Wet modulus of rupture of WWCB containing excelsior of *G. arborea*, *A. auriculiformis* and *A. mangium* soaked for 0, 6, 12 or 24 h prior to board production, as affected by varying wood:cement ratio and chemical accelerator

## Modulus of elasticity

The dry modulus of elasticity values (MOE) of boards manufactured from acacia excelsior and $CaCl_2$ as accelerator were generally higher than those of boards made from *G. arborea* excelsior. There was a positive correlation between MOE and cement content of boards, as shown in Fig. 3. The largest values obtained were 1711 MPa, 1970 MPa and 2080 MPa for *G. arborea* (12 h soaked), *A. auriculiformis* (24 h soaked) and *A. mangium* (12 h soaked), respectively. The use of $Al_2(SO_4)_3$ as cement setting accelerator also improved the dry MOE of boards made from the acacias. The improvement was particularly pronounced for boards made from unsoaked excelsior.

Dramatic reductions in MOE were observed when the boards were tested wet after 24 h immersion in water (Fig. 4), but the general trend of increasing MOE with increasing cement content was maintained. For *G. arborea*, reductions in strength ranged from 13% to 56%; the minimum was obtained for boards with $CaCl_2$ while the maximum was for a board without an accelerator. Reductions in MOE of boards containing *A. auriculiformis* excelsior were observed to be 28–49%, 29–48% and 22–49% with $CaCl_2$, $Al_2(SO_4)_3$ and no accelerator, respectively. The reductions in MOE for boards containing *A. mangium* excelsior were 7–43%, 23–57% and 12–46% for boards with $CaCl_2$, $Al_2(SO_4)_3$ and no accelerator, respectively.

## Thickness swelling and water absorption

The results for the thickness swelling tests of boards are shown in Fig. 5. In general, boards containing unsoaked excelsior exhibited higher thickness swelling values, particularly at wood:

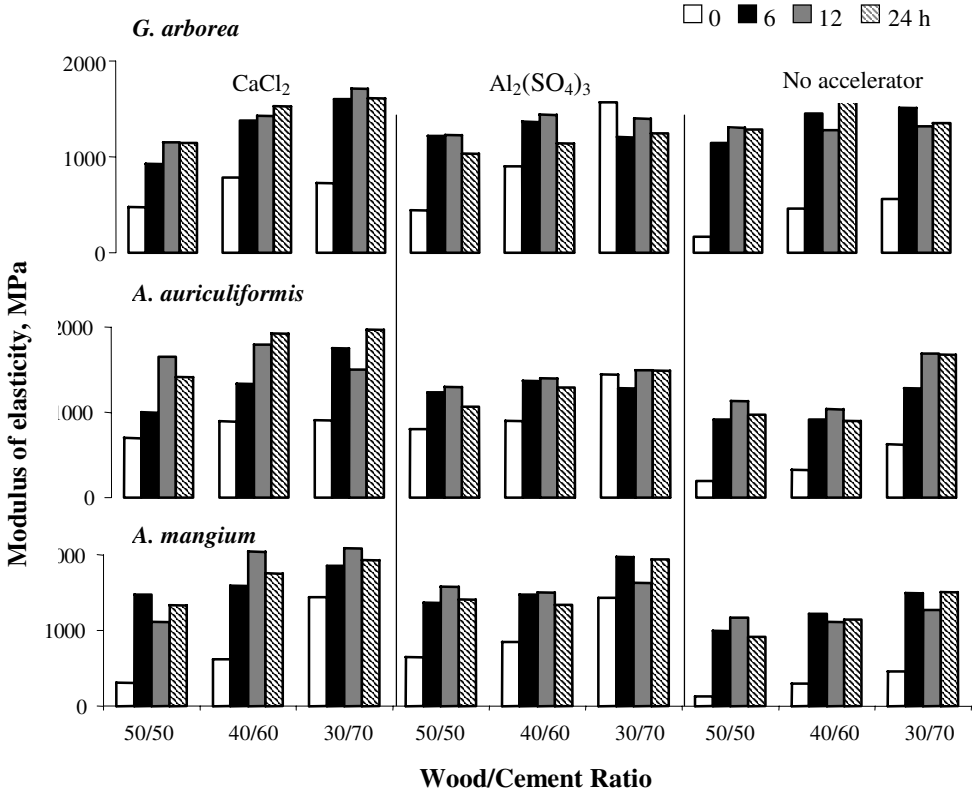


**Figure 3.** Dry modulus of elasticity of WWCB containing excelsior of *G. arborea*, *A. auriculiformis* and *A. mangium* soaked at 0, 6, 12 or 24 h prior to board production as affected by varying wood:cement ratio and chemical accelerator

cement ratios of 50:50 and 40:60. This may have been due to the lower cement content and poorer bonding between wood and cement allowing greater absorption of water by wood and inability of the specimens to resist stresses generated by swelling of wood and springback of compressed excelsior. The thickness swelling values of boards containing soaked *G. arborea* and *A. auriculiformis* excelsior were better than the thickness swelling values of boards containing *A. mangium.* There was some evidence to suggest that increasing the soaking time resulted in lower thickness swelling for boards containing $CaCl_2$, but for boards containing $Al_2(SO_4)_3$ or unsoaked excelsior the trend is less obvious.

In accord with results for thickness swelling, boards containing unsoaked excelsior generally had larger water absorption values, particularly at 50:50 wood:cement ratio, except for *A. auriculiformis* boards containing $Al_2(SO_4)_3$ as cement setting accelerator (Fig. 6). Again, this may have been due to water soluble extractives not being leached out prior to board production, resulting in poor bonding between wood and cement. Spaces or voids in the boards may have contributed to greater absorption of water. Boards with 50:50 wood:cement ratio contain more wood than those with 30:70 wood:cement ratio and absorbed more water; thus water absorption is higher. As with thickness swelling, there is a greater negative correlation between water absorption and soaking for boards containing $CaCl_2$. In the case of boards containing no accelerator, 6 h soaking appears to be sufficient to reduce water absorption.

## Conclusions and Recommendations

The highest MOR values for WWCBs made from the three wood species were obtained when $CaCl_2$ was used as cement setting accelerator, the

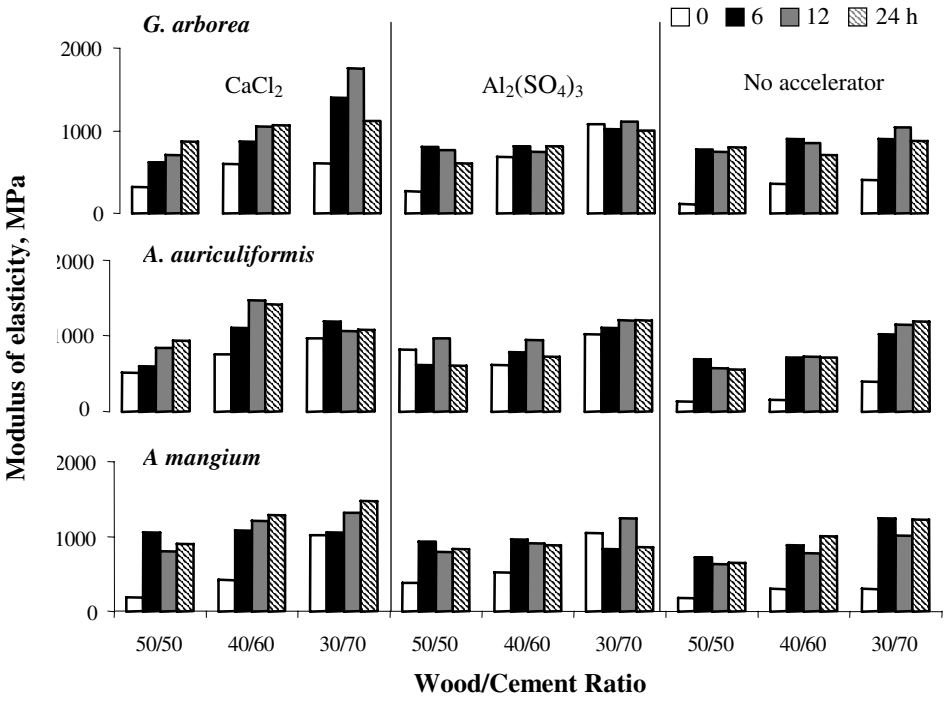


**Figure 4.** Wet modulus of elasticity of WWCB containing excelsior of *G. arborea*, *A. auriculiformis* and *A. mangium* soaked at 0, 6, 12 or 24 h prior to board production as affected by varying wood:cement ratio and chemical accelerator

excelsior was soaked for at least 12 h and a wood:cement ratio of 40:60 was used. As expected, the lowest values were obtained for boards with unsoaked excelsior and with no accelerator added.

In the case of boards made from unsoaked excelsior, the adverse effect of chemical extractives on MOR was minimised when $Al_2(SO_4)_3$ was used as accelerator, particularly for boards containing acacia wood at 40:60 and 30:70 wood:cement ratios.

The WWCBs containing soaked excelsior of acacias exhibited better MOE than boards with *Gmelina arborea* excelsior when $CaCl_2$ was used as accelerator. The MOE tended to increase as the amount of cement increased, i.e. 30:70 wood:cement ratio.

Both MOR and MOE dramatically decreased when the boards were tested wet after 24 h water immersion; neither of the accelerators minimised the strength reductions.

Boards containing unsoaked excelsior exhibited higher thickness swelling and water absorption values, particularly at wood:cement ratios of 50:50 and 40:60. Extending the soaking time from 6 to 24 h lowered thickness swelling and water absorption values for boards containing $CaCl_2$, but had little effect for boards containing $Al_2(SO_4)_3$ or unsoaked wood-wool. Both thickness swelling and water absorption declined as the amount of cement increased.

Acacias can be used as raw material for the commercial production of WWCBs, by soaking the excelsior for at least 12 h instead of the 24 h being practised in WWCB plants at present, and by using a cement setting accelerator.

The reactions of $Al_2(SO_4)_3$ with chemical components of the species used in this study need further analysis, because this compound had a favourable effect when unsoaked excelsior was used.

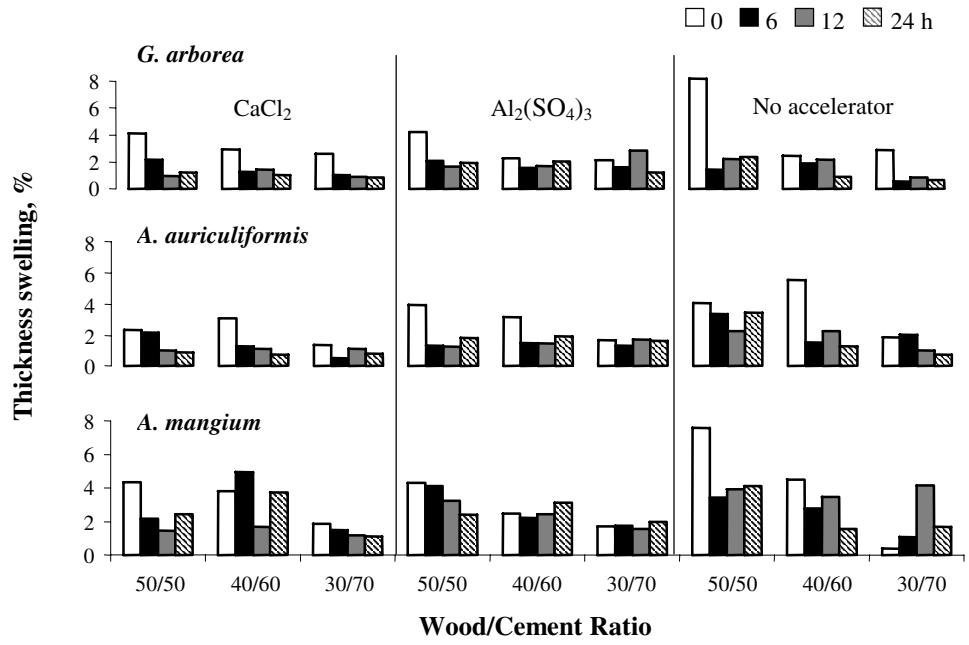


**Figure 5.** Thickness swelling of WWCB containing excelsior of *G. arborea*, *A. auriculiformis* and *A. mangium* soaked at 0, 6, 12 or 24 h prior to board production as affected by varying wood:cement ratio and chemical accelerator

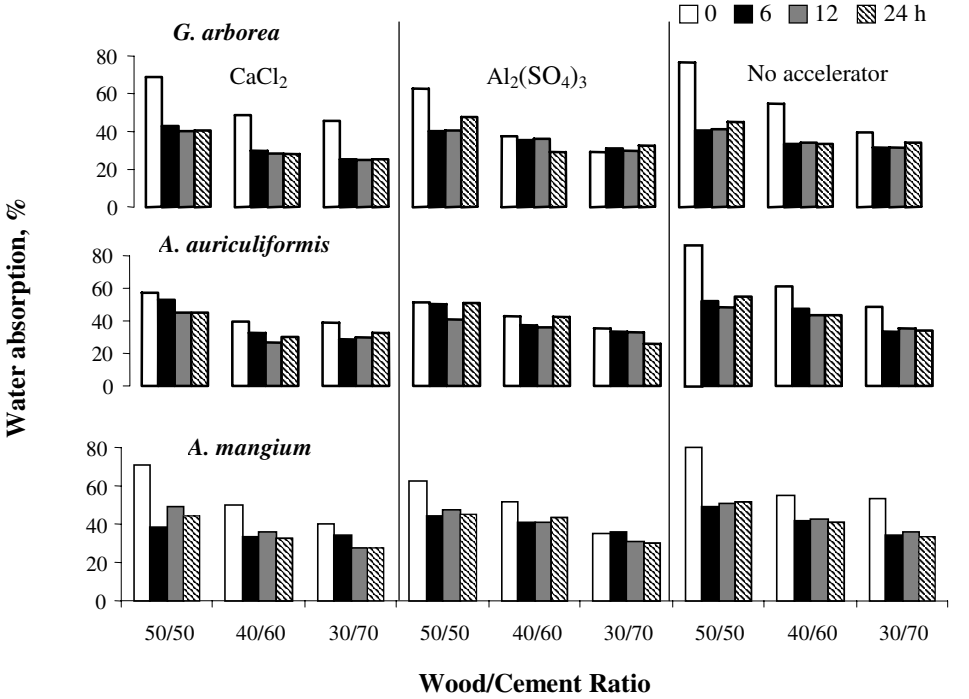


**Figure 6.** Water absorption of WWCB containing excelsior of *G. arborea*, *A. auriculiformis* and *A. mangium* soaked at 0, 6, 12 or 24 h prior to board production as affected by varying wood:cement ratio and chemical accelerator

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# The Development of the Hybrid Poplar Processing Industry in P. R. China

**Hua Yukun and Zhou Xiaoyan**

*Abstract*

Hybrid poplar was introduced to China in the 1970s and rapidly established itself as an important plantation timber. Poplar is grown in several provinces including Shandong, Heinan, Jiangsu, Anhui, Hubei and Hunan and supports a large number of industries producing a variety of products including plywood, blockboard, sliced veneer, MDF, particleboard, OSB, LVL and reassembled veneer. This paper outlines the development of the hybrid poplar processing industry, the main products produced by the industry, and its future prospects.

NATURAL forests are decreasing at a rate of 16–20 million ha annually, and almost 80% of the world's natural forests have disappeared. Demand for wood products, however, continues to increase and statistics from the Food and Agriculture Organization of the United Nations (FAO) predict that consumption of wood will rise by 20% by 2010. The development of plantations of fast-growing trees is an important means of protecting natural forests and meeting the growing demand for wood. Hybrid poplar was imported into China in the 1970s and a program of plantation establishment was developed. On good sites poplar grows fast, reaching a diameter of 18 cm in five years and plantations of poplar are increasing at the rate of 15–20% annually near the Huaihe River and in the agricultural areas on the plain along the middle and lower reaches of the Yangtze River. Poplar has now become the main raw material for a wide variety of wood processing industries including plywood, MDF, LVL and particleboard in China.

## The Poplar Resource in China

At present, poplars are mainly distributed in Shandong, Heinan, Jiangsu, Anhui, Hubei and Hunan Provinces (Fig. 1). For example, in Jiangsu Province, 200 million poplar trees have been planted over a 20 year period. Plantations cover about 0.2 million ha, the standing volume of industrial timber is about 20 million $m^3$ and currently the annual volume available to industry is about 2 million $m^3$. In five to seven years, the volume of industrial timber is predicted to rise to 40 million $m^3$ and the annual cutting volume will be 4 million $m^3$. As the poplar resource has increased, poplar processing has rapidly developed. More than 1000 mills for processing poplar have been built since the 1980s in Jiangsu Province alone. Processing of poplar has played an important role in the agricultural economy of China.

