

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

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## 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<sub>2</sub>, Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>) on board properties were examined. The highest dry MOR values of the WWCBs were obtained from boards containing CaCl<sub>2</sub> 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.

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-

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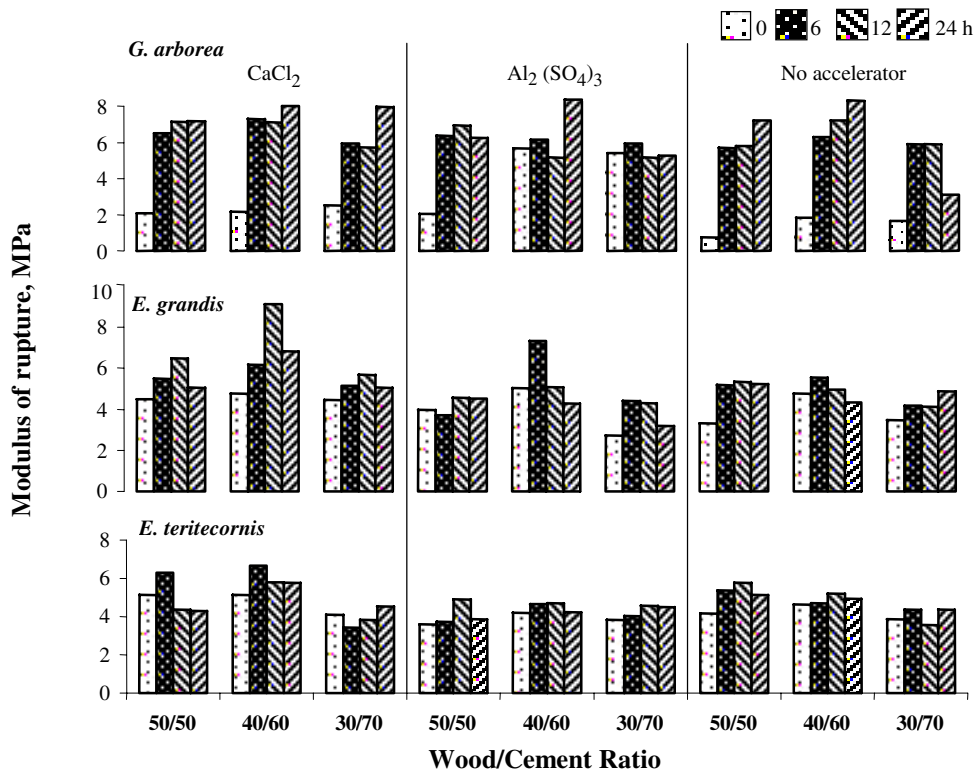
tions cover probably between 8 and 12 million ha worldwide (SBS 1990; Turnbull 1991).

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 ( $\text{CaCl}_2$  and  $\text{Al}_2(\text{SO}_4)_3$ ) on board properties.

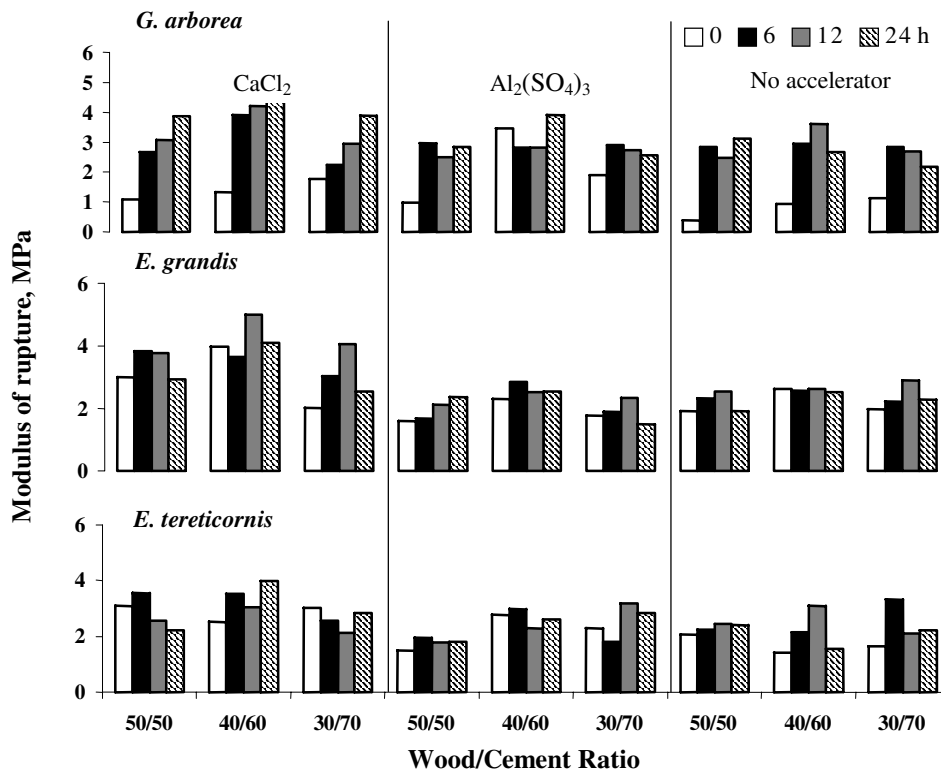
#### Materials and Methods

The wood species used in this study were 8–12-year-old *E. grandis*, *E. tereticornis* and *G. arborea* grown in Oriental Mindoro, Philip-

pinas. The binder used was Type I ordinary Portland cement (OPC) while calcium chloride ( $\text{CaCl}_2$ ) and aluminium sulphate ( $\text{Al}_2(\text{SO}_4)_3$ ) 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<sup>-3</sup> 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