## Properties of Poplar

The edited proceedings of a conference on the properties and utilisation of fast-growing trees (Chison et al. 1994) contains a large body of information on the properties of poplar grown in China and the Chinese poplar processing industry. This paper summarises the main findings of Chinese research into the properties of poplar and provides an update on the development of associated processing industries. The average fibre length of Chinese poplar ranges from 0.92 to 1.3 mm and there is no obvious effect of

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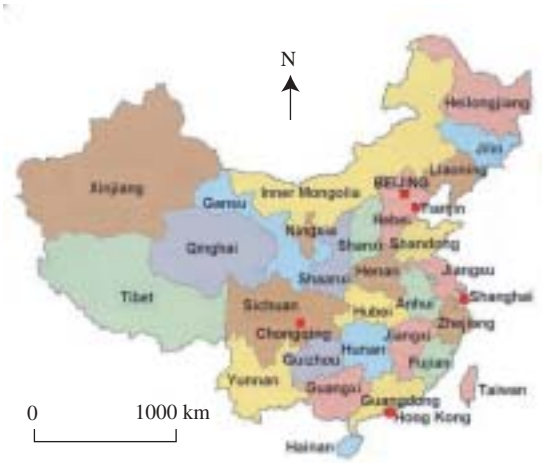


**Figure 1**. Map of China showing locations of provinces, autonomous regions and municipalities

different silvicultural practices on fibre length. A study found that the pH of heartwood was 7–8, while sapwood pH was approximately 6 (Xu 1994). Sapwood of poplar is therefore more suitable than heartwood for UF resin curing under acid conditions. The density of hybrid poplar ranges from 0.25 to 0.39 g $cm^{-3}$, microfibril angles are 19.8–25.1°, MOR is 31.7–72.6 MPa, MOE is 2.9–8.4 GPa. Poplar grows fast and with good form (circular and straight). It is easily processed and can be used as a suitable raw material for the wood-based panel industry. In addition, the properties of poplar can be tailored to meet specific end uses by selection of improved genetic material and varying silvicultural regimes. Poplar has therefore become an important source of wood in China (Chison et al. 1994).

## The Status of Poplar Processing in China

As mentioned above, poplars were first imported into China in the 1970s and mature stands were available in the 1980s, which brought about the development of the poplar processing industry. Figure 2 lists the current uses of each of the different parts of trees by Chinese industry.

### Main wood products of poplar

*Core veneer*

Since the diameter of most poplar trunks is less than 30 cm, they are not suitable for peeling into 8' veneer. Instead, they are peeled into 4' veneer (1300 × 850 mm) and used as the core veneer for plywood and LVL. Three pieces of this size can be used to form the core layer of full-sized plywood sheets. Many factories producing core veneer are in operation in Jiangsu Province, Shandong Province and Anhui Province. Core veneer is peeled, dried, selected, sorted and packed in these mills and then sold to plywood or LVL factories. The uses and prices of core veneers are shown in Table 1.

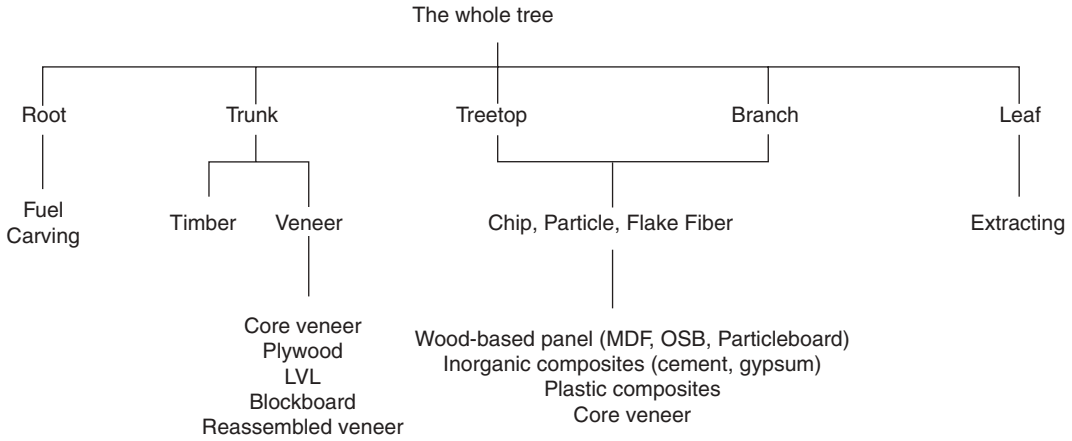


**Figure 2.** The uses of poplar in China

**Table 1.** The main series of core veneer

| Thickness (mm) | Usage | Price (Yuan $m^{-3}$) |
|---|---|---|
| 1.7 | Plywood | 800–900 |
| 2.6 | Multi-plywood | 900–1000 |
| 3.6 | LVL | 1000–1100 |

*Plywood*

In China, three-layer plywood is normally made from imported surface veneer and poplar core veneer. The thickness of surface veneer is about 0.55–0.65 mm, while that of core veneer is about 1.6–1.8 mm. The recovery rate for poplar used in plywood is about 60%. As well as three-layer plywood, multi-ply plywood is manufactured in China and used for interior decoration and concrete formwork. This type of plywood is made up of poplar or imported veneer for the surface and poplar veneer for the core. Usually the thickness of core veneer is 1.6–3.6 mm. Table 2 shows the properties of multi-ply plywood produced by four different mills in China. Recently, plywood products have been exported to Japan, Korea and Singapore.

Because poplar is a fast-growing tree, the properties of the wood have an effect on the processing of plywood.

- Since poplar is soft, it does not have to be thermally softened before peeling. Smooth veneer can be obtained by controlling the peeling conditions correctly.
- The moisture content of poplar varies considerably and differential shrinkage and stresses develop in the veneer as it is being dried. The veneer will deform and warp. Therefore, poplar veneer should not be dried to too low a moisture content. For thick veneers, drying in a platen drier has proved to be better than drying in a belt drier.
- The density of poplar is less than 0.4 g $cm^{-3}$; therefore, the glue is rapidly absorbed by the veneer. If insufficient glue is applied to veneer, then thin glue lines develop. To offset such tendencies glue spread is normally more than 280 g $cm^{-2}$, for two sides. In addition, the pressing pressure should be maintained at around 0.5 MPa.
- To improve the quality of finished plywood, a double spreading process is used in many factories. First, the core veneer is spread on one side and formed with the back veneer. After pre-pressing, the overlap and open joint of the core layer veneer are patched up. Then after spreading the other side of the core veneer and forming it with the surface veneer, the mat is pressed in the hot-press.

*Blockboard*

Small diameter poplars and peeler cores are usually cut into small blocks to produce blockboard. Several blocks are bonded to form a

**Table 2.** The properties of multi-plywood made from poplar in four different mills in China

| | Mill A | Mill B | Mill C | Mill D |
|---|---|---|---|---|
| Thickness (mm) | 18 | 18 | 15 | 18 |
| Moisture content (%) | 9.5 | 6.4 | 9.3 | 8.3 |
| Bonding strength | 0.42–1.90 | 1.3–2.43 | 0.65–2.22 | 0.88–3.01 |
| MOR (MPa) | 49 | 47 | 39 | 38 |
| MOE (MPa) | 5500 | 4800 | 4500 | 4900 |

**Table 3.** The properties of blockboard made from poplar in three different mills in China.

| | Mill A | Mill B | Mill C | GB/T8849–1999 |
|---|---|---|---|---|
| Glue | UF | UF | UF | UF |
| Thickness (mm) | 18 | 18 | 18 | |
| Moisture content (%) | 10.6 | 12.2 | 12.9 | 6–14 |
| MOR (MPa) | 32.0 | 27.5 | 25.2 | ≥22 |
| Internal bonding (MPa) | 1.03 | 1.18 | 1.09 | ≥0.70 |

**Table 4.** The properties of LVL made from poplar and Chinese fir

| | LVL made from poplar | LVL made from Chinese fir | JAS 50v–43H |
|---|---|---|---|
| Thickness (mm) | 40 | 46 | |
| Glue | UF | UF | UF |
| Moisture content (%) | | 9.3 | ≤14 |
| MOR (MPa) | 61.1 | 58.6 | ≥30 |
| MOE (MPa) | 8500 | 9500 | ≥8040 |

**Table 5.** The properties of MDF from some mills in China

| | Mill A | Mill B | Mill C |
|---|---|---|---|
| Proportions of pine and poplar | 0:1 | 2:1 | 3:2 |
| Density (g $cm^{-3}$) | 0.76 | 0.77 | 0.73 |
| Glue | UF | UF | UF |
| Thickness (mm) | 15 | 15 | 18 |
| Moisture content (%) | 7.0 | 6.9 | 4.7 |
| Internal bonding strength (MPa) | 0.62 | 0.44 | 0.32 |
| MOR (MPa) | 40 | 45.9 | 39.2 |
| MOE (MPa) | 2844 | 3543 | 3717 |
| Thickness swelling (%) | 5.4 | 6.9 | 3.2 |
| Screw holding capability (N) | 1480 | 1430 | |

**Table 6.** The properties of OSB and particleboard made from poplar

| | OSB | Particleboard |
|---|---|---|
| Density (g $cm^{-3}$) | 0.74 | 0.69 |
| Glue | UF | UF |
| Thickness (mm) | 6 | 16 |
| Moisture content (%) | 7.7 | 10.2 |
| MOR (MPa) | 37.2 | 21.8 |
| Internal bond strength (MPa) | 0.71 | 0.63 |
| Thickness swelling (%) | 3.2 | 3.4 |
| Screw holding capability (N) | 1809 | 1446 |

4' × 8' timber core. Poplar veneer, 1.7 mm in thickness, is glued to both sides of this core, followed by two pieces of 0.6 mm thick imported veneer. The final thickness of blockboard is about 18 mm. It is mainly used for furniture manufacture and interior decoration. Table 3 shows the properties of blockboard made from poplar in three different mills in China.

*Laminate veneer lumber*

Recently, China has developed the technology to manufacture laminate veneer lumber (LVL). Some mills are now starting to produce LVL. The main raw materials used by these mills are poplar and Chinese fir. Table 4 shows the properties of LVL made in China.

*Particleboard, OSB and MDF*

The fibre of poplar is longer than the fibre of many hardwoods. It is suitable for manufacturing medium density fibreboard (MDF) and particleboard. Normally treetops, branches and small diameter logs are the main raw materials for MDF and particleboard. Sometimes poplar is mixed with pine for the production of MDF and particleboard. The properties of MDF in three mills in China are shown in Table 5.

Currently, oriented strand board (OSB) can be successfully produced from the low-density wood of fast growing trees, such as poplar. A domestic production line for making OSB from poplar has been built in Jiangsu Province, with a capacity of 15 000 $m^3$ p.a. The products can be used for packaging and construction. The properties of OSB and particleboard made from poplar in China are shown in Table 6.

*Reassembled veneer*

Poplar is good material for the manufacture of reassembled veneer. The poplar veneer is bleached, dyed, spread, formed into a thick mat and finally put into a press. The reassembled veneer sheets can be cut at various angles to produce pieces which can imitate the grain of rare natural species. Such pieces can then be used to finish plywood. More than 10 factories have been built in Jiangsu Province to produce reassembled veneer.

*Mineral-bonded composites*

Cement-bonded poplar particleboard has been developed in China (Chison et al. 1994). Untreated poplar wood inhibits the setting of cement and therefore the wood needs to be treated by physical or chemical methods to increase its compatibility with cement before it can be used to manufacture particleboard. The density of cement-bonded poplar particleboard had the largest influence on board properties. MOR, MOE and internal bond strength were all positively correlated with board density. The wood:cement ratio in the range 1:2 and 1:3 also had a significant effect on the MOE and internal bond strength of boards. The water:cement ratio in the range 0.5–0.55 had no effect on board properties, but when the ratio increased to 0.6, board properties decreased.

Research in China has also examined the suitability of poplar for other mineral-bonded composites, for example slag-bonded particleboard and gypsum fibreboard. It is technologically feasible to manufacture slag-bonded particleboard from Italian poplar using a wood:slag ratio of 1:2 to 1:3.5, water:slag ratio 0.5 to 0.55, activator 10–12% and 10–12% by weight of slag. Poplar fibre has been shown to be compatible with gypsum and suitable for the production of gypsum fibreboard.

## The Poplar Processing Industry in China

In addition to the development of the aforementioned industries a system has been put in place for poplar planting, product development and marketing.

On the basis of research on poplar at the population, tree, fibre and molecular levels, scientists have improved the techniques for cultivating poplar for plywood. Some of the key steps in the tree improvement process were:

1) selecting appropriate poplar clones for various regions according to their growth rate and wood quality;
2) choosing good sites for growing poplar;
3) adopting planting densities which maximise yield as well as producing timber that meets the needs of the plywood industry.

If these techniques are adopted, poplar forests with a high yield and high quality can be ensured. Many poplar plantations have been sited around the processing industries, and they are providing plenty of high quality raw materials for the factories.

Apart from the poplar products mentioned above, some new products are being developed, such as reinforced poplar products, fire-retardant products, electrically conductive plywood and dimensionally stable products (Weidong et al. 1994; Yukun and Feng 1994). These high quality products are used not only for furniture manufacture and interior decoration, but also for construction. In addition, some special treatments have been developed to improve the properties of poplar, for example, surface reinforcing treatments, bleaching, dyeing, and anti-fungal treatment (Wang et al. 1994).

Poplar products made in China are sold on the domestic market and also for export to countries such as Japan, Korea and Singapore. A large export market for poplar products is being built up. In recent years many foreign enterprises have focused more attention on the Chinese poplar processing industry. For example, a Singapore company has invested $US20 million to build a poplar blockboard factory. A Canadian company now owns a plantation for fast-growing trees in

Guangdong Province and has a particleboard factory with 0.1 million $m^3$ capacity. In addition, this company is building a particleboard mill with a capacity of 0.15 million $m^3$ in Jiangxi Province and an OSB mill with capacity of 0.3 million $m^3$ in Jiangsu Province. To support the poplar processing industry, international cooperation should be encouraged.

The poplar processing industry and its associated technology have developed over more than ten years. To avoid problems caused by the scale and rapid development of the industry, some principles should be observed.

1. ISO-9000 Quality Control and ISO 1400 Environment Control should be abided by when each new factory is built.
2. The Four **R** principle should be applied to the production process; namely, use **R**egrown material completely — fast-growing trees, bamboo and non-wood plants; try to **R**educe environmental pollution and consumption of energy during production; consider the **R**euse of products when designing them; think about **R**ecycling the products after they have been used.
3. Improve the automatic control technology in the production process.
4. Develop new products using workshop imitation technology.
5. Establish a market network to provide timely news of trends in supply and demand.
6. Try to attract people who are creative to improve the competitive position of your company.

If these principles are adopted and adhered to then the future success of the poplar processing industry in China should be guaranteed.

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# Novel Cement-bonded Wood Composites and Applications

# Natural Fibre–cement Composites: An Australian Perspective

**Robert S.P. Coutts**[1]

*Abstract*

Over the last three decades considerable research has been undertaken to find an alternative fibre to replace asbestos in asbestos–cement products. Australian research focused on natural fibres and ultimately it was a natural fibre — wood pulp fibre — that proved to be a suitable replacement for asbestos fibres. This paper reports on some of the Australian research that led to the commercial exploitation of natural fibres as reinforcement for cement products. The preparation and properties of the fibres are discussed, as well as their compatibility with existing processing technology. Some explanation of the bonding and microstructural behaviour (under load) within these composite materials is presented and related to their performance in service. The spread of the Australian wood fibre–cement technology and the range of applications for which the natural fibre–cement composites are used are discussed briefly, particularly with reference to activities in the USA and Asia.

In the early 1970s a global effort was initiated to legislate for the removal of asbestos reinforcement from a wide range of products. Fibre–cement composites were a major consumer of asbestos and therefore new reinforcing fibres were sought as alternatives to asbestos.

### Legislation Against the Use of Asbestos

Those countries that recognised the need to legislate against the use of asbestos on health grounds have proved to be the ones that have achieved the most significant advances with respect to asbestos substitution.

In 1982 the German Government and industry agreed to reduce asbestos content by 30–50% before 1986. In 1984 they revised the agreement so that it stated that all building construction materials would be free of asbestos by 1990. Since 1988, two producers of fibre–cement products in Germany, Eternit and Fulgurit, have received approval to produce large-size pressed and air-cured asbestos-free corrugated sheets. Unfortunately, in Germany the Government subsidises metal roofing to the detriment of the fibre–cement industry, and this has caused Fulgurit to close down its Wunstorf plant that had been manufacturing air-cured wood-fibre-reinforced cement composites.

By 1987, Sweden, Norway and Denmark had prohibited the use of asbestos. After 1989, with the easing of trade barriers in Europe, Italy, Belgium, the Netherlands, Austria and Switzerland introduced relevant bills that proposed to partly or completely prohibit the use of asbestos within 10 years. Countries such as France and Spain have been slower in changing to non-asbestos formulations, but with the advent of investments in new plant a transition to asbestos-free products can be expected.

Eastern European countries such as the former Yugoslavia and Czechoslovakia, which have been exporting fibre–cement products to Western Europe, will also be changing to asbestos-free products in an attempt to retain their market share of fibre-reinforced cement composites.

Russia and China, which produce more than half the world's asbestos, are obvious users of asbestos fibre in cement products and are expected to

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continue to be so for some time into the future. Although some research is being conducted into non-asbestos fibre–cement composites, there is no obvious strong drive towards legislation against the use of asbestos in those countries at the present time.

Although there is no legislation banning asbestos in fibre–cement composites in Australia, it was still the first country in the world to produce asbestos-free fibre-reinforced cement composites (New Zealand adopted this technology immediately afterwards). James Hardie Industries has been manufacturing asbestos-free cement sheeting since 1981 (Anon. 1981), and all products, including moulded products and non-pressure pipes, have been free of asbestos since 1987. The success of James Hardie's technology encouraged two more producers of natural fibre-reinforced cement products—BGC Fibre Cements and CSR Fibre Cements—to commence operations in Australia in 1994 and 1996, respectively. James Hardie Industries has since taken its asbestos-free technology overseas to New Zealand, Asia and North America.

The situation is different in developing countries. Older technology is much more prevalent there because of less stringent rules about occupational health and safety. Hence, high levels of production of asbestos-containing fibre–cements composites in Asia and South America are expected to continue for some time.

At the other end of the spectrum there exist many cottage-industry-type operations. The products of such enterprises are usually corrugated roofing, roofing tiles and flat sheet products that depend on a cheap fibre source and labour intensive production methods (IUTRLMS 1983, 1985; Swamy 1992). It is unfortunate that, even though millions of dollars have gone into this area of research in the form of foreign aid, the success of such activities has been somewhat limited by product failure (Lola 1992). However, the picture is not as bleak in this area as some have painted it. Efforts are being made to control the performance of low-cost building materials for use in developing countries. For example, in 1987 Gambia was the first country in Africa to adopt regulations supporting the use of indigenous, low-cost building materials suited to the needs and financial capabilities of its inhabitants (Anon. 1987).

There remains a great need to study new cheaper methods of fibre production, low-cost production processes, and the all-important question of durability of fibre-reinforced cement composites. Durability is related to matrix formulations, processing methods and curing regimes, and if natural fibre-reinforced cement products are to be readily available for low-cost housing much research still remains to be conducted.

## Research in Australia

### James Hardie research

The history of fibre–cement composites in Australia starts long before the 1970s. James Hardie and Coy Pty Ltd, hereafter referred to as James Hardie, began manufacturing asbestos–cement products in Australia in 1917. After establishing manufacturing plants around Australia, the company extended production to New Zealand in 1938. International expansion continued in the 1960s with the formation in 1966 in Malaysia of United Asbestos Cement Berhad, a joint venture (51% Malaysian ownership) with James Hardie, Turner and Newall and the European Eternit Company. In 1970, Indonesian production started with P.T. Harflex Asbes Semen. By 1977 James Hardie had 29 plants in Australia, New Zealand, Indonesia and Malaysia employing 6500 people.

James Hardie took an active interest in the use of cellulose as an economic asbestos substitute in fibre-reinforced cement in the early to mid-1940s. This work was intensified during the post-World War II years when there was a worldwide shortage of asbestos fibre. An investigation was conducted at Camellia, NSW, by Heath and Hackworthy (JHI 1947) to discover whether paper pulp could be used to replace asbestos completely or partially in asbestos–cement sheets. Fibres studied included bagasse, groundwood, wheat straw, cement bags and brown paper. The experimental autoclaved sheets showed that brown paper (kraft) was the best of the pulp sources, giving greatest strength to the composite material. However, when abundant supplies of asbestos became available, this work was discontinued.

Renewed interest in wood fibres began almost inadvertently in 1960 (Greenwood 1983; Seach, B.G. pers. comm. 1987). In those days, the asbestos fibreboard, containing 15% asbestos,

was made between steel interleaves. James Hardie's was believed to be the only group in the world to be steam-curing its sheets at that time. To make a cheap board as an alternative interleaf, a composite was made in which half the asbestos was replaced by wood fibres. Surprisingly, this material was found to be better than James Hardie's commercial product. This board became the first generation Hardiflex, and full production started in 1964. From the 1960s onwards James Hardie products contained no more than 8% asbestos, which was about half the amount their competitors were using.

Attempts to further reduce the asbestos content by adding more wood fibre were unsuccessful because these fibres were not as effective as asbestos in trapping the cement particles during formation of the sheet in a conventional Hatschek machine. It was in the 1970s, following health concerns about asbestos, that James Hardie made a strong commitment to the total replacement of asbestos reinforcement in their products.

## CSIRO and industry research

CSIRO in the early 1970s had active research programs studying ways of using wood fibres as reinforcement in a broad range of composite materials. They were also testing modification of the surface of wood pulp fibres to make them more compatible with various organic and inorganic matrices.

In 1977 James Hardie approached CSIRO Division of Chemical Technology (currently, CSIRO Forestry and Forest Products) about the possible use of natural fibres in their Indonesian subsidiary. After several meetings the organisations entered into a collaborative project to study the reinforcement of cement products with wood fibres. This project continued over the period 1978–82 (Anon. 1981).

After over 50 years of research into the science and application of wood and paper pulp CSIRO was well equipped to study, among other things, the refining of wood fibres. This was examined in an attempt to overcome the major problem of retaining the cement particles during the production of the wood-fibre-reinforced cement sheet. The project proved successful and it was later demonstrated by scanning electron microscopy (SEM) that refining opened up the structure of the individual fibres resulting in a fibrillated ('hairy') surface. During sheet production these refined fibres acted as a net, retaining the matrix material, similar to the situation occurring when asbestos was used (Coutts and Kightly 1982). By May 1981 a new generation of asbestos-free cement products, Hardiflex II, was being commercially manufactured. This autoclaved product was asbestos-free and totally reinforced by refined kraft wood fibres (Coutts and Ridikas 1982; Australian Patent No. 515 151).

### *Refining of fibres*

Refining and beating are both defined as the mechanical treatment of pulp carried out in the presence of water, usually by passing a suspension of pulp fibres through a relatively narrow gap between a revolving rotor and a stationary stator. The term 'beating' is usually applied to a batch treatment of pulp suspension, whereas 'refining' is used when the stock is passed continuously through one or more refiners in series (Britt 1970; Clark 1987).

It should be pointed out that refining does not produce the same effects on chemical pulp as it does on mechanical pulp. Chemical pulps contain less lignin, and hydroxyl groups are much more accessible. In mechanical pulps, hydroxyl groups are blocked by the presence of lignin. The refining of mechanical pulp is necessary to defibrate the fibre bundles that are produced by thermo-mechanical pulping.

Changes in fibre structure resulting from refining depend on the type of refiner, the refining conditions used, the fibre type (hardwood or softwood) and the pulp (mechanical or chemical). The main effects that are observed can be classified into four areas:

(i) internal fibrillation or delamination,
(ii) external fibrillation of the fibre surface,
(iii) fines formation,
(iv) fibre shortening.

Internal fibrillation effects, (i), are difficult to observe under a microscope, but they can be understood by considering a piece of rope. Rope is a helical wrap of strands that are themselves helical wraps of fibres. If a rope is twisted in the direction of the helical wrap the rope becomes 'stiffer'; likewise, if the twist is in the opposite

direction the rope unwinds (or delaminates) to open up the structure, and becomes 'floppy'; this is the case with internal fibrillation. The main effect of internal fibrillation is to increase fibre flexibility and swelling. The fibres may also undergo excessive curling and twisting.

External fibrillation, (ii), is easily observed by scanning electron microscopy. The fibrils or fibrillar lamellae attached to the fibre surface can vary widely in size and shape (but the process is again similar to the unravelling of a piece of rope at its surface).

The last stage, (iii), of external fibrillation is the peeling off of the fibrils from the fibre surface, with the formation of fines. The latter depends on the forces acting on the fibres during refining, and the duration of refining.

Fibre shortening, (iv), is the other primary effect attributed to refining. An indication that fibre shortening has occurred is the change observed in particle size distribution, which is a result of the cutting action of the blades or discs in the machinery on single fibres.

Refining plays an important role in producing a large surface area for fibre-to-fibre or fibre-to-matrix (in the case of composites) bonding and, more importantly, can assist in controlling the drainage rates of processing liquids during the manufacture of products. This is one of the main advantages of wood fibre compared to synthetic fibres such as glass, steel, etc., and a key factor in the success of kraft pulp as a replacment for asbestos when existing processes are used to manufacture wood fibre–cement composites.

*Chemical modification of fibres*

During this same period of time it was believed that modification of the fibre surfaces by chemical means might assist in the bonding to inorganic matrices. This complemented earlier studies at CSIRO on the use of coupling agents for composite products, and surface treatments of pulp for paper production. A collaborative research project with Australian Chemical Holdings was carried out during 1979–81. Although many novel polymeric systems were studied and certain benefits were achieved, the mechanical approach of refining fibres proved far superior with respect to performance and cost.

*Fibre selection*

The choice of wood pulp fibre as the preferred replacement for asbestos in fibre–cement occurred in spite of strong competition from other fibre types. During the 1970s and '80s, glass-fibre-reinforced cement was being acclaimed as the prime alternative to asbestos reinforcement (Hannant 1978). Also, steel fibres and a wide range of synthetic polymeric fibres as well as other natural fibres were actively under research in various countries around the world (Hodgson 1985). Although kraft wood pulp fibres were suitable they were reasonably expensive. Considerable research was conducted into alternative methods of producing fibres, and into extending the range of natural fibres suitable for reinforcing cement products.

The search for a replacement for asbestos fibres resulted in many natural fibres being examined in numerous laboratories around the globe as well as by Australian researchers. Obviously the fibre–cement industry has considerable in-house data, the results of which have not been made available to the general scientific community. At CSIRO a wide range of natural fibres, prepared by several pulping methods, was studied in various cement systems. Some representative published results are summarised in Table 1.

Some of the research at CSIRO on fibre selection was done in collaboration with overseas scientists who were evaluating the potential of local fibres to reinforce cement composites.

## University research

Sydney University was involved with James Hardie Industries in the 1970s through Professor Snow Barlow who was investigating plant structure. The identification of plant fibres as substitutes for asbestos was also a priority in his laboratory.

Sydney University had a strong interest in the mechanical performance of a wide range of materials, and, under Professor Mai, extensive testing of wood-fibre-reinforced sheeting was carried out to establish the products' performance under slow crack growth (Mai and Hakeem 1984a,b) and the generation of fracture toughness (Mai et al. 1982).

Research by Victoria University of Technology (Coutts et al. 1994; Zhu et al. 1994; Coutts and Ni 1995) was carried out in collaboration with CSIRO

**Table 1.** Natural fibres examined at CSIRO for their potential to reinforce cement composites

| Fibre | Pulping[1] | Refining[2] | Matrix[3] | Cure[4] | Reference |
|---|---|---|---|---|---|
| *Pinus radiata* (softwood) | K, TMP, CTMP | R/NR | C, M | A, AC | Campbell and Coutts 1980; Coutts and Ridikas 1982; Coutts 1984, 1986, 1987b; Coutts and Warden 1985 |
| *Eucalyptus regnans, E. grandis, E. saligna, E. pellita* (hardwoods) | K, CTMP | R/NR | C, M, GFS | A, AC | Coutts and Michell 1983; Coutts 1987a; Evans et al. 2000; Savastano et al. 2000a,b |
| *Acacia mangium* | K, CTMP | NR | C, M | A, AC | Eusebio et al. 1998a,b |
| Waste paper | — | NR | M | AC | Coutts 1989 |
| New Zealand flax | NaAQ | R/NR | M | A | Coutts 1983 |
| Abaca | K | R | C | AC | Coutts and Warden 1987 |
| Banana | K | NR | C | AC | Coutts 1990; Zhu et al. 1994; Savastano et al. 2000b |
| Sisal | K, S | NR | C, GFS | AC | Morrissey et al. 1985; Coutts and Warden 1992; Savastano et al. 2000a |
| Bamboo | K | R | C, M | A, AC | Coutts et al. 1995; Coutts and Ni 1995 |

[1]K = Kraft pulp, TMP = Thermomechanical pulp, CTMP = Chemithermomechanical pulp, S = Soda pulp, NaAQ = Soda anthraquinone pulp
[2]R = refined, NR = not refined
[3]C = Cement, M = Cement and sand/silica mix, GFS = Ground furnace slag matrix
[4]A = Autoclaved, AC = Air-cured

at the Division of Forestry and Forest Products and was focused on non-wood pulp fibres.

More recently, The Australian National University, in collaboration with CSIRO and the Forestry and Forest Products Research and Development Institute in the Philippines, has become involved with wood–cement products and some of this work has involved wood fibre–cement composites (Eusebio et al. 1998a,b; Evans et al. 2000).

### Other manufacturers within Australia

After the initial success of James Hardie, other Australian companies became interested in wood fibre–cement products. Pulp manufacturers from both Australia and New Zealand carried out considerable research on the suitability of their range of pulps as replacements for asbestos. Cement companies also looked at the opportunities for manufacturing products from cement and natural fibres. However, the main thrust of research in Australia remained with wood fibre–cement panel products.

Early in 1991 Atlas-Chemtech (now BGC Fibre Cement) asked CSIRO to assist them in establishing a plant to manufacture wood-fibre-reinforced-cement composites. They had acquired a second-hand Hatschek machine from Toschi in West Germany. This company, which had no prior experience in fibre–cement production, began constructing its factory in 1993. Its location, adjacent to the Aerated Autoclaved Cement (AAC) plant, was selected to take advantage of a silica ball mill and a gas-fired boiler for autoclaves. This enterprise enabled the parent company to supply their extensive building empire in Western Australia with fibre-reinforced-cement sheeting. At the same time, due to cheap (backload) freight (from west to east), they could compete with James Hardie, selling their excess capacity to the east coast market of Australia. It is believed they have about 5% of the local market.

The original formulation for wood fibre–cement composites was based on that of Supradur (Canada) which had a high cement content and 10% bleached cellulose fibre. This mix produced a high strength sheet that did not suit certain applications in Australia, because it lacked flexibility and nailability and there was excessive sheet movement. After much research and development, BGC developed a new formulation using New Zealand fibre–cement-grade cellulose pulp. This produced a better product that could be used as a building material in a greater range of applications. The quality and production efficiency of BGC was recognised by USA building products manufacturer Temple-Inland when it decided to enter the US fibre–cement siding market. In 1996, Temple-Inland signed an agreement with BGC for its technology and assistance in constructing a fibre–cement plant in Texas, USA.

BGC is currently operating one line with a capacity of 5 million Standard Metres, and has plans to increase production. Sales and warehouse facilities exist in Perth, Adelaide, Melbourne, Sydney, Brisbane and Auckland. As well as having Australian and New Zealand markets the company exports to Singapore and New Caledonia.

In 1994 CSR also asked CSIRO to assist it in producing fibre–cement composites. CSR is one of the world's largest building and construction materials companies, with operations in Australia, New Zealand, USA and Asia. At that time it employed about 20 000 people in nine countries with sales worth over A$6 billion per annum. Its entry into the market was a little less demanding in that it had built a turn-key plant for about A$56 million. The big advantage that this company had was that it already had large distribution centres in Australia that could guarantee its entry into the market — a feature lacking for James Hardie, which in many cases had been supplier to CSR-owned outlets! CSR currently has about 25% of the domestic market in Australia with distribution outlets in all Australian States and in New Zealand. Their product is also exported to several Asia–Pacific countries.