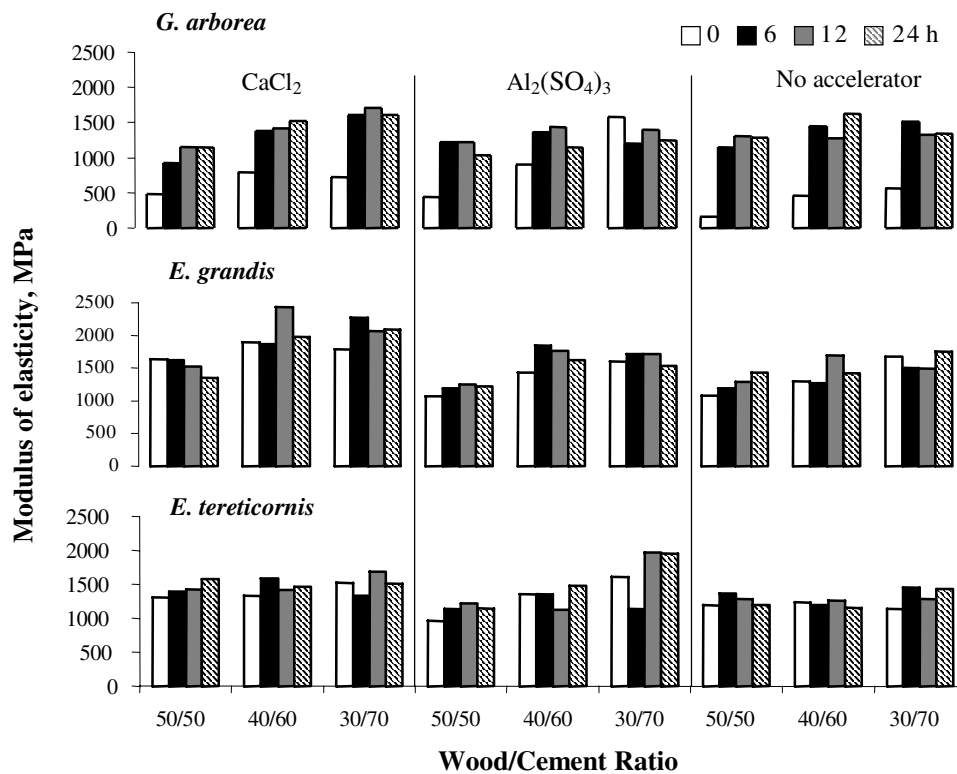
and 0.25 mm (*E. tereticornis*), respectively. The excelsior of each wood species was soaked in water for 6, 12 and 24 h in separate tanks. Batches of unsoaked (0 h) excelsior were set aside and also used in board production. Water-soaked excelsior was air-dried to an equilibrium moisture content of 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<sup>-1</sup> 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

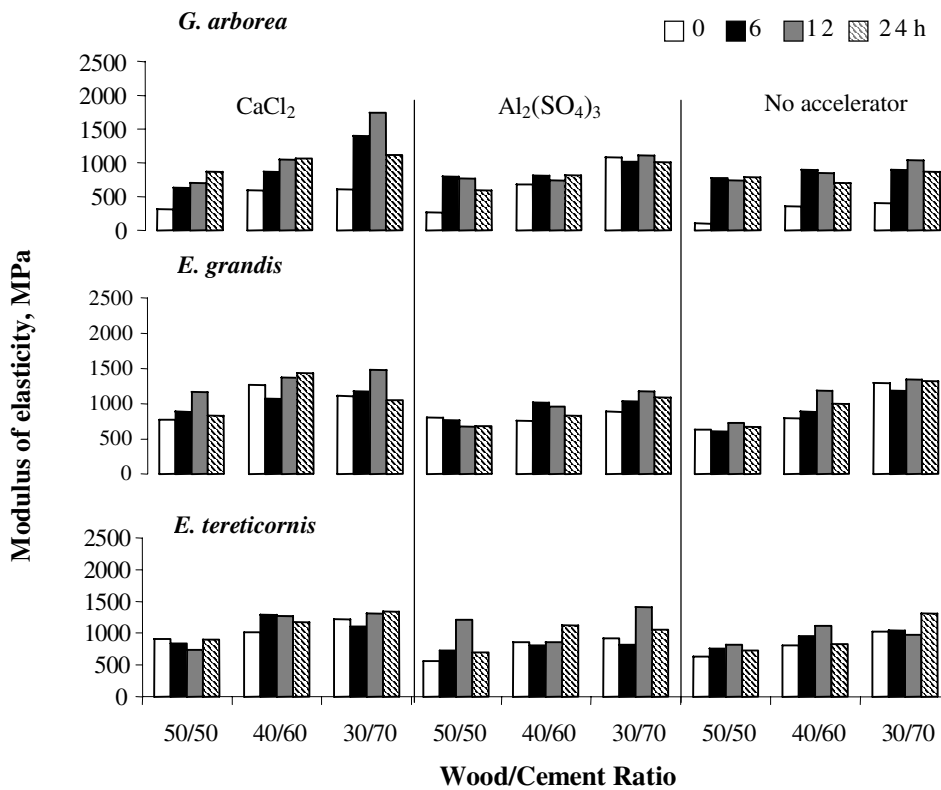
### Effect of species

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,  $\text{CaCl}_2$  seemed more promising than  $\text{Al}_2(\text{SO}_4)_3$ . The  $\text{Al}_2(\text{SO}_4)_3$  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  $\text{Al}_2(\text{SO}_4)_3$  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  $\text{CaCl}_2$  as cement setting accelerator.



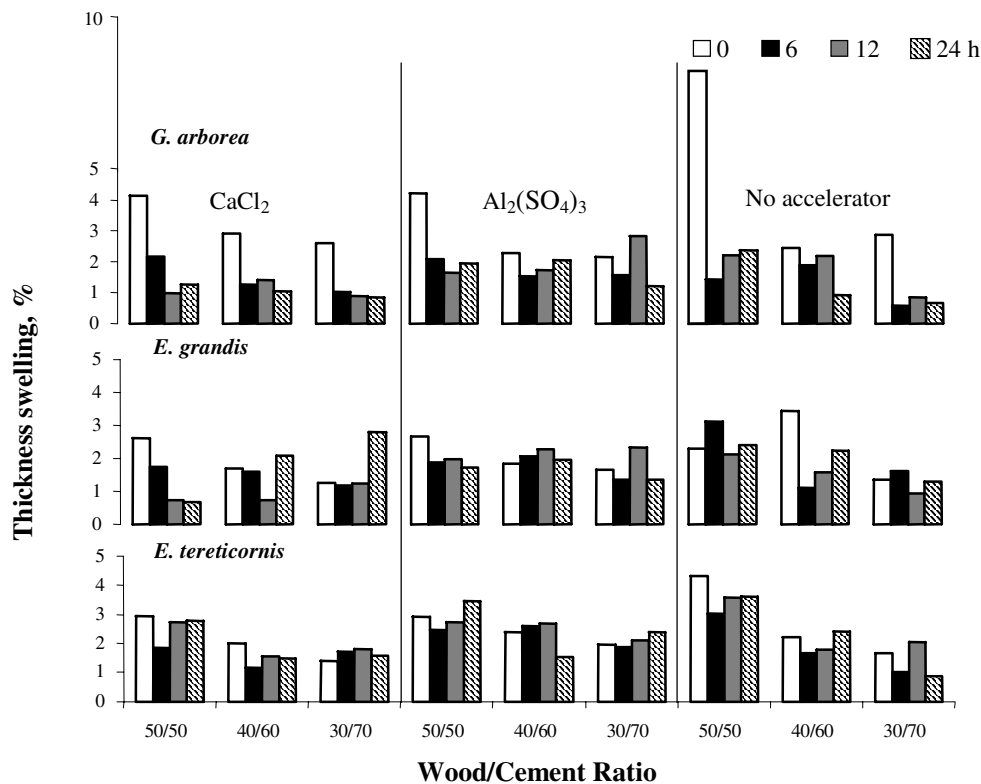
**Figure 4.** Wet modulus of elasticity of WWCB containing excelsior of *G. arborea*, *E. grandis* and *E. tereticornis* soaked for 0, 6, 12, 24 h prior to board production, as affected by varying the wood:cement ratio and chemical accelerator

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  $\text{CaCl}_2$  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  $\text{Al}_2(\text{SO}_4)_3$  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  $\text{CaCl}_2$  accelerators were stronger than those with  $\text{Al}_2(\text{SO}_4)_3$  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  $\text{CaCl}_2$  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

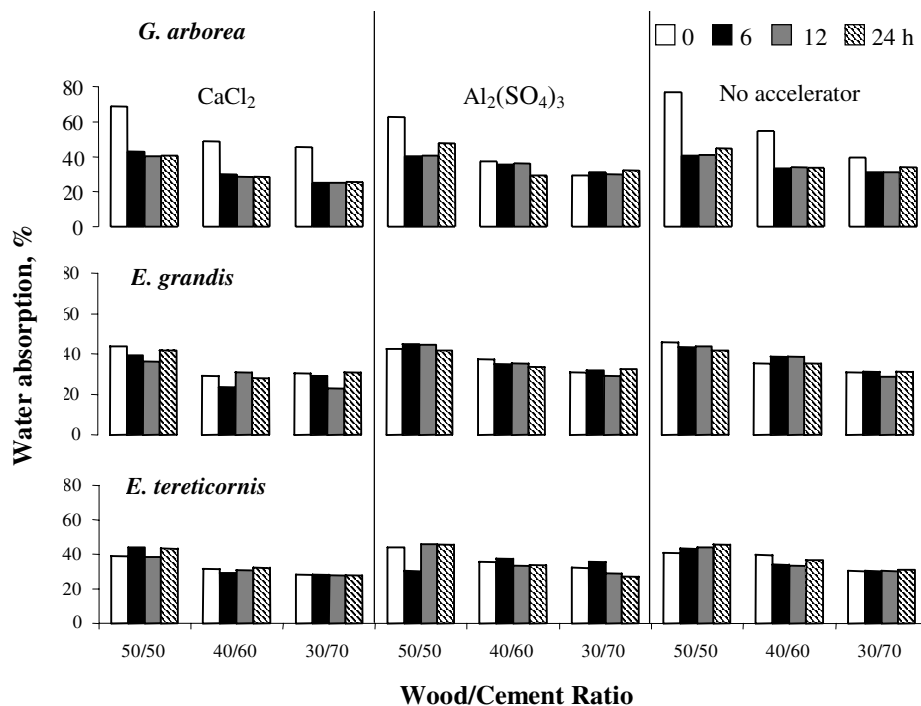
setting accelerator.  $\text{CaCl}_2$  was more effective than  $\text{Al}_2(\text{SO}_4)_3$  in increasing MOE. Boards with the lowest MOE were those containing unsoaked excelsior of *G. arborea* and containing no accelerator.

The importance of soaking the excelsior even for 6 h was very pronounced in boards containing *G. arborea* excelsior and either  $\text{CaCl}_2$  or no accelerator. However, a different response was found with  $\text{Al}_2(\text{SO}_4)_3$  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  $\text{CaCl}_2$ ,  $\text{Al}_2(\text{SO}_4)_3$  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  $\text{CaCl}_2$ ,  $\text{Al}_2(\text{SO}_4)_3$  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  $\text{CaCl}_2$ ,  $\text{Al}_2(\text{SO}_4)_3$  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  $\text{CaCl}_2$ ,  $\text{Al}_2(\text{SO}_4)_3$  and  $\text{FeCl}_3$  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,  $\text{CaCl}_2$  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  $\text{CaCl}_2$  as cement setting accelerator at all wood:cement ratios and soaking times, compared to boards with  $\text{Al}_2(\text{SO}_4)_3$  or those with no accelerator. This suggests that  $\text{CaCl}_2$  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,  $\text{CaCl}_2$  seemed more promising than  $\text{Al}_2(\text{SO}_4)_3$  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.

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

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## 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<sub>2</sub>, Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>) 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<sub>2</sub>. The incorporation of CaCl<sub>2</sub> and Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> 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), particle-board (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  $\text{CaCl}_2$  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 ( $\text{CaCl}_2$ ) and aluminium sulphate ( $\text{Al}_2(\text{SO}_4)_3$ ) 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).