In 1998, Applied Technology and Planning Pty Ltd (ATP) developed a patented manufacturing process called Micro Internal Compaction. This injection moulding style process allows the rapid production of two- and three-dimensional aerated fibrous cement products. Ultimate Masonry Australia Pty Ltd (UMA), from its factory in Brisbane, is using this technology to produce what it claims to be the world's first commercial, hollow aerated concrete block. Production is currently limited to the full range of 400 mm x 400 mm x 200 mm hollow 'SmartBlocks'. These blocks have compression strength superior to that of conventional concrete blocks at half the weight (see also Klatt and Spiers, these Proceedings).

In 1999 Assedo Pty Ltd advised ATP on the use of wood pulp fibres as reinforcement in cement products. The UMA SmartBlock is currently made from an aerated slurry of cement, fly-ash, cellulose fibre and water. In this application, compression strength is of primary importance. A low fibre content is used to stabilise the rheology of the three-phase air, water, powder mix during the vacuum dewatering stage of the Micro Internal Compaction moulding process. Smart-Blocks are autoclaved after moulding. The density of this product is 1100 kg $m^{-3}$ while the hollow product with a 50% void ratio has a gross density of 550 kg $m^{-3}$. There is no significant alignment of fibres and the process produces an essentially isotropic material.

UMA claims a wide range of advantages for its product, including environmental and occupational health and safety benefits, reduced construction costs and improved thermal and other functional characteristics. The fine-grained high precision surface of the SmartBlock can be sanded and painted to achieve a plaster style finish for both internal and external applications. By January 2001 a new three-head moulding machine will have allowed production to increase from the current 5000 blocks per week to 50 000 blocks per week. In the longer term UMA plans to establish a series of plants adjacent to coal-fired power stations to take full advantage of the benefits of industrial ecology. The first of these is planned to commence production in 2002 and will have a capacity of 10 million blocks per annum. Negotiations are underway regarding the development of plants in both India and China.

ATP continues research directed towards exploring other applications of its Micro Internal Compaction technology. In particular, it is working with high cellulose fibre mixes on a variety of linear, sheet and decorative products where flexural strength becomes significant. It

aims to use the unique characteristics of its production technology, including the ability to mould aerated low-density products, to open up new applications for fibre–cement products.

Australian research led the world in finding an alternative to asbestos in fibre–cement products. That revolution in relation to the material was not matched by any significant change to production processes. Cellulose fibre–cement sheeting and pipe products continue to make use of the old Hatschek process originally developed nearly 100 years ago for use with asbestos-based products. The Australian-developed Micro Internal Compaction process, together with developments in cellulose material technology, opens up possibilities for new environmentally sustainable products that could transform the building industry.

## Further Global Expansion: James Hardie Industries

In 1983 James Hardie and Cape Industries of the UK formed a joint venture, Fibre Cement Technology (JHI 1984). The objective was to market the new technology they had developed, to manufacture asbestos-free fibre–cement building products to interested companies throughout the world.

It was stated in 1985 that the UK manufacturers had replaced asbestos in about 50% of fibre–cement sheeting products (Crabtree 1986). James Hardie by this time had totally replaced asbestos fibre in its range of building products, which included flat sheet, corrugated roofing and moulded products, throughout Australia and New Zealand. Part of the Malaysian production by the company was also free of asbestos. The Indonesian interests had been sold in 1986 for financial reasons. The Malaysian operation also ceased about this time.

As well as flat-sheet products, James Hardie had become a world leader in injection moulded fibre–cement products and non-pressure fibre–cement pipes, all based on wood fibre as the reinforcing material. The first experimental production of wood-fibre-reinforced cement pipe was undertaken at the Brooklyn factory in September 1980. Commercial production began in Western Australia at the Welshpool factory in July 1984. The last asbestos pipes made by James Hardie were manufactured in March 1987.

In the late 1980s James Hardie introduced imported wood-fibre-reinforced cement products into the USA market. At that time fibre–cement composites represented less than 1% of the large sidings market. The market comprised wood-based materials (~51%), vinyl (~28%) and inorganic products (~20%). By 1999, fibre–cement could claim more than 9% of the sidings market in the USA.

In 1990 James Hardie built its first plant at Fontana, California, to start manufacturing in the USA. Although the product was initially slow to be accepted by the building industry, the superior durability, fire resistance and value for money resulted in increasing market share, and by 1994 the company started to build its second plant at Plant City, Florida. It was not until 1995 that demand for the product suggested that the technology had been fully accepted. In 1997 a third plant at Cleburne, Texas, was opened followed by a fourth plant at Tacoma, Washington (1999). In November 1999 James Hardie announced that a fifth plant would be constructed at Peru, Illinois.

The in-house research that James Hardie has undertaken over many years has provided it with proprietary product and process technology that enables it to offer the widest product range and to benefit from significantly lower capital and operating costs, compared to competing fibre–cement technologies.

Recent research by James Hardie, involving a team of staff from the Sydney and Perth laboratories in Australia and the Fontana laboratory in USA, has resulted in the development of ‘Harditrim’. This innovative material is a low-density product that can be made thicker than normal panel products and therefore can be used on corners, columns, windows and gables where current products are unsuitable. James Hardie commits some A$25 million per annum to continuing research into wood-fibre-reinforced cement products and process technology and estimates the potential long-term fibre–cement market in the USA, in areas such as sidings, roofing and trim products, to be worth up to A$4.8 billion a year. At the moment James Hardie has ~A$400 million sales — 85% of the fibre–cement market in USA.

The global market could be a large as A$15 billion when it is noted that more than two-thirds

of the fibre–cement industry still uses asbestos; global pressure will drastically change this situation in the near future. The European Union has declared that it will ban asbestos–cement products by 2005. South American countries are also starting to move against asbestos.

A joint venture with Jardine Davies, Inc., resulted in the development of a $50 million plant in the Philippines. This plant was commissioned in 1998. James Hardie has recently further expanded its manufacturing capability in Asia. Once again it has formed a joint venture with Malaysia's UAC Berhad. This 50/50 venture will link the James Hardie Philippines plant with the UAC plant in Malaysia, giving the combined group a capacity of 220 million square feet a year. James Hardie has estimated that within five years its Asian business could be as big as its billion square feet a year USA business. James Hardie is confident that fibre–cement composites will replace traditional materials such as plywood in house construction in Indonesia, Malaysia and the Philippines, and masonry products in Taiwan and Hong Kong.

## Conclusions

Australian research groups have been major contributors to the global success of wood-fibre-reinforced cement composites, products totally free of asbestos fibres.

James Hardie Industries deserves the position it holds in the global marketplace due to its commitment and perseverance, especially during the early years in the USA when it experienced a period of operation without profit.

## Acknowledgements

The author acknowledges the wonderful facilities and creative environment provided to him during his 36 years at CSIRO. My thanks to the excellent staff, students and guest workers from Australia and overseas who not only maintained my enthusiasm for research but usually did most of the work! In particular I would like to single out Peter Warden for keeping me honest during the last twenty plus years!

Special thanks to the Australian companies who made research interesting by openly discussing their problems and providing information (often only available within company archives) and, more importantly, for their financial support to the various research projects.

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# Production and Properties of Oriented Cement-bonded Boards from Sugi (*Cryptomeria japonica* D. Don)

**Ling Fei Ma[1, 3], Hidefumi Yamauchi[1], Orlando R. Pulido[1], Hikaru Sasaki[1] and Shuichi Kawai[2]**

*Abstract*

Extractives in sugi (*Cryptomeria japonica*) inhibit the curing of cement, and hence wood–cement composites manufactured from sugi invariably have poor mechanical properties. The aim of this study was to manufacture high strength wood–cement composites from sugi by making boards from sapwood, which contains less of the extractives that inhibit cement curing, using a cement setting accelerator and orientating strands in the boards to maximise strength properties. By adopting these strategies, high strength boards could be produced despite cement hydration tests that showed that sugi sapwood inhibited the curing of cement. Manipulation of surface:core ratio and, to a lesser extent, strand thickness can be used to modify mechanical properties in bending (MOR and MOE), but not internal bond strength.

THERE have been many studies of the manufacture of cement-bonded boards (CBB) from wood or other lignocellulosic materials. The inhibitory effects of these materials on the curing of cement have also been widely studied. Wood species have been classified as highly suitable, suitable and less suitable (Hachmi and Moslemi 1989) for the manufacture of wood–cement composites, or as having non-inhibitory, moderately inhibitory or highly inhibitory effects on the curing of cement (Alberto et al. 2000). Various compounds are thought to be responsible for the inhibitory effects of wood on cement setting, including soluble sugars, arabinogalactans, phenolics and other extractives. Geographic location, felling season and storage period also influence curing through their effects on the extractive content of wood (Yasuda et al. 1992).

To improve the suitability of wood for CBB manufacture numerous pre-treatments designed to remove extractives or minimise their deleterious effect on cement hydration have been developed. Aqueous extraction and use of cement setting accelerators are the most common pre-treatment (Ma et al. 1996, 1997). Our group has also examined a variety of other pre-treatments, manufacturing techniques and post-treatment methods designed to improve the suitability of inhibitory wood species for CBB. Methods tested have included extraction, rapid curing by hot pressing or steam injection pressing, and post-curing by immersion in magnesium chloride solution or heat treatment (Nagadomi et al. 1996; Ma et al. 1998a,b, 1999). Results have shown that each method has inherent advantages and disadvantages. Extraction is too expensive and produces unnecessary or toxic wastes as by-products. Moreover, each species must be treated separately, a feature that is unacceptable in commercial CBB production which demands the use of mixed raw materials or species. Better

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**Table 1.** Dimensions of sugi (*Cryptomeria japonica* D. Don) particles and strands

| Type | *n* | Length L, mm | | Width W, mm | | Thickness T, mm | | L/W | L/T |
|---|---|---|---|---|---|---|---|---|---|
| | | Ave | SD | Ave | SD | Ave | SD | | |
| RF* | 198 | 7 | 4 | 1.9 | 1.3 | 0.39 | 0.21 | 5 | 21 |
| St 25** | 170 | 69 | 12 | 14.6 | 15.6 | 0.25 | 0.07 | 16 | 299 |
| St 40 | 414 | 63 | 16 | 7.3 | 6.3 | 0.40 | 0.20 | 22 | 183 |
| St 66 | 198 | 68 | 12 | 6.7 | 5.1 | 0.66 | 0.32 | 21 | 120 |
| St 82 | 278 | 64 | 18 | 6.6 | 6.0 | 0.82 | 0.34 | 22 | 91 |

*RF — particles were prepared by chipper then ring flake
** St — strands were prepared by rotary cutting in veneer lathe

treatment methods are obviously required. It may be possible to manufacture boards with the desired strength from species that have inhibitory effects on the setting of cement by altering the structure of boards to take maximum advantage of the high strength of wood. A veneer lathe with the added function of producing oriented-strand-board-type flakes has been developed at the Institute of Wood Technology, Akita Prefectural University. The lathe can be used to control the length, thickness and width of the strands. While strand or particle orientation is widely applied in the resin-bonded board industry, there are few studies on the use of this technique for CBB and, to our knowledge, none on sugi, a species known to have inhibitory effects on cement setting.

Therefore, manipulation of strand orientation was tried as part of a strategy to manufacture high strength CBB from sugi. Two other more conventional strategies were employed to improve board properties: (i) the use of sapwood which contains less of the extractives that inhibit cement curing; (ii) use of a cement setting accelerator to minimise the inhibitory effects of sapwood effects on board properties. In addition to the main aim of the study the effects of strand thickness, surface:core ratio and water:cement ratio on board properties were also assessed.

## Materials and Methods

The wood raw materials were strands of sugi sapwood. Sugi logs were obtained from a 70-year-old sugi plantation in Akita Prefecture. Felling of trees took place in winter and undebarked logs (35 cm in diameter) were stored for 6 weeks outdoors before conversion into veneer. Logs were debarked and peeled into veneer. Oriented strand board (OSB) strands were produced using the veneer lathe described above. Strands of four different thicknesses were produced (Table 1). The dimensions of 150–400 strands for each type were measured (Table 1). The aspect (length/width) and slenderness (length/thickness) ratios of the strands were very high, making them ideal for mechanical orientation. Portland cement and calcium chloride (3.75% $CaCl_2$ based on cement weight) were used as binder and additive, respectively, at a cement:wood ratio of 2.6 and a water:cement ratio of 0.5 or 0.6. The mechanical orienting plates were 25 mm apart and the free fall distance was less than 5 mm. Particles produced by a chipper and ring flaker were used as core material in some boards.

Three types of mats were formed manually, namely a) single layer mats of unidirectionally oriented strands, b) three-layer mats of strands with oriented surfaces and random core, and c) three-layer mats of oriented strands and random core of ring flaker particles from sugi chips (Fig. 1). The cement/wood/water contents of the surfaces and core were the same for each mat. The weight ratios of surface and core materials were varied. The mats were cold pressed for 20 h, cured at 20°C and 60% RH for 14 days, dried at 60°C for 8 h then conditioned at ambient temperature for 7 days. Testing was conducted according to the Japan Industrial Standards for Particleboards JIS A5908.

For the hydration tests, sugi strands were powdered in a Willey mill and those passing a #40-mesh screen were used. The hydration temperatures of neat cement paste and of mixtures of cement–sugi and cement–sugi–additive were measured, using 200 g cement, 15 g sugi powder,

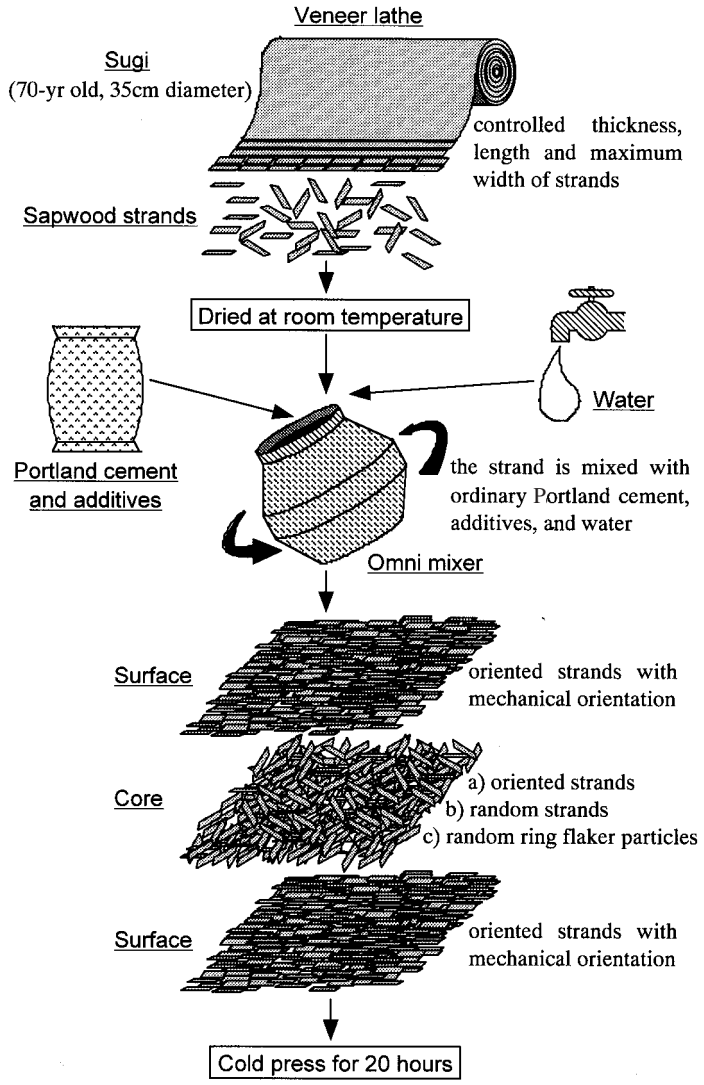


**Figure 1.** Method of producing sugi sapwood strands and manufacturing oriented CBB

100 g water and 3.75% $CaCl_2$ based on the cement weight for one test.

## Results and Discussion

The hydration temperatures of neat cement paste, sugi sapwood powder with cement and the mixture of sugi powder, cement and 3.75% $CaCl_2$ are shown in Fig. 2. The addition of sugi sapwood powder to the cement paste reduced the hydration rate of cement suggesting that inhibitory substances were present in the wood. Magnesium chloride ($MgCl_2$) has been shown to ameliorate the inhibitory effects of sugi wood on cement curing, whereas $CaCl_2$ has been found to be less effective (Yasuda et al. 1992). However, contrary to the findings of Yasuda et al. (1992), the hydration of cement was accelerated by the addition of $CaCl_2$ in this study. This additive was therefore used in preference to $MgCl_2$ for the

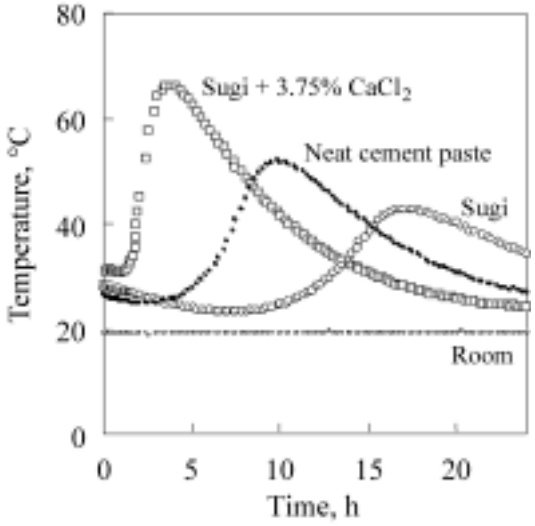


**Figure 2.** Hydration temperatures of cement–sugi (*Cryptomeria japonica* D. Don) mixtures

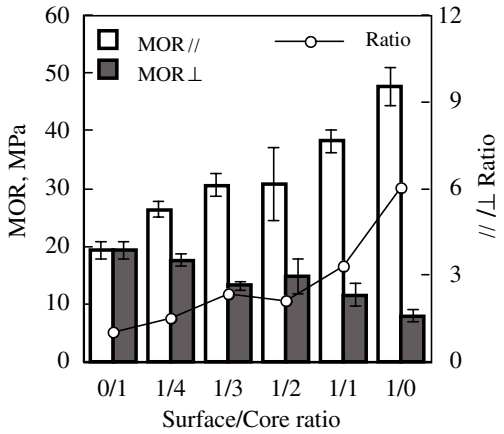


**Figure 3.** Modulus of rupture of cement-bonded strandboards from sugi with oriented surfaces and random cores. Notes: Type = Strand 40; additive = 3.75% $CaCl_2$ based on cement weight; cement:wood:water = 2.6:1.0:1.3.

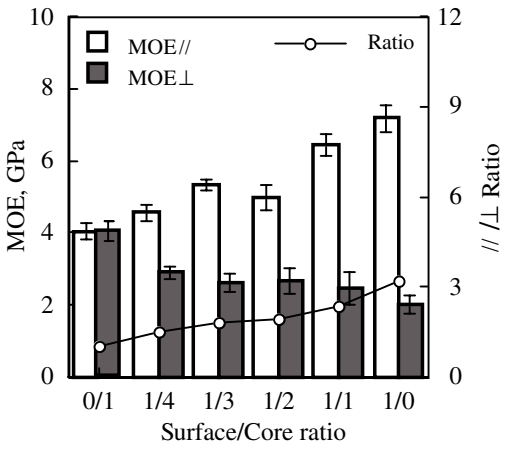


**Figure 4.** Modulus of elasticity of cement-bonded strandboards from sugi with oriented surfaces and random cores. Notes as in Fig. 3.

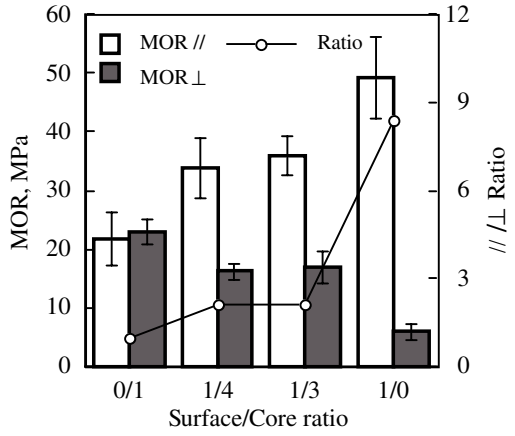


**Figure 5.** Modulus of rupture of cement-bonded strandboards from sugi with oriented surfaces and random cores. Notes: Type = Strand 40; additive = 3.75% $CaCl_2$ based on cement weight; cement:wood:water = 2.6:1.0:1.56.

production of oriented CBB because it is cheaper than $MgCl_2$.

The modulus of rupture (MOR) and modulus of elasticity (MOE) of CBBs at a water:cement ratio of 0.5 are shown in Figs 3 and 4, respectively, while those at a water:cement ratio of 0.6 are shown in Figs 5 and 6. There was little effect of varying water:cement ratio, within these limits, on strength properties, confirming that both ratios are suitable for CBB production, as we have shown previously (Ma et al. 1998a,c). The MOR values in the oriented direction of oriented cement-bonded strandboards were 2.5 times greater than in boards with randomly oriented strands; the increase in MOE was about two times. Orienting even only 25% of the strands (surface) resulted

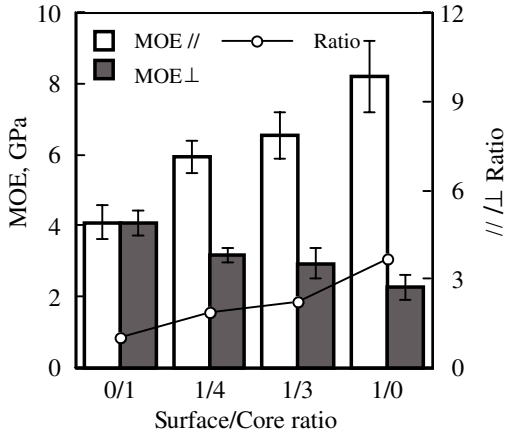


**Figure 6.** Modulus of elasticity of cement-bonded strandboards from sugi with oriented surfaces and random cores. Notes as for Fig. 5.

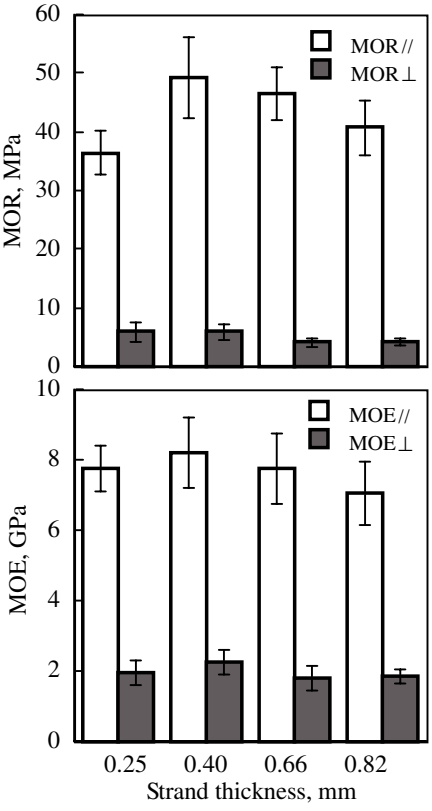


**Figure 7.** Effect of strand thickness on the MOR and MOE of oriented cement-bonded strandboard from sugi. Notes as for Fig. 5. All strands are oriented.

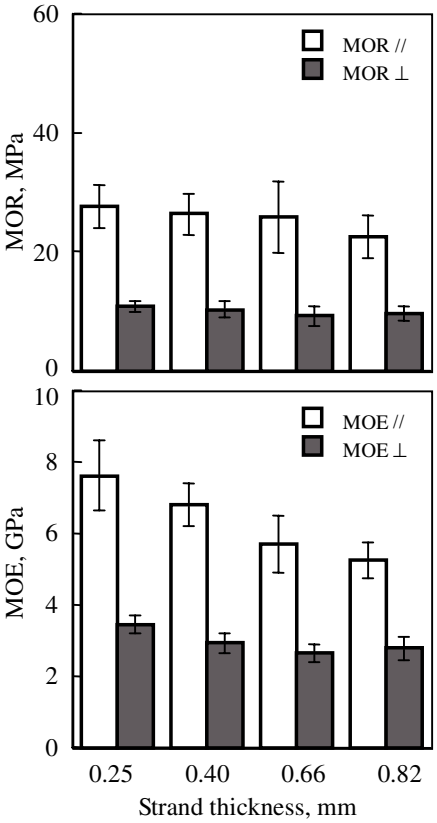


**Figure 8.** Effects of strand thickness on the MOR and MOE of cement-bonded strandboards from sugi with oriented surfaces and random cores. Notes: surface = strands; core = ring flakes; additive = 3.75% $CaCl_2$ based on cement weight; cement:wood: water = surface 2.6:1.0:1.56 and core 2.6:1.0:1.3; surface (oriented):core (random) = 1:4.

in significant increases in the MOR and MOE values of the boards. The anisotropy in strength (ratio of MOR or MOE in the oriented (//) and cross directions (⊥) increased as the ratio of the oriented surface to the random core increased. In boards that contained only oriented strands, this ratio ranged from 6 to 8 for MOR and from 3 to 3.5 for MOE. All boards had high strength values compared to ordinary cement-bonded boards, and easily passed the JIS standards.

Very high values of MOR and MOE were obtained when all the strands were oriented in one direction. Boards made from strands 0.4 mm thick gave values as high as 57 MPa (average =

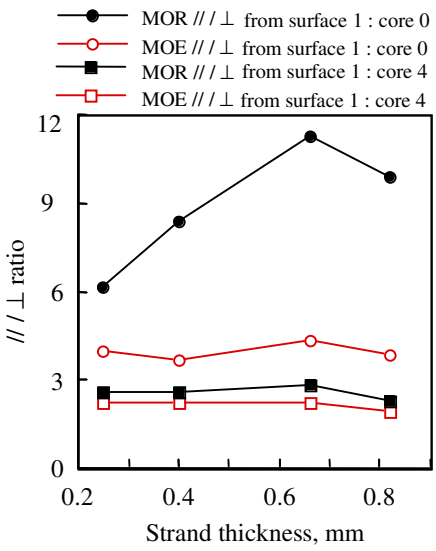


**Figure 9.** Anisotropy in MOR and MOE values of cement-bonded strandboards from sugi with oriented strand surfaces and random ring flake cores

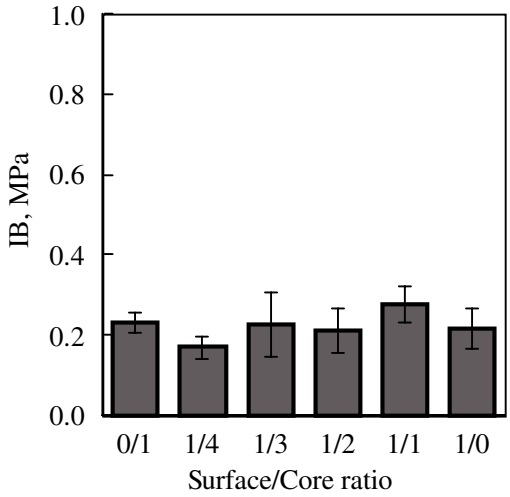


**Figure 10.** Internal bond strength (IB) of cement-bonded strandboards from sugi with oriented surfaces and random cores. Notes: as in Fig. 3.

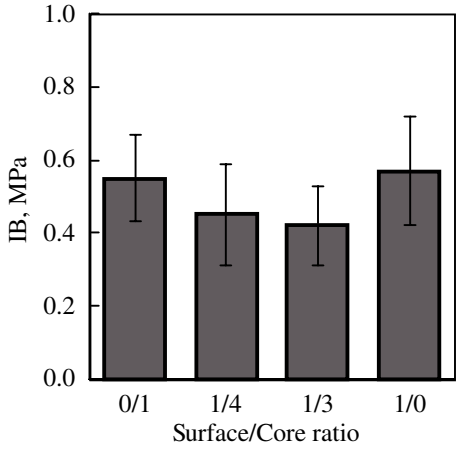


**Figure 11.** Internal bond strength (IB) of cement-bonded strandboards from sugi with oriented strand surfaces and random cores. Notes: as in Fig. 5.

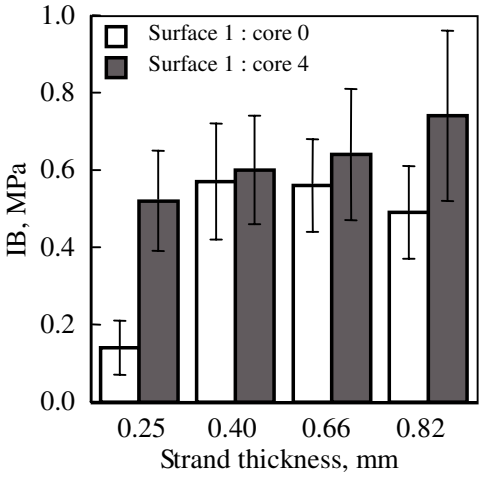


**Figure 12.** Internal bond strength (IB) of cement-bonded strandboards from sugi with oriented strand surfaces and random ring flake cores

49 MPa) and 9.5 GPa (average = 8.3 GPa) for MOR and MOE respectively, as shown in Fig. 7.

Figure 8 shows the MOR and MOE values of cement-bonded strandboards with oriented surfaces and random cores at 1:4 surface:core weight ratio. The ratios of these properties (Figs 7 and 8) in the parallel and cross directions are shown in Fig. 9. The oriented strandboards made from 0.66 mm-thick strands were highly anisotropic with a ratio of 11 for MOR// : MOR⊥. There were slight differences in the MOR values of boards containing strands of different thicknesses. Boards made from thin strands tended to give higher MOE values than boards made from thicker strands. All boards had high strength, even in the cross direction.

**Table 2.** Dimensional stability of cement-bonded strandboards from sugi

| Surface/Core | | Strand thickness mm | Oven-dry density kg/m$^3$ | 24-h expansion, % | | | | | | 24-h water absorption, % |
|---|---|---|---|---|---|---|---|---|---|---|
| Type | Weight ratio | | | Thickness | SD | Width | SD | Length | SD | |
| | 0/1 | 0.40 | 1225 | 8.4 | 1.3 | 0.38 | 0.10 | 0.34 | 0.03 | 24.1 |
| | 1/4 | 0.40 | 1073 | 10.5 | 1.8 | 0.55 | 0.18 | 0.48 | 0.13 | 37.1 |
| St/St | 1/3 | 0.40 | 1113 | 10.2 | 1.5 | 0.41 | 0.05 | 0.41 | 0.11 | 32.4 |
| | 1/2 | 0.40 | 1134 | 10.0 | 1.1 | 0.45 | 0.06 | 0.38 | 0.06 | 32.5 |
| | 1/1 | 0.40 | 1152 | 10.4 | 2.3 | 0.43 | 0.10 | 0.33 | 0.06 | 31.1 |
| | 1/0 | 0.40 | 1080 | 9.9 | 1.5 | 0.70 | 0.12 | 0.33 | 0.07 | 32.3 |
| | 0/1 | 0.40 | 1014 | 3.4 | 1.1 | 0.27 | 0.08 | 0.27 | 0.08 | 19.3 |
| St/St | 1/4 | 0.40 | 1081 | 3.2 | 1.4 | 0.30 | 0.13 | 0.20 | 0.06 | 18.6 |
| | 1/3 | 0.40 | 1104 | 3.6 | 0.9 | 0.23 | 0.07 | 0.25 | 0.03 | 17.7 |
| | 1/0 | 0.40 | 1122 | 3.8 | 1.2 | 0.33 | 0.06 | 0.19 | 0.07 | 17.1 |
| | 1/0 | 0.25 | 1056 | 3.6 | 0.8 | 0.40 | 0.10 | 0.18 | 0.06 | 17.7 |
| St/St | 1/0 | 0.40 | 1126 | 3.8 | 1.2 | 0.33 | 0.06 | 0.19 | 0.07 | 17.3 |
| | 1/0 | 0.66 | 1091 | 3.7 | 1.0 | 0.36 | 0.05 | 0.18 | 0.04 | 17.4 |
| | 1/0 | 0.82 | 1099 | 4.2 | 1.2 | 0.44 | 0.18 | 0.17 | 0.09 | 18.1 |
| | 1/4 | 0.25 | 1100 | 2.4 | 0.3 | 0.25 | 0.06 | 0.20 | 0.06 | 23.0 |
| St/RF | 1/4 | 0.40 | 1087 | 2.3 | 0.6 | 0.27 | 0.03 | 0.22 | 0.05 | 22.9 |
| | 1/4 | 0.66 | 1070 | 2.4 | 0.5 | 0.27 | 0.04 | 0.20 | 0.04 | 24.5 |
| | 1/4 | 0.82 | 1064 | 3.0 | 0.6 | 0.30 | 0.05 | 0.17 | 0.02 | 24.5 |

Notes: see also Table 1.