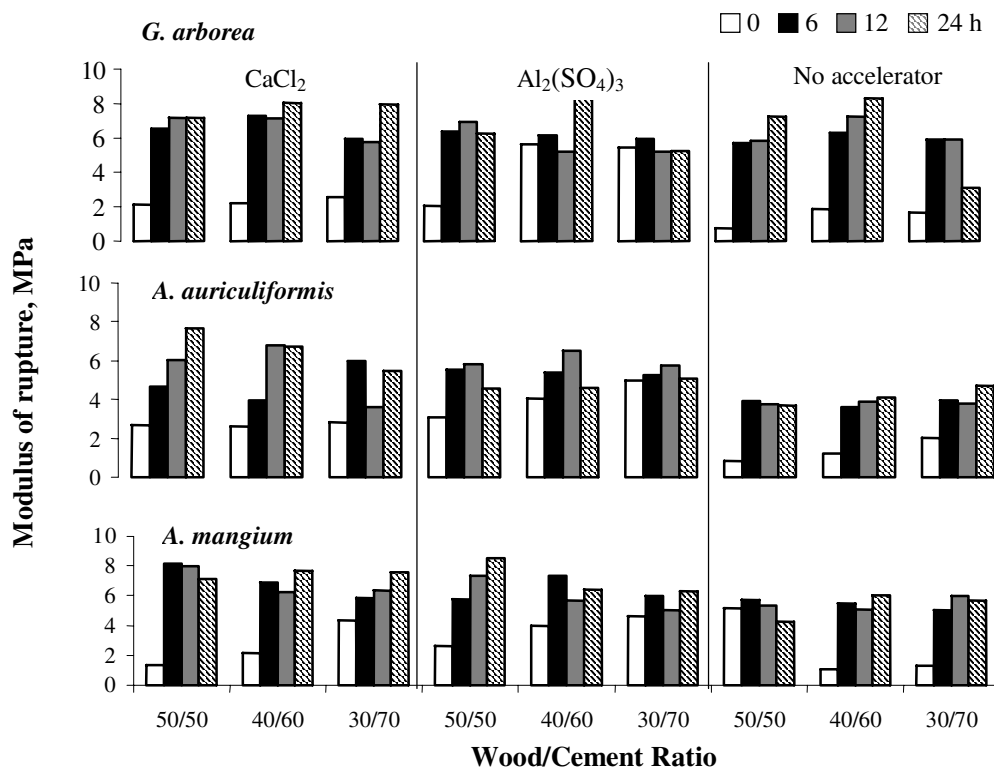
## Results and Discussion

### 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  $\text{CaCl}_2$  and  $\text{Al}_2(\text{SO}_4)_3$  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  $\text{CaCl}_2$  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

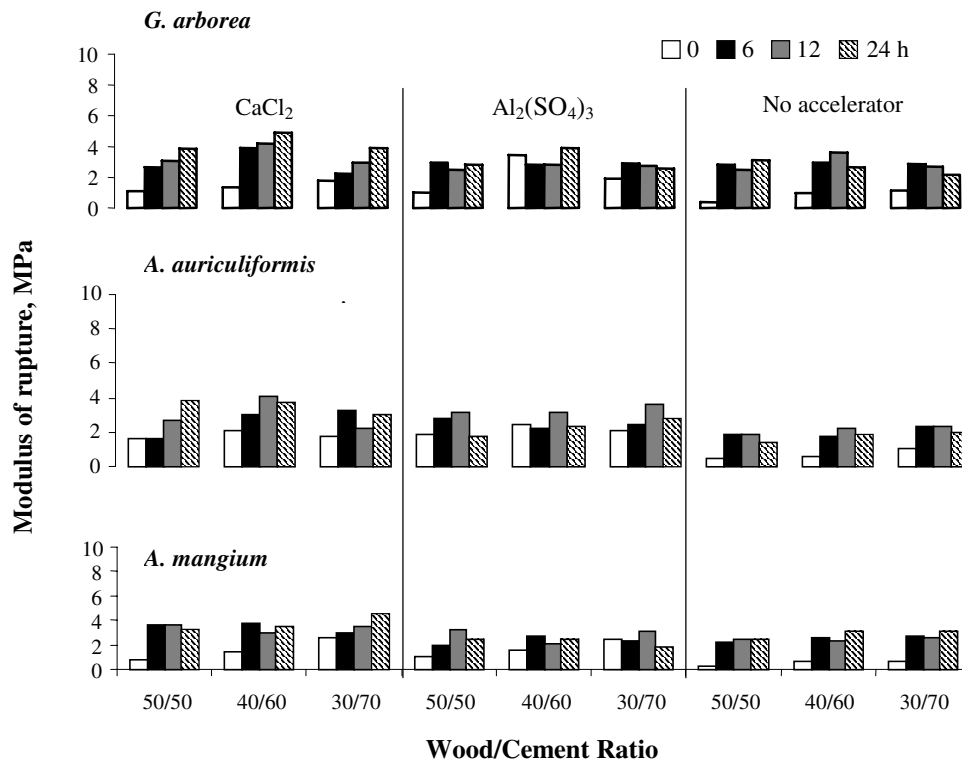


**Figure 1.** Dry modulus of rupture of WWCB containing excelsior of *G. arborea*, *A. auriculiformis* and *A. mangium* soaked for 0, 6, 12 or 24 h prior to board production as affected by wood:cement ratio and chemical accelerator

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<sub>2</sub> had the highest wet MOR compared to boards containing Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> or no accelerator. It was suggested in an earlier study that Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> was a more effective accelerator than CaCl<sub>2</sub> 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

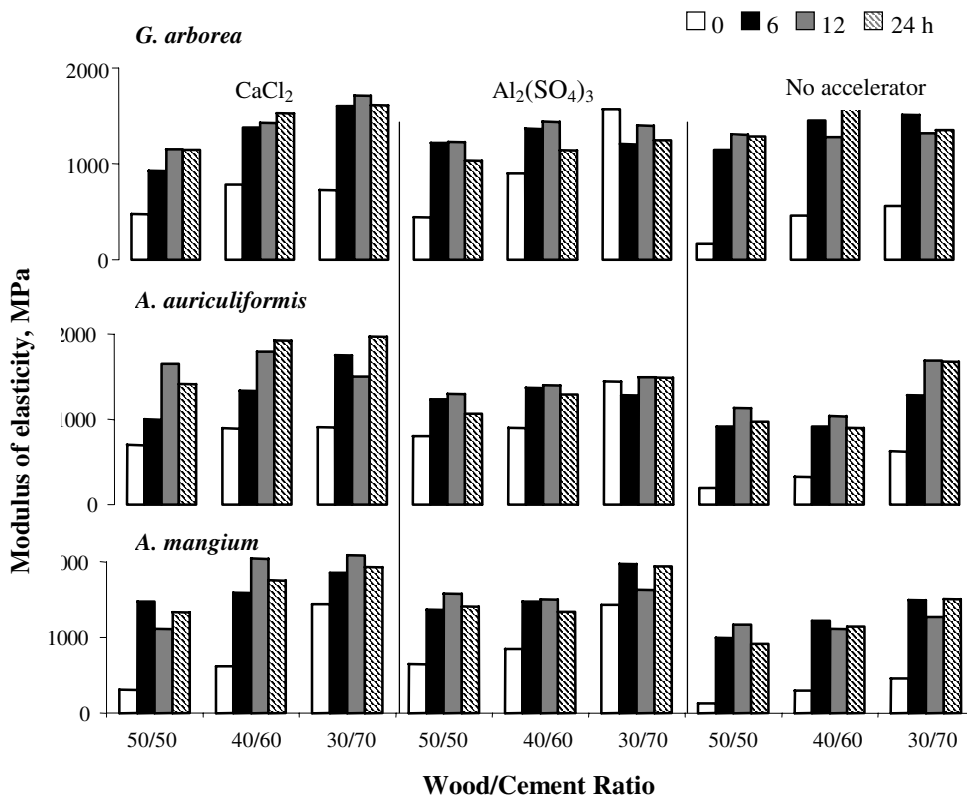
The dry modulus of elasticity values (MOE) of boards manufactured from acacia excelsior and CaCl<sub>2</sub> as accelerator were generally higher than those of boards made from *G. arborea* excelsior. There was a positive correlation between MOE and cement content of boards, as shown in Fig. 3. The largest 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<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> 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<sub>2</sub> 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<sub>2</sub>, Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> 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<sub>2</sub>, Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> 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