The internal bond strengths of boards are shown in Figs 10 and 11 for cement-bonded strandboards and Fig. 12 for three-layer boards with oriented strand surfaces and random cores of ring flaker chips. Orientation did not affect the internal bond strength of boards. Most failures occurred in the core. Boards with ring flaker particles as core materials had higher internal bond strength than those with strands as core materials. The distribution of cement during the mixing process was more even on the surfaces of the particles than on the strands. Although this did not have much effect on the strength of boards (MOR, MOE), the effect was noticeable when load was applied at right angles (internal bond strength) to the thickness of boards.

The dimensional stability, that is, changes in thickness, length and width, of boards after 24 h immersion in water, is summarised in Table 2. The boards had relatively poor dimensional stability in thickness, length and width. Due to the nature of the strands, there was difficulty in mixing wood and cement and there could have been incomplete coatings of cement at the surfaces of the strands.

## Conclusions

Our findings clearly show that high strength CBB can be produced from sugi sapwood, despite the fact that the wood inhibits the setting of cement. Calcium chloride, when used as additive in small amounts (3.75% in this experiment), appears to ameliorate the inhibitory effects of the sapwood. Orientation of strands improves the strength properties of CBBs and is a more economical alternative than aqueous extraction of wood if boards with high bending properties and good dimensional stability are required. However, the materials should be properly prepared. In this experiment, the strands were from good quality sapwood of sugi, eliminating the inhibitory effects of extractives that are in the heartwood and bark. Orientation of strands in combination with the use of sapwood and $CaCl_2$ is a good alternative to extraction or post-treatment conditioning when using wood species that are poorly suited to wood–cement composites.

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# Manufacture of Wood Strand–Cement Composite for Structural Use

**Atsushi Miyatake[1], Tsuyoshi Fujii[1], Yasushi Hiramatsu[1], Hisashi Abe[1] and Mario Tonosaki[1]**

*Abstract*

A new composite composed of wood strands and a cement-based matrix named Cement Strand Slab (CSS), was developed and the influence of manufacturing conditions on its strength properties was examined. Wood strands were produced by splitting slabs of sugi (*Cryptomeria japonica*) using a roll press-slitter which was developed by the Forestry and Forest Products Research Institute. Wood strands were air-dried, dipped in water or cement solution, treated with water by pressure-vacuum or coated with paraffin. The wood strands were mixed with mortar (Portland cement, sand, water, calcium chloride) and aligned longitudinally in a steel mould. The mortar was cured under pressure at room temperature for 48 h. The slab was removed from the mould and cured for 2 to 6 months before being subjected to a bending test. The modulus of rupture (MOR) of CSS was 20–40 MPa and its modulus of elasticity (MOE) was 20–25 GPa. The strength properties of CSS are therefore sufficiently high for it to be used for structural members. It may also possess greater fire resistance than competing wood composite lumber substitutes because of its high cement content. The MOR was improved by treating wood strands with cement solution and it was also affected by the vacuum-pressure treatment of strands with water. From these results it may be inferred that contact between the wood and the cement is an important factor affecting the strength properties of the composite.

ENVIRONMENTAL pressure over the last decade has focused attention on the utilisation of fast growing trees for the manufacture of bio-based composites. The Forestry and Forest Products Research Institute has developed a new processing technology to use fast-growing trees, small diameter logs and sawmill residues for the manufacture of a variety of wood composites. The key process in the new technology is the production of thin wood strands using a roll press-slitter (Fig. 1). The roll press-slitter splits logs or sawmill slabs into strands along the grain.

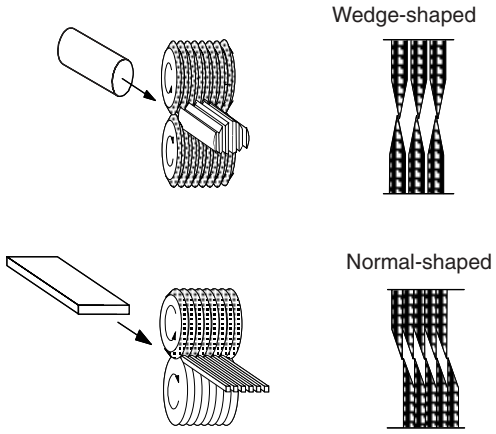


**Figure 1.** Diagram of a roll press-slitter

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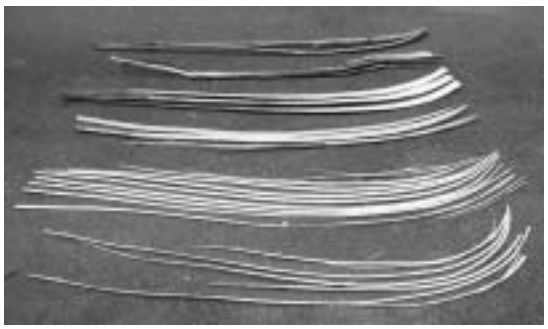

**Plates 1 and 2.** Wood strands from small bent logs; and the appearance of SST

Therefore the strands have little damage across the grain and retain the natural strength of the wood fibre. In addition the yield of strands is quite high, more than 90% in volume, and the process can use whole logs even if they are bent (Plate 1). Species that have low density, small knots and straight grain, such as willow (*Salix* spp.) and sugi (*Cryptomeria japonica*), are very suitable for the production of such strands.

The composite in which wood strands are bonded with normal resin is named SST (Plate 2). The mechanical and strength properties of SST are high and enable it to be used in structural members (Miyatake and Fujii 1997). Panel products composed of wood flakes and cement have been used for structural purposes and it should be possible to manufacture structural timber substitutes from wood strands and cement. The aim of this study was to optimise the raw materials and process conditions required to manufacture wood strand–cement composites, hereafter referred to as cement strand slab (CSS), for use in structural applications.

## Materials and Methods

### Preparation of strands

The wood materials for this study were slabs of sugi that were residues of the sawmilling industry. Slabs 50–200 mm wide × 10–30 mm thick × 3000 mm long were cross-cut into 600 mm lengths and split into strands with the roll press-slitter. The strand cross-section was almost rectangular, about 10 mm × 4 mm.

### Treatment of strands

The wood strands were given the following treatments before being mixed with mortar.

a) Air-dry (A): strands were kept in a log pond until they attained a moisture content of approximately 200%. Green strands were dried in an air-conditioned room at 20°C, 45% relative humidity (RH), until the moisture content of strands was about 12%.
b) Dip in water (Wd): air-dried strands were dipped in water at room temperature for 5 min. After the treatment, the moisture content of strands was about 150%.
c) Soak in water (Ws): air-dried strands were soaked in water at room temperature for 24 h. After the treatment, the moisture content of strands was about 200%.
d) Vacuum-pressure in water (Wvp): air dried strands were pressure treated with water using an initial vacuum of –84.7 kPa for 5 min and then pressure (0.5 MPa) for 6 h at room temperature. After the treatment, the moisture content of strands was about 300%.
e) Dip in cement solution (Cd): air-dried strands were dipped in cement solution before the strands were mixed with mortar. The cement solution consisted of 0.25:1 – 1.0:1 weight ratio of cement to water.
f) Coat with paraffin wax (P): air-dried strands were dipped in melted paraffin wax.

### Preparation of CSS

Treated strands and mortar were hand-blended and the strands were aligned longitudinally in a steel mould into 600 mm x 300 mm mats. Mortar consisted of cement, sand, water and $CaCl_2$ (Table 1). The cement was commercial Portland cement. First the sand was added to the cement

**Table 1.** Manufacturing condition of CSS (treatment of strands and weights (g) of components)

| Treatment of strand | Cement solution | | Mortar | | | | Total | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Water | Cement | Cement | Sand | Water | $CaCl_2$ | Strand | Cement | Sand | Water | Total |
| — | — | — | 5000 | 5000 | 2500 | 50 | 1200 | 5000 | 5000 | 2500 | 13700 |
| | | | 5000 | 5000 | 2500 | 50 | 1200 | 5000 | 5000 | 2500 | 13700 |
| Paraffin coating (P) | — | — | 5000 | 5000 | 2500 | 50 | 1200 | 5000 | 5000 | 2500 | 13700 |
| | | | 5000 | 5000 | 2500 | 50 | 1200 | 5000 | 5000 | 2500 | 13700 |
| Water *V-P (Wvp) | 2810 | — | 5000 | 5000 | 2500 | 50 | 1200 | 5000 | 5000 | 5310 | 16510 |
| Water soaking (Ws) | 2082 | — | 5000 | 5000 | 2500 | 50 | 1200 | 5000 | 5000 | 4582 | 15782 |
| Water dipping (Wd) | 1700 | — | 7000 | 3500 | 2800 | 70 | 1200 | 7000 | 3500 | 4500 | 16200 |
| Cement solution | 1900 | 500 | 5000 | 4500 | 2500 | 50 | 1200 | 5500 | 4500 | 4400 | 15600 |
| dipping (Cd) | 1500 | 1500 | 3500 | 3500 | 1750 | 35 | 1200 | 5000 | 3500 | 3520 | 12950 |
| | 1700 | 1000 | 5000 | 2500 | 2500 | 50 | 1200 | 6000 | 2500 | 4200 | 13900 |
| | 1700 | 1000 | 5000 | 2500 | 2200 | 50 | 1200 | 6000 | 2500 | 3900 | 13600 |
| | 1700 | 1700 | 6000 | 2000 | 2400 | 60 | 1200 | 7700 | 2000 | 4100 | 15000 |

*V-P = vacuum and pressure treatment

and mixed, and then $CaCl_2$ solution, accounting for 1% of the cement weight, was added and mixed fully. Manufacturing conditions of CSS are given in Table 1.

The mats were cold-pressed at 1.5 MPa for 48 h. Then they were removed from the mould and immediately some of them were cut longitudinally into specimens, 30 mm wide. These specimens were stored for post-curing in an air-conditioned room (20°C, 65% RH), and subjected to a bending test after 1, 2, 4 or 8 weeks. Other specimens were stored for post-curing at ambient conditions, and their weight and modulus of elasticity (MOE) were measured every two or three weeks. After about six months, the pressed slabs were also were cut into test specimens and tested for bending properties.

The MOE was measured by the flexural vibration method and calculated using the following equation:

$$\text{MOE} = \frac{48\pi^2 f^2 \ell^4 P}{m^4 h^2},$$

where $f$ is the resonance frequency to the first mode, $\ell$ is the length of specimens, $P$ is the density, $m = 4.73$ and $h$ is the thickness of specimens (Tonosaki et al. 1983).

The bending properties were measured by the four-point loading test, the span length was 520 mm and the shear span length was 130 mm. The displacement at the centre of span and load were recorded. Load was applied in the flat direction (perpendicular to the press direction) and edge-wise (parallel to the press direction). The size of test specimen was 600 mm (length) × 30 mm (width, flat), and the height, flat, was the same as the board thickness.

## Results and Discussion

The MOR of CSS was 20–40 MPa, and the MOE of CSS measured by the vibration method was 20–25 GPa. The treatment of strands, however, affected the bending properties.

### Effect of treatment of strands on bending properties

The effects of treatment of strands on their bending properties are shown in Table 2. Treatment with water (Wd, Ws, Wvp), especially vacuum-pressure treatment (Wvp), affected MOR. It is well known that the ratio of water to cement (W:C) is a very important factor in influencing the curing of cement, and too much water mixed into the composite has a negative effect on strength properties. Accordingly, the water treatments here led to an increase in W:C, and consequently the treatments Wd, Ws, Wvp caused MOR to decrease. Treatment with cement solution also increased the W:C ratio, but MOR was improved by this treatment. From these results, it may be inferred that the contact between wood and cement is an important factor affecting strength properties of CSS.

**Table 2.** Relationship between manufacturing conditions and mechanical and strength properties of CSS

| Treatment of strand | Mortar weight ratio | | Total weight ratio | | Mechanical and strength properties | | |
|---|---|---|---|---|---|---|---|
| | sand/cement | water/cement | sand/cement | water/cement | SG[2] | MOR edge[3] | MOR flat[4] |
| — | 1.00 : 1 | 0.50: 1 | 1.00: 1 | 0.50: 1 | 1.56 | 28.7 | 26.0 |
| — | 1.00 : 1 | 0.50: 1 | 1.00: 1 | 0.50: 1 | 1.58 | 27.2 | 26.7 |
| Paraffin coating (P) | 1.00 : 1 | 0.50: 1 | 1.00: 1 | 0.50: 1 | 1.53 | 26.3 | 18.2 |
| | 1.00 : 1 | 0.50: 1 | 1.00: 1 | 0.50: 1 | 1.53 | 26.7 | 17.8 |
| Water V-P[1] (Wvp) | 1.00 : 1 | 0.50: 1 | 1.00: 1 | 1.06: 1 | 1.49 | 20.3 | — |
| Water soaking (Ws) | 1.00 : 1 | 0.50: 1 | 1.00: 1 | 0.92: 1 | 1.53 | 25.7 | — |
| Water dipping (Wd) | 0.50 : 1 | 0.40: 1 | 0.50: 1 | 0.64: 1 | 1.53 | 30.7 | — |
| Cement solution | 0.95 : 1 | 0.50: 1 | 0.82: 1 | 0.80: 1 | 1.53 | 32.7 | — |
| dipping (Cd) | 1.00 : 1 | 0.50: 1 | 0.70: 1 | 0.65: 1 | 1.57 | 30.9 | — |
| | 0.50 : 1 | 0.50: 1 | 0.42: 1 | 0.70: 1 | 1.47 | 37.4 | — |
| | 0.50 : 1 | 0.44: 1 | 0.42: 1 | 0.65: 1 | 1.52 | 39.1 | — |
| | 0.33 : 1 | 0.40: 1 | 0.26: 1 | 0.53: 1 | 1.61 | 36.1 | — |

[1]V-P = vacuum and pressure treatment; [2]SG = specific gravity; [3]MOR edge = modulus of rupture under loading perpendicular to laminated direction (MPa); [4]MOR flat = modulus of rupture under loading parallel to laminated direction (MPa)

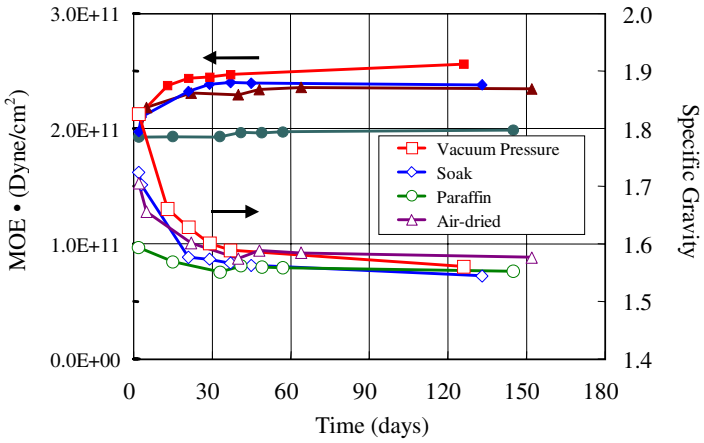


**Figure 2.** Relationships between changes in specific gravity and MOE during post-curing in response to manufacturing conditions

Figure 2 shows the changes in MOE during post-curing. The MOE of CSS increased at the beginning of the curing stage and reached its maximum after one or two months. However, the MOE of CSS made using strands coated with paraffin did not increase at all, suggesting that water movement into or out of wood strands, which would be retarded in strands pre-treated with paraffin wax, plays an important role in the increases in strength of CSS that occur during curing.

## Changes in specific gravity, MOE, MOR during post-curing

Figure 3 shows the changes in specific gravity, MOE and MOR during post-curing. The results are expressed relative to the values attained at the end of the first week. The value is the average of five specimens manufactured using strands subjected to treatment Cd (dip in cement solution). The MOR decreased for two weeks at the beginning of the post-curing stage, while MOE was constant for eight weeks. The decrease in specific gravity

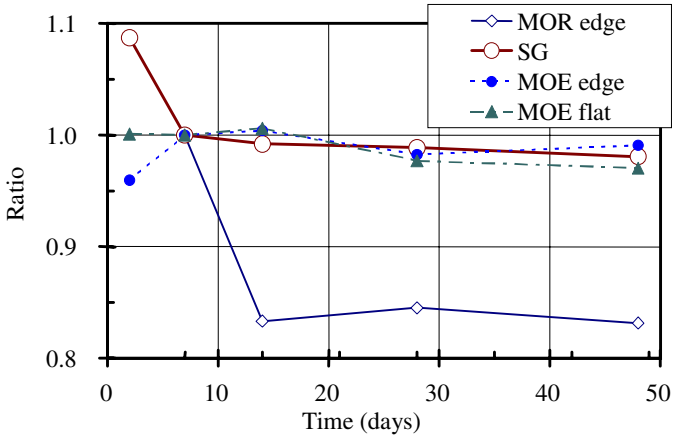


**Figure 3.** Changes in mechanical and strength properties during post-curing

during the first week may have been due to the evaporation of water. These specimens were cut immediately after the board was removed from the mould, and stored under dry air conditions. Therefore, it is possible that the cement had not cured enough. However, the reason for the decrease of MOR is not clear.