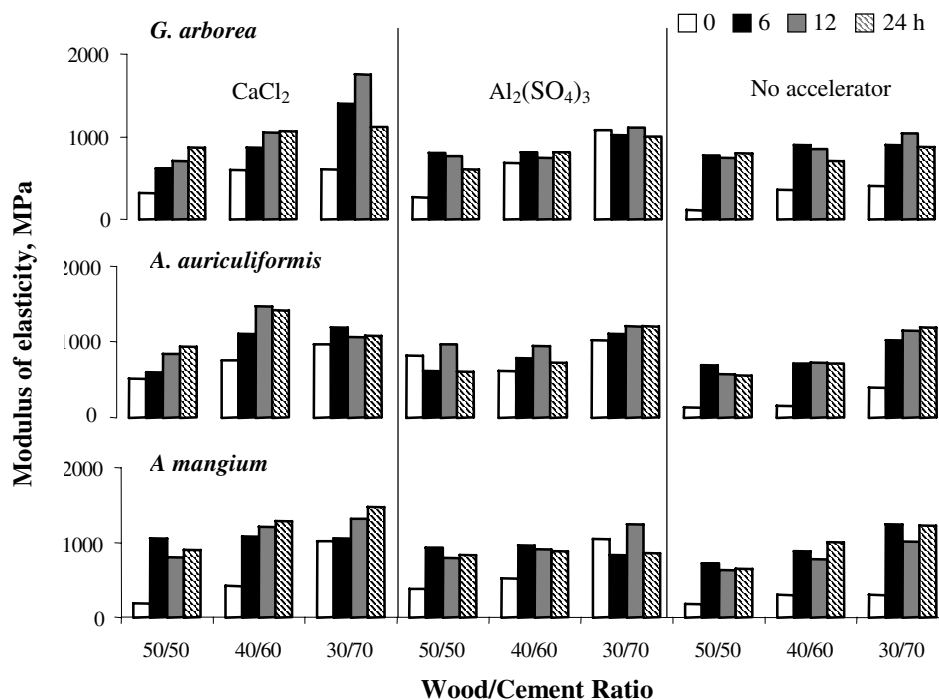
cement ratios of 50:50 and 40:60. This may have been due to the lower cement content and poorer bonding between wood and cement allowing greater absorption of water by wood and inability of the specimens to resist stresses generated by swelling of wood and springback of compressed excelsior. The thickness 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  $\text{CaCl}_2$ , but for boards containing  $\text{Al}_2(\text{SO}_4)_3$  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  $\text{Al}_2(\text{SO}_4)_3$  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  $\text{CaCl}_2$ . 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  $\text{CaCl}_2$  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  $\text{Al}_2(\text{SO}_4)_3$  was used as accelerator, particularly for boards containing acacia wood at 40:60 and 30:70 wood:cement ratios.

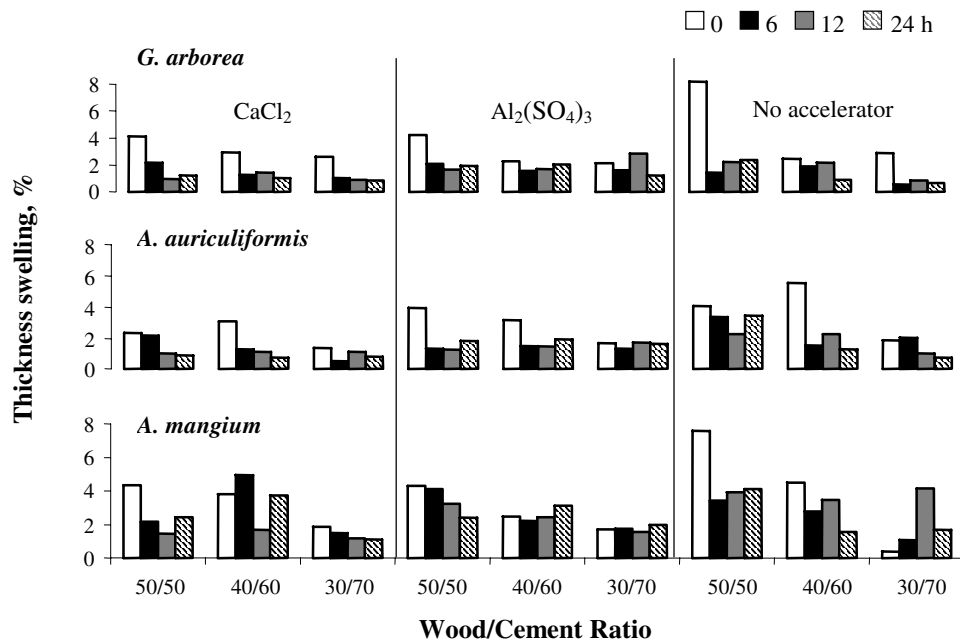
The WWCBs containing soaked excelsior of acacias exhibited better MOE than boards with *Gmelina arborea* excelsior when  $\text{CaCl}_2$  was used as accelerator. The MOE tended to increase as the amount of cement increased, i.e. 30:70 wood:cement ratio.

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.

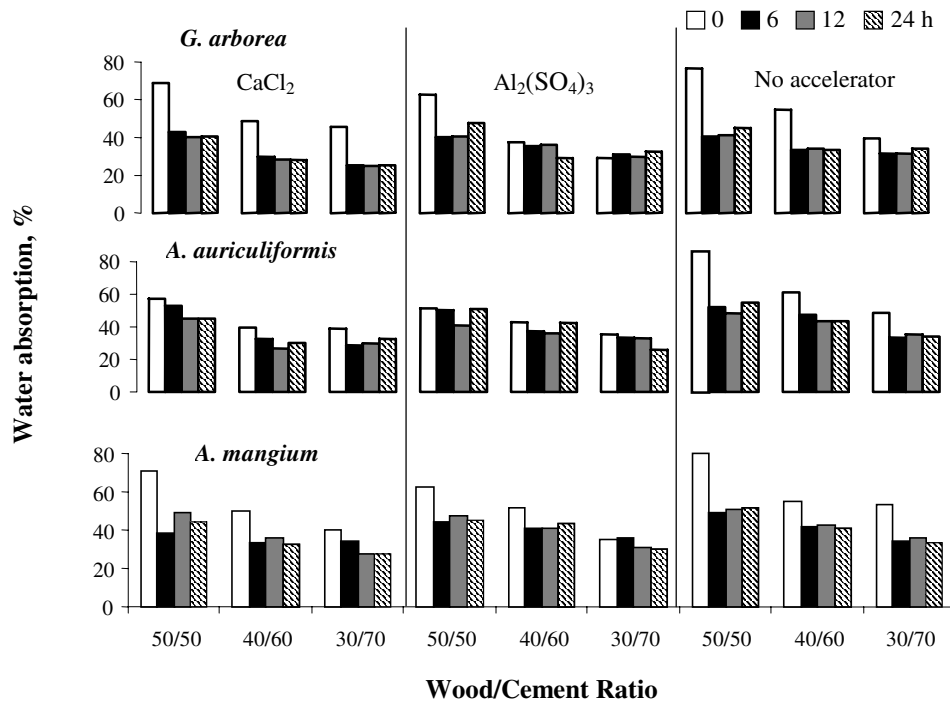
Boards containing unsoaked excelsior exhibited higher thickness swelling and water absorption values, particularly at wood:cement ratios of 50:50 and 40:60. Extending the soaking time from 6 to 24 h lowered thickness swelling and water absorption values for boards containing  $\text{CaCl}_2$ , but had little effect for boards containing  $\text{Al}_2(\text{SO}_4)_3$  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  $\text{Al}_2(\text{SO}_4)_3$  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

### Acknowledgements

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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<sup>3</sup> and currently the annual volume available to industry is about 2 million m<sup>3</sup>. In five to seven years, the volume of industrial timber is predicted to rise to 40 million m<sup>3</sup> and the annual cutting volume will be 4 million m<sup>3</sup>. 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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**Table 1.** The main series of core veneer

Thickness (mm)	Usage	Price (Yuan m <sup>-3</sup> )
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<sup>-3</sup>; 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<sup>-2</sup>, 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 <sup>-3</sup> )	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 <sup>-3</sup> )	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<sup>3</sup> 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<sup>3</sup> capacity. In addition, this company is building a particleboard mill with a capacity of 0.15 million m<sup>3</sup> in Jiangxi Province and an OSB mill with capacity of 0.3 million m<sup>3</sup> 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<sup>1</sup>

## *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. Unfortu-

nately, 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 replacement 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 <sup>1</sup>	Refining <sup>2</sup>	Matrix <sup>3</sup>	Cure <sup>4</sup>	Reference
<i>Pinus radiata</i> (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
<i>Eucalyptus regnans</i> , <i>E. grandis</i> , <i>E. saligna</i> , <i>E. pellita</i> (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
<i>Acacia mangium</i>	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

<sup>1</sup>K = Kraft pulp, TMP = Thermomechanical pulp, CTMP = Chemithermomechanical pulp, S = Soda pulp,

NaAQ = Soda anthraquinone pulp

<sup>2</sup>R = refined, NR = not refined

<sup>3</sup>C = Cement, M = Cement and sand/silica mix, GFS = Ground furnace slag matrix

<sup>4</sup>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. SmartBlocks are autoclaved after moulding. The density of this product is 1100 kg m<sup>-3</sup> while the hollow product with a 50% void ratio has a gross density of 550 kg m<sup>-3</sup>. 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 as 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.

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

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## 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.

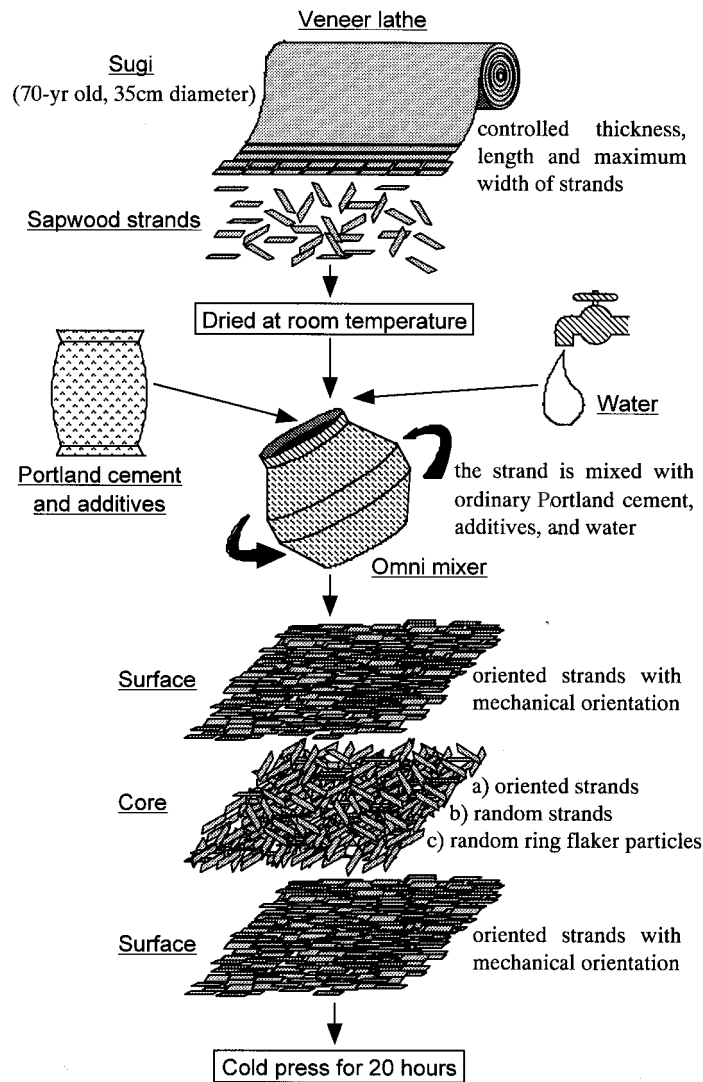
### Materials and Methods

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<sub>2</sub> 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,