## Conclusions

The MOR of CSS ranged from 20 to 40 MPa and its MOE ranged from 20 to 25 GPa. These strength properties make CSS adequate for use as structural members. The MOR was improved by treatment with cement solution and affected by vacuum-pressure treatment with water. From these results it may be inferred that contact between wood and cement is an important factor influencing strength properties of CSS. The MOR decreased during the post-curing period, so further studies are required to identify more suitable conditions for post-curing.

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# Application of Wood-Wool Cement Boards for Shop-fabricated Emergency Shelters in the Philippines

**Florence P. Soriano[1], Thomas Rolan E. Rondero[1], Allan C. Manalo[1], Claro R. Carino[1], Teofisto C. Saralde Jr.[1] and Erwin A. Bonaagua[1]**

*Abstract*

The Forest Products Research and Development Institute (FPRDI) recently developed the '**F** shelter'[2] — a **f**ast-to-build, **f**irm and **f**oldaway emergency shelter using locally manufactured medium and high-density wood-wool–cement boards for floor, wall and roof boards. The use of WWCBs has resulted in relatively lightweight shop-fabricated components that require as few as four workers, equipped with simple carpenters' tools, to erect the shelter at a site. In several trials of two prototypes, it has been found that it takes four workers an average of 15 minutes to unfold the shelter and fix the components in place, and another 15 minutes to attach architectural accessories. When eight workers were used, i.e. four workers unfolding each side of the shelter, the whole on-site procedure took only 20 minutes. Like a tent, the F shelter can be quickly assembled, folded, packed, stored and used repeatedly. Unlike a tent, however, the F shelter has a floor that can be elevated on specially designed prefabricated footings. The height of the footing pedestals can be adjusted when the terrain is not flat. Doors and windows, similar to those in site-built shelters, make the F shelter more secure than a tent. Compared to typical low-cost site-built shelters that take 2–3 months from planning to construction, the F shelter can be acquired very quickly. End-users can be assured that its construction method has been well planned and engineered, and its fabrication has been adequately supervised in the shop and that only quality-tested materials have been used. Hence, buying the F shelter saves time as well as providing a comfortable and safe refuge. The prospect of establishing an industry for the production of emergency shelters is good, especially for those regions with existing wood- or metal-work industries. The direct cost of constructing a timber-framed prototype at FPRDI was PhP 6350.06 ($US124) per $m^2$ while a light metal-framed one cost PhP 6936.32 ($US135). It is anticipated that costs would be reduced if mass production techniques were used to make the shelters.

THERE is an enormous need for emergency shelters in the Philippines because it has the greatest number of natural disasters and the highest incidence of flooding in the world (Balana 1999). Prolonged use of schools, gymnasiums, churches and other public buildings as evacuation centres may cause further disruption to the normal livelihoods and activities of people, including those who have not been directly affected by a disaster.

Whenever available, tents that are easy to transport and assemble have been used as emergency shelters. However, tents are impractical where there is not sufficient ground anchorage, when the terrain is not flat, or when

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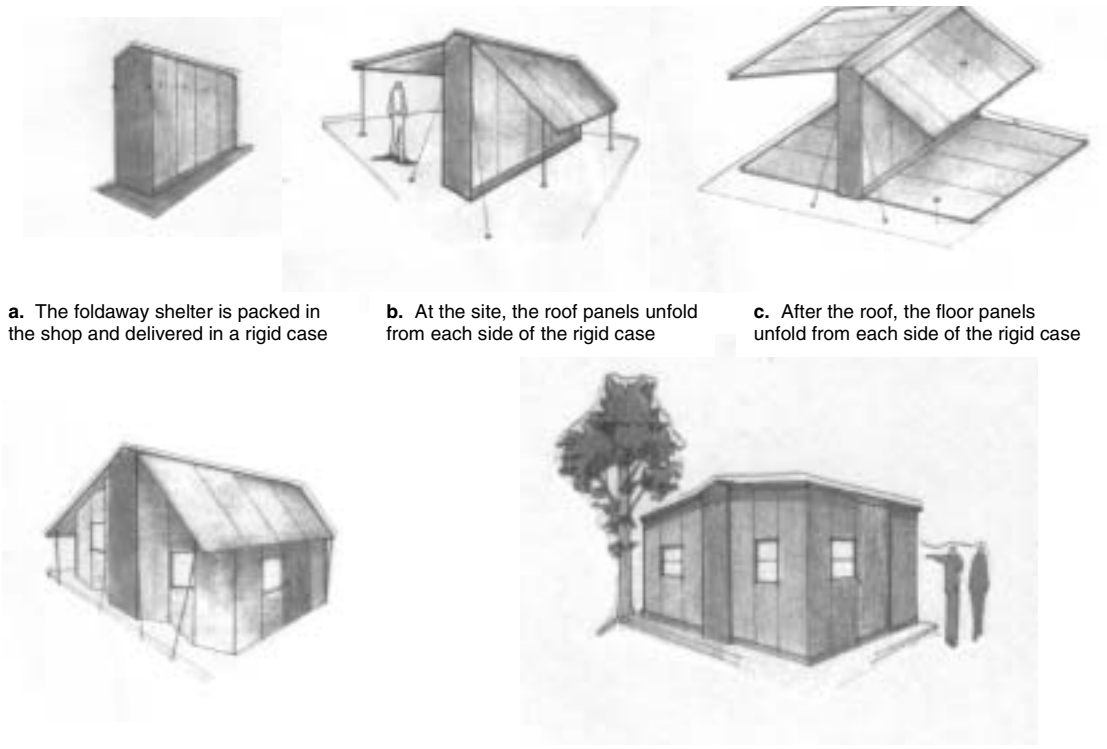
[2]Patent pending



**a.** The foldaway shelter is packed in the shop and delivered in a rigid case

**b.** At the site, the roof panels unfold from each side of the rigid case

**c.** After the roof, the floor panels unfold from each side of the rigid case

**d.** The accordion walls with built-in windows and doors, unfold from the case

**e.** The walls are fixed in place, additional accessories are installed, and the shelter is ready to be occupied

**Figure 1.** The concept of a tent-like foldaway emergency shelter

an elevated floor is required. Tent materials are often not fire-resistant and are weather-resistant only for a limited time. Furthermore the indoor temperature of tents cannot be controlled and this can create further discomfort in traumatised victims, during periods of extreme weather. Also, putting up heavy-duty tents may not be a straightforward process for unskilled workers.

Currently, emergency temporary shelters in the Philippines are mostly prefabricated, i.e. they are either fully assembled in the plant before delivery at the site, or partially assembled in the plant and completed at the site. In most cases, heavy equipment is needed to transport or position prefabricated shelter components at the site, and power tools are needed to fix and fasten them. Shop-fabrication of shelters is an effective means of implementing quality control compared to the conventional stick-and-stone on-site construction. Aside from being able to monitor workmanship during mass-fabrication of components and strictly impose building codes and standards, the more convenient working conditions in the plant significantly improve the efficiency of workers compared to working in weather-exposed conditions. Workmanship and supervision during construction are important as it has been observed that damage to houses, caused by disasters, is due mainly to poor workmanship, especially in the connections between building components, rather than failure of materials (Soriano 1987).

This paper outlines the design, development and construction of an emergency shelter for the Philippines which is made from components and joints that are fully shop-fabricated before delivery to the site.

Using the initial concept of a foldaway shelter (see Fig. 1) (Soriano et al. 2000), combined with observations made in the plant of a leading

manufacturer of mobile homes in the United States (Soriano 1997), a design was prepared for a core shelter made up of relatively light and weather-resistant panels made from wood–cement composite boards. In this project, locally manufactured wood-wool cement boards (WWCB) were used. These boards are cement-bonded composite panels made of shredded wood called excelsior, Portland cement, water and chemical additives that accelerate cement curing.

## Objectives

The general objective of the project was to develop a building technology for shop-fabricated shelters that required minimum on-site construction activities, workers and equipment.

Specifically, the project aimed to:

(i) prepare a scaled-down model to verify the workability of the initial concept of a foldaway emergency shelter;
(ii) construct two prototype core shelters using locally manufactured WWCBs for wall, floor and roof boards, i.e. one with timber structural frames and another with light-weight metal;
(iii) determine the cost of producing the prototype shelters;
(iv) prepare two construction manuals, i.e. one on fabrication and the other on site assembly.

## Materials and Methods

### The scaled-down model

From the drawing board, the structural analysis and design of frame members and joints, assuming extreme load conditions, were prepared. Two types of frame members, wood and light-weight metal, were used for the designs. Dimensions of structural members were determined and joints were detailed considering extreme load conditions. The workability of the concept was verified by producing a wooden-framed architectural model scaled down to one-fifth of its actual size. The WWCB panels were simulated using foam boards and the structural frames were made of wooden sticks. Full-size joints were miniaturised so the movement and position of the structural panels could be simulated while the shelter was unfolded and refolded. Using the scale model, the concept was presented in disaster-planning workshops and technical seminars and to potential technology adopters and end-users. Constructive comments were considered and integrated when improving the design.

### Construction of prototypes

The workability of the construction method was further verified by constructing two full-size prototype units at FPRDI. The first prototype was made of apitong (*Dipterocarpus grandiflorus* Blanco) timber frames, and the second was made of lightweight metal ($F_Y$ = 245 MPa). Medium density (750 kg $m^{-3}$) and high-density (900 kg $m^{-3}$) WWCB panels were used as floor, wall and roofing boards in both prototypes. The dimensions of structural members and jointing details were structurally designed.

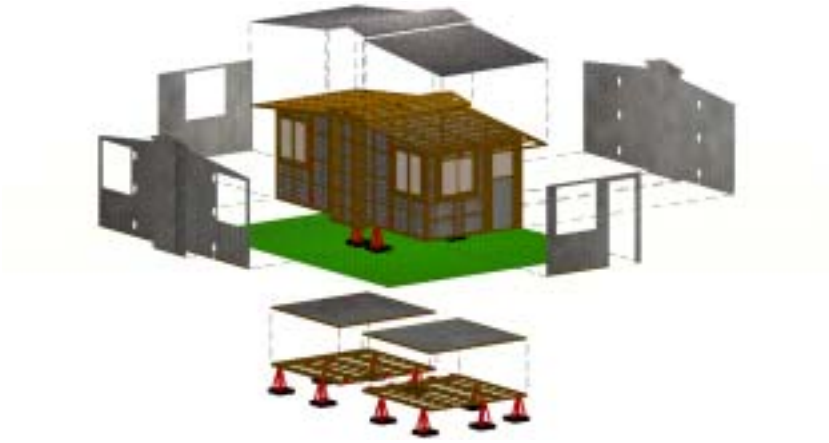
Construction materials were purchased within the Laguna and Metro-Manila areas. The use of materials, equipment and tools and the worker requirements were monitored and recorded and these were used in estimating production cost. Time and motion studies were conducted to determine the time and effort required to fabricate each component. During this stage, changes in the design were introduced to improve shop-fabrication and reduce assembly time. Constant and close coordination between the drawing board, shop-fabrication and structural design activities was necessary on a daily basis.

### Preparation of builders' manuals

Two types of builders' manuals were prepared. The fabricators' manual is intended to guide those who wish to set up their own plant and adopt the production technology, while the site manual is intended as a guide for end-users. Working drawings and design details for both prototype shelters were computer encoded in two and three-dimensional views, and then rendered using AUTOCADD 2000.

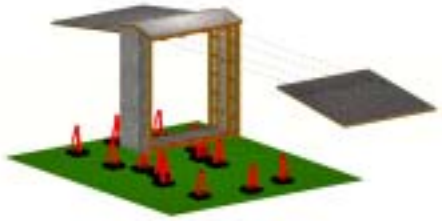
## Results and Discussion

From the initial concept and plans all the technical specifications and guidelines in shop fabricating the roof, wall, floor components and the rigid



**a.** Exploded view of the core shelter showing the roof, wall, floor and rigid case structural frames, the corresponding wwcb panel sheathing, and the shop-fabricated footings

**b.** case-to-floor details



**c.** case-to-roof details

**d.** case-to-wall details

**e.** case-to-floor, wall and roof details

**Figure 2.** Assembly of roof, wall, floor components and the rigid case at the shop

case of a timber-framed emergency shelter were developed.

Considering the dimensions of commercially available lightweight panels that can potentially be used for this shelter, the floor area was set at 2440 mm x 4880 mm (11.52 $m^2$), the height of the walls ranged from 2185 to 2485 mm, and the rigid case from 2555 to 2655 mm. The structural details of each component, as well as the connections between them, were designed for extreme load conditions. Similarly, structural details and technical specifications were made for a lightweight metal-framed prototype. The technical details were incorporated in shop drawings, encoded into two- and three-dimensional (2D and 3D) configurations, and exploded views were rendered (see Fig. 2).

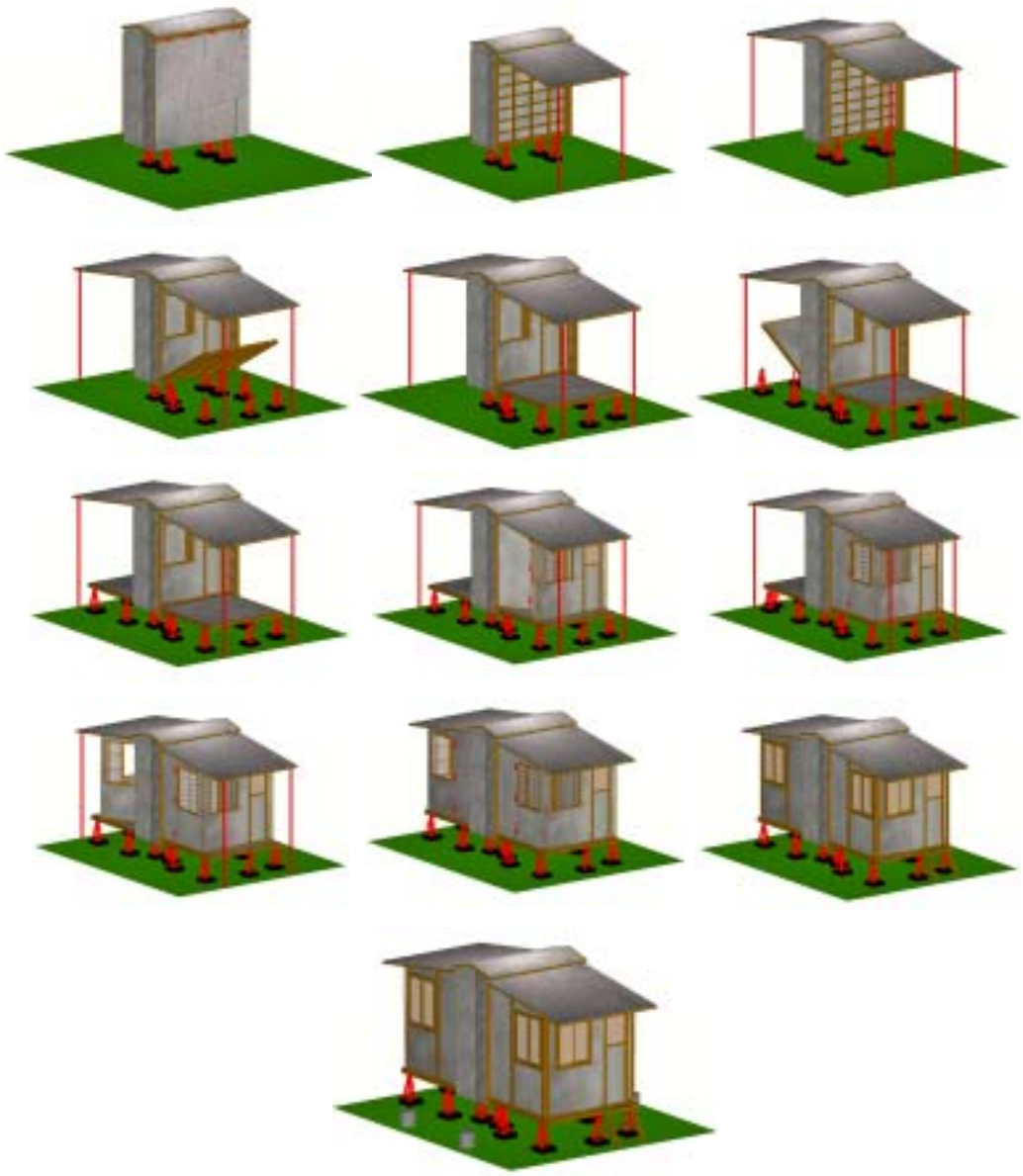


**Figure 3.** The step-by-step transformation of the proposed emergency shelter from the packed folded state to the fully erect shelter with false posts and tie-down straps in case of extreme wind conditions

After completing shop drawings, the step-by-step transformation of the timber- and light metal-framed prototype shelters, from their packed folded state to fully erected shelters, were encoded in 2D and 3D views and rendered (see Fig. 3). Encoding dimensions (to the nearest mm) of each component, including minute details of fasteners such as bolts, nails and screws, enabled verification that the components in the folded state, as well as in the fixed position, were dimensionally coordinated.