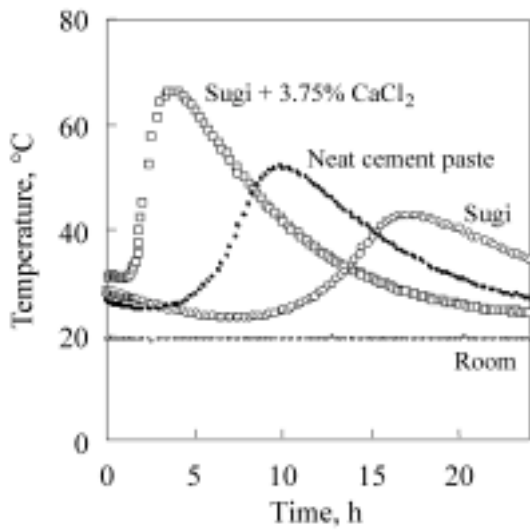
**Figure 1.** Method of producing sugi sapwood strands and manufacturing oriented CBB

100 g water and 3.75%  $\text{CaCl}_2$  based on the cement weight for one test.

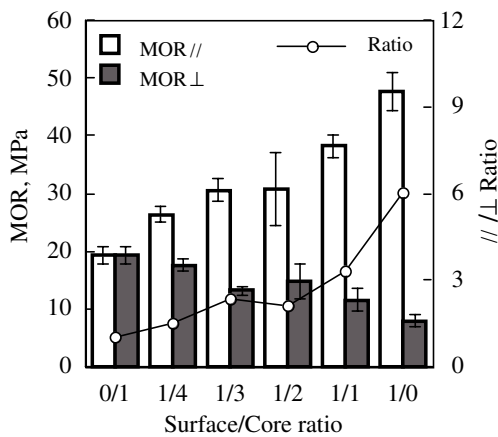
### Results and Discussion

The hydration temperatures of neat cement paste, sugi sapwood powder with cement and the mixture of sugi powder, cement and 3.75%  $\text{CaCl}_2$  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 ( $\text{MgCl}_2$ ) has been shown to ameliorate the inhibitory effects of sugi wood on cement curing, whereas  $\text{CaCl}_2$  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  $\text{CaCl}_2$  in this study. This additive was therefore used in preference to  $\text{MgCl}_2$  for the



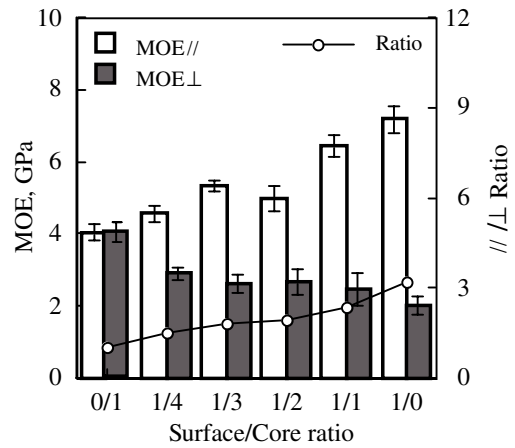
**Figure 2.** Hydration temperatures of cement-sugi (*Cryptomeria japonica* D. Don) mixtures



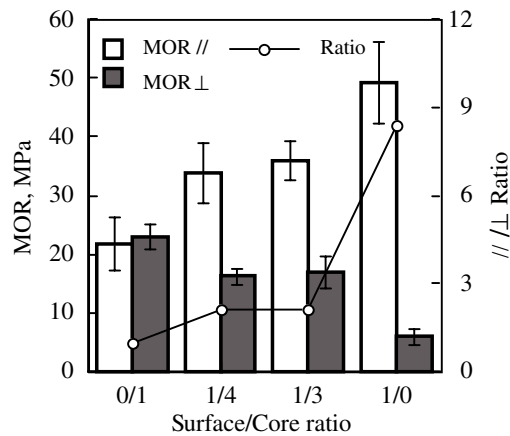
**Figure 3.** Modulus of rupture of cement-bonded strandboards from sugi with oriented surfaces and random cores. Notes: Type = Strand 40; additive = 3.75%  $\text{CaCl}_2$  based on cement weight; cement:wood:water = 2.6:1.0:1.3.

production of oriented CBB because it is cheaper than  $\text{MgCl}_2$ .

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

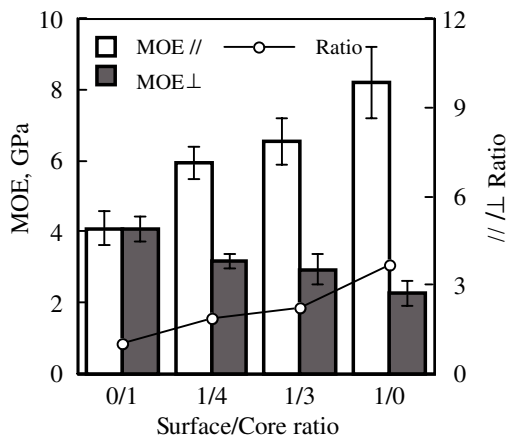


**Figure 4.** Modulus of elasticity of cement-bonded strandboards from sugi with oriented surfaces and random cores. Notes as in Fig. 3.

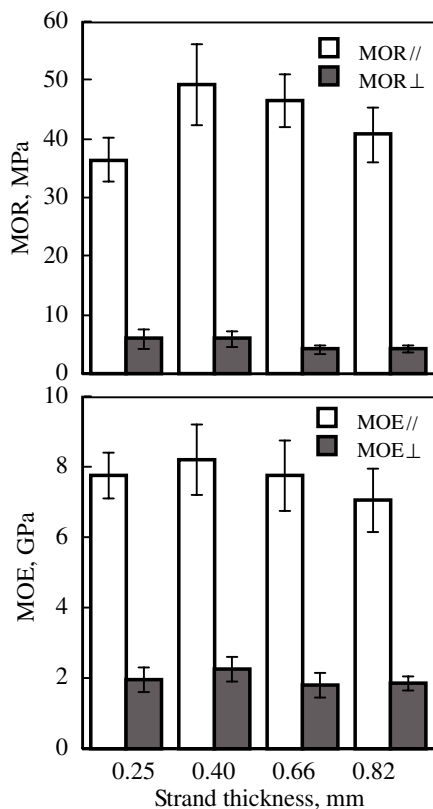


**Figure 5.** Modulus of rupture of cement-bonded strandboards from sugi with oriented surfaces and random cores. Notes: Type = Strand 40; additive = 3.75%  $\text{CaCl}_2$  based on cement weight; cement:wood:water = 2.6:1.0:1.56.