The scaled-down architectural model was made of 5-mm-thick foam boards glued to wooden frames. The roof, wall and floor components, as well as specially designed metal plate fasteners and locks that fix the roof to the walls and the

**a.** The scaled model in the packed folded state

**b.** The roof panels at each side of the case are raised

**c.** The roof panels are temporarily supported

**d.** The floor panels are unfolded from the rigid case

**e.** The floor panels are levelled

**f.** The walls are drawn out from the rigid case

**g.** The walls are locked in place and the roof temporary supports are removed

**h.** The shelter is fully unfolded and essentially ready to be occupied.

**Figure 4.** The architectural model (scale = 1:5) of the emergency shelter is used to demonstrate the step-by-step on-site assembly process

walls to the floor were also scaled-down. Hinge connections between components were miniaturised so that movement of the panels from the folded state to the fixed position in service could be simulated. Figure 4 shows the completed scale model being unfolded as originally conceptualised and designed. At this stage additional fasteners were conceptualised, as well as false columns to improve the shelters' aesthetic appearance and protect connections from being unnecessarily tampered with by the shelter's occupants.

It was observed that dimensional coordination of the roof, wall and floor components contribute to the stability and integrity of the shelter at various stages: (i) fixed folded state; (ii) while components are being unfolded; (iii) in the fixed erected state; and (iv) when the components are folded back into the rigid case.

Based on an estimated weight of components, and the assumption that one medium-built worker could carry 50 kg, it was found that a minimum of four medium-built workers were needed to erect the shelter at a site. No power tools or heavy equipment would be needed during on-site construction.

**a.** Trial fitting of the folded wall, floor and roof components in the case

**b.** Trial run to check roof-to-case connection

**c.** Trial unfolding and folding to check floor-to-case connection

**Figure 5.** Trial runs in the shop to verify movement of components and adequacy of connectors

## Prototype shelters

Two prototype emergency shelters were constructed. The timber-framed prototype was constructed first. Timber was cut to exact dimensions using a circular saw. While its floor, wall, roof and case structural frames were being built, the metal plate connectors between components were fabricated simultaneously. Metal plate connectors were cut using either manual shears or an acetylene torch, and then bent using a manual metal bending machine. Timber and metal were cut based on a pre-determined cutting schedule, whenever possible. All timber and metal sections were brushed with a protective coating prior to installation.

Upon completion of the structural frames, they were assembled with the floor frames directly resting on flat pavement. Trial runs of folding and unfolding components were conducted to test the strength of connectors. Adjustments were made and dimension tolerances were noted and recorded. After obtaining smooth and spontaneous movement of components during unfolding and folding, the structural frames were disassembled so that WWCB panels of appropriate thickness could be fixed to the frames. The roof frames were clad with high-density 12 mm

**a.** The emergency shelter is delivered to the site in a rigid case. The rigid case is mounted on adjustable prefabricated footings.

**b.** The roof, which is an integral face of the casing, is raised and temporarily supported

**c.** The floor is unfolded from the vertical to the horizontal position, mounted on prefabricated footings and levelled

**d.** The walls are drawn-out from the rigid case, then fixed and locked in place

**Figure 6.** Trial on-site assembly of the first prototype shop-fabricated emergency shelter at FPRDI, using four medium-built workers

WWCB, the floor frames with 12 mm high-density WWCB, and the wall frames with 8 mm medium-density WWCB. Ordinary flathead nails were used to fasten WWCB to timber members. When cladding was complete, the frames were again assembled, and trial runs of unfolding and folding were conducted in the shop (see Fig. 5). The exterior faces of WWCB walls, roof and floor boards were brushed with a weather-resistant coating.

Since the completion of the prototype, it has been subjected to trial on-site folding/unfolding at least once a month while being service-tested at FPRDI (see Figs 6, 7). No sign of deterioration of the joints or disintegration of the WWCBs has been observed.

The general process of fabricating the steel-framed prototype was similar to the timber-framed one; however, delays were experienced due to power interruption. Fabrication of steel frames necessitated the use of electric power-driven tools for welding and grinding. Figure 8a shows the lightweight metal structural frames (without WWCB cladding) of the second prototype. Figure 8b shows the prototype on shop-fabricated footings, while Figs 8c and 8d are trial

**Figure 7.** The timber-framed shop-fabricated emergency shelter, complete with false posts, stairs and tie-down straps attached to ground anchorages, currently being service tested at FPRDI

runs of assembling the shelter. The designs of connectors between components of the steel-framed and timber-framed prototypes are similar; but the cost of fixing WWCB to the structural frames of the steel-framed prototype was higher than the timber prototype because rivets rather than nails were used.

After completing the core shelters, footings were fabricated. Each footing had a pad underneath made of layers of 50 mm WWCB, an adjustable rod to enable levelling of the floor, and clamps that grip onto a structural member of the floor frame. Two 2-ton hydraulic jacks were used during the levelling process. Corner and intermediate false posts made of shop-bent galvanised iron sheets were provided to improve the aesthetic appearance of the shelter. More importantly, these would also cover connections that could be tampered with by the shelter's occupants.

In both prototypes, electrical raceways were installed for room lights and two power outlets. No water supply and sanitary equipment were installed, because these emergency shelters are intended as temporary refuges for calamity victims, and as such they have not been designed to be self-contained. In any case, portable toilets, mobile kitchens, and public shower rooms are generally available for a community of emergency shelter occupants.

If foldaway shelters can be increased to a size suitable for permanent shelters, then water and sanitary facilities and room dividers can easily be installed. A study of other applications of the foldaway shelter is proposed for the second phase of this project.

From trial runs with four workers assembling the shelter, it was found that mounting the rigid case and unfolding the shelter until it was ready to be occupied took an average of 15 minutes under normal conditions, 5 minutes of which were spent in levelling the floor. Installation of accessories and additional fasteners, however, took an average of 15 minutes more. Folding and packing the house took 25 minutes. If, however, there were eight workers, i.e. four workers working on each side simultaneously, erecting the house took 20 minutes. It was also found that levelling the floor of the case, as well as the floor components that unfold from each side of the case, was critical and must be done carefully and accurately. The ease of subsequent steps, especially those involving fasteners, bolts or pins

**a.** Structural frame of the second prototype emergency shelter

**b.** The second prototype assembled at the shop. Accessories and stairs are not installed.

**c.** Trial run of erecting the second prototype

**d.** Workers installing accessories using simple carpenter's tools

**Figure 8.** The second prototype shop-fabricated emergency shelter with lightweight metal structural frames and WWCB roof, wall and floor boards

that are fitted in pre-bored holes or formed metal accessories, depends to a large extent on proper alignment of the floor.

Based on the experience of building two prototypes at the shop, and several trial assembly and packing exercises, there is increasing confidence in the **f**ast-to-build, **f**irm and **f**oldaway shelter, and the name **F shelter** is used to describe the technology.

### Production Cost of F shelters

The costs of building two prototype units at FPRDI were determined, based on the number of workers used and current prices of construction materials in the Laguna and Metro-Manila areas.

Table 1 shows that, based on the FPRDI experience, the cost of constructing the timber-framed prototype is less than that of the light-weight metal-framed one by about 9.23%. When mass produced (see Table 2), this figure increases to about 10.64%. The higher direct cost in the second prototype is attributed mostly to higher labour cost. It must be noted that these values do not include the cost of operating electrical power tools in the construction of the lightweight metal-framed prototype.

Table 2 shows that mass producing the shelters results in cost reductions of about 20.5% for the timber-framed prototype and about 19.5% for the lightweight metal-framed one. Comparing the direct costs of shop-fabricated emergency shelters with the costs of two types of site-built low-cost permanent shelters in Table 2, the costs of the shop-fabricated shelters are at least 20% lower than the site-built ones.

The production costs presented in Table 1 are based on the FPRDI experience of constructing the prototypes in the shop. It is anticipated that costs would be less if prototypes were built in shops that were better equipped and had more

**Table 1.** Direct costs (materials + labour) in PhP (and equivalent US$) of the prototype F shelters as produced at FPRDI using wood-wool cement board (WWCB)

| Materials used | Prototype F shelters | |
|---|---|---|
| | Wood-framed WWCB roof, wall* and floor boards | Steel-framed WWCB roof, wall* and floor boards |
| Total | 73 159.33 (US$1424) | 79 906.50 (US$1555) |
| Cost per $m^2$ | 6350.06 (US$124) | 6936.32 (US$135) |

*In both prototype emergency shelters, walls are 8–12 mm WWCB on structural frames; in permanent shelters, 50 mm WWCB with stiffeners is preferred.

**Table 2.** Direct costs (materials + labour) per unit in PhP (and equivalent US$) of the prototype F shelters if mass-produced compared to the costs of site-built permanent shelters

| Materials used | Prototype F shelters | | Site-built permanent shelters | |
|---|---|---|---|---|
| | Wood-framed; WWCB roof, wall* and floor board | Steel-framed; WWCB roof, wall* and floor boards; plywood ceiling | WWCB walls*, elevated RC slab floor, GI roof with ceiling | CHB walls, elevated RC slab floor, GI roof |
| Total | 60 113.00 (US$1170) | 66 508.00 (US$1294) | 84 296.83 (US$1641) | 80 022.33 (US$1558) |
| Cost per $m^2$ | 5048.46 (US$98) | 5585.52 (US$109) | 7317.43 (US$142) | 6946.38 (US$135) |

WWCB wood-wool cement board
RC reinforced concrete
GI galvanised iron
CHB concrete hollow blocks

*In both prototype emergency shelters, walls are 8–12 mm WWCB on structural frames; in permanent shelters, 50 mm WWCB with stiffeners is preferred.

experienced builders. In Table 2, it was assumed that if several shelters of the same design were mass-produced, the purchase of materials in bulk combined with the use of jigs and more efficient cutting schedules would result in more economical use of materials. Worker efficiency would also increase due to better working conditions in the shop; hence, overall material and labour costs would be lower.

The cost of a prototype foldaway shelter can vary depending on the materials used. Alternative indigenous and lightweight panel products that are weather and fire-resistant, as well as windows and doors made from other lightweight materials other than those used in building the prototypes in this project, could also be used. It must be noted that the innovations in technology are currently focused on the development of completely shop-fabricated shelters that can be erected at a desired location with minimal on-site manpower, time, equipment and energy requirements.

## Advantages of the F shelter Technology

There are several advantages of the F shelter building technology. The advantages of the technology compared to site-built low-cost permanent houses, tents, alternative prefabricated houses and other emergency shelters are described below.

*Compared to conventional site-built low-cost permanent houses*

- The F shelter can be acquired very quickly. Low-cost houses built using traditional or emerging technologies usually take 3–4 months from planning to construction. Hence, buying the F shelter saves time as well as providing a comfortable and safe refuge.
- Monitoring the mass construction of houses at a plant requires less time and manpower than monitoring individual houses being constructed at a site. Shop fabrication allows

better supervision resulting in the use of quality-tested materials and specialised labour skills. In contrast, during the construction of site-built houses, workers are exposed to the weather and supervision/monitoring is generally lacking.
- End-users can be assured that the F shelter technology has been well planned and engineered. Previous research has shown that damage to houses during typhoons is due mainly to poor workmanship and not due to the lack of durability of materials. Despite the national structural code, as well as the building code of the Philippines, some builders devise ways to circumvent these in order to save costs, resulting in substandard houses that fail during disasters, and aggravating the enormous housing backlog in the Philippines.

*Compared to tents*

- The F shelter has an elevated floor. The height of the footings can be adjusted when the terrain is not flat. Tents rest directly on the ground and can be difficult to put up on slopes.
- Doors and windows, similar to those in site-built houses, render the F shelter more secure and more private than a tent.
- Indoors, the F shelter is comfortable, just like a permanent house. The temperature inside a tent cannot be controlled in extreme weather conditions.
- The F shelter is structurally designed to resist weathering, extreme temperatures, winds and other harmful natural forces. The roof and walls of tents are not impermeable enough to resist the ingress of rain and wind during extreme conditions.

*Compared to other emerging prefabricated houses*

- On-site assembly of the F shelter takes less than an hour. Other prefabricated houses take several hours to a few days.
- The F shelter requires four unskilled medium-built workers using only simple tools, whereas other prefabricated houses cannot be built on site without semi-skilled to skilled workers, and they require more sophisticated tools and equipment.

*Compared to other emergency shelters*

- The F shelter can be packed and stored when not in use. When packed, it occupies only one-fifth of its total floor area in service. Other emergency shelters cannot be folded and packed and, thus, will occupy a considerably greater area for storage when not in use.
- There is no need for a covered warehouse to store several F shelters. The rigid case of the F shelter forms the roof and portions of the exterior wall and hence, is designed to withstand the weather. Therefore, several F shelters can be stored in a limited open space when not needed.

## Builders' Manuals

Fabricators' and site-assembly manuals have been prepared for both the timber-framed and the steel-framed prototype emergency shelters, but distribution of the builders' manuals is restricted until the F shelter's patent is approved. The fabricators' manuals contain the suggested production layout at the plant, the basic shop equipment and tools, the step-by-step construction process of the floor, wall and roof components, the process of assembling these components, and preparing the shelter for delivery. It also includes details of fabricating footings and tie-down straps and ground anchorages. The site assembly manual contains guidelines for transporting, unpacking, levelling and unfolding the shelter at the site.

## Conclusions and Recommendations

The F shelter — a fast-to-build, firm and foldaway shop-fabricated emergency shelter — has been developed at FPRDI. Wood-wool cement board was found to be a very workable sheathing material for prefabricated house components. There were no problems encountered in the use of WWCB for fully shop-fabricated shelters, or during site assembly. Assembling the WWCB-clad shelter at the site required four medium-built unskilled workers using simple carpenter's tools. On average, it took four men 15 minutes to unfold the house until it was ready for occupancy and another 15 minutes to attach accessories on the exterior of the house. With eight workers, i.e.

four workers on each side, working simultaneously, the whole procedure, on average, took only 20 minutes.

The development of this construction technology involved detailed structural analysis, design and engineering, considering critical loads for at least four conditions; namely (i) when the roof, wall and floor components are folded and packed in the rigid case, (ii) when the house is transported, (iii) when the house is unfolded and unpacked and then mounted on prefabricated footings, and (iv) when occupied and used in service. Thus, it is anticipated that, as long as the F shelter is properly and adequately maintained, it will equal, if not surpass, the durability and service performance of site-built shelters that are intended for permanent use. Its advantages are enormous compared to site-built permanent shelters, tents, other emerging prefabricated houses, and existing emergency shelters. Hence, buying an F shelter saves time when a safe and comfortable refuge is needed most.

The potential of the F shelter technology for the production of multi-purpose shelters should be explored. Hence, further development work is needed. Future improvements in the design could include the following:

- expansion of the house with minimal wastage and disturbance of the original core shelter;
- integration of sanitary and water supply lines in the fabrication process;
- use of alternative panels such as bamboo-wool cement boards, and other cement-bonded composites made from indigenous materials and agricultural wastes so that the total weight of the house (currently about 800 kg) can be reduced;
- new connectors and fasteners devised for cement-bonded panels;
- mounting of the rigid case on a chassis with wheels and axle so that each unit can be individually transported, i.e. a truly mobile F shelter.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