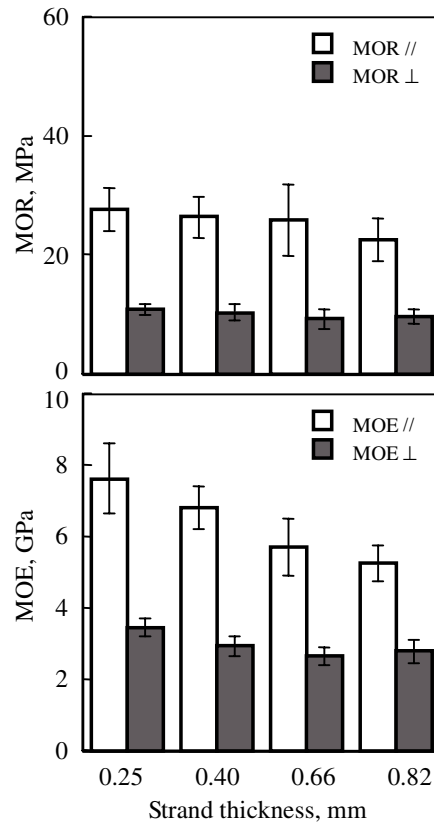
of varying water:cement ratio, within these limits, on strength properties, confirming that both ratios are suitable for CBB production, as we have shown previously (Ma et al. 1998a,c). The MOR values in the oriented direction of oriented cement-bonded strandboards were 2.5 times greater than in boards 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.



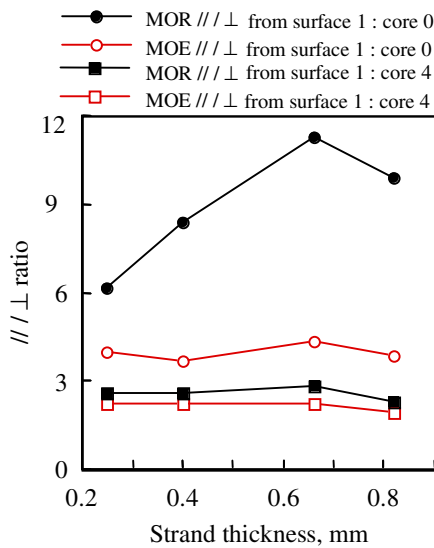
**Figure 7.** Effect of strand thickness on the MOR and MOE of oriented cement-bonded strandboard from sugi. Notes as for Fig. 5. All strands are oriented.



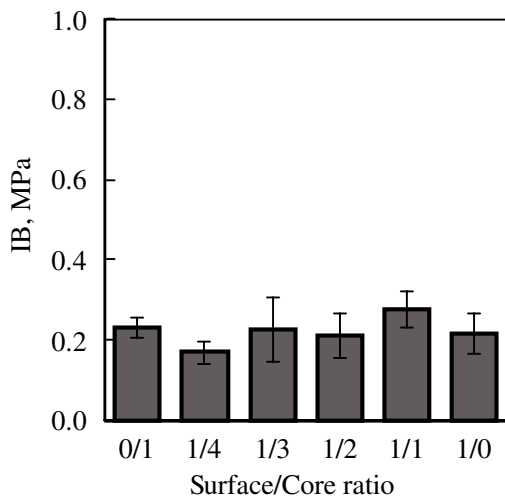
**Figure 8.** Effects of strand thickness on the MOR and MOE of cement-bonded strandboards from sugi with oriented surfaces and random cores. Notes: surface = strands; core = ring flakes; additive = 3.75%  $\text{CaCl}_2$  based on cement weight; cement:wood: water = surface 2.6:1.0:1.56 and core 2.6:1.0:1.3; 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 ( $\perp$ )) 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 =



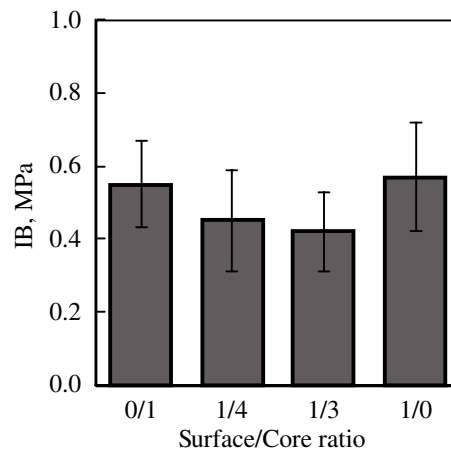
**Figure 9.** Anisotropy in MOR and MOE values of cement-bonded strandboards from sugi with oriented strand surfaces and random ring flake cores



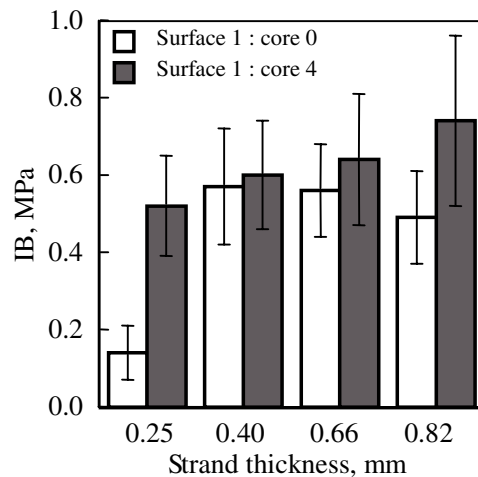
**Figure 10.** Internal bond strength (IB) of cement-bonded strandboards from sugi with oriented surfaces and random cores. Notes: as in Fig. 3.

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



**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

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<sub>⊥</sub>. 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

Type	Surface/Core		Strand thickness mm	Oven-dry density kg/m <sup>3</sup>	24-h expansion, %					24-h water absorption, %	
	Weight ratio				Thickness	SD	Width	SD	Length		SD
St/St	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
	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
St/St	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
	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
St/St	1/0		0.25	1056	3.6	0.8	0.40	0.10	0.18	0.06	17.7
	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
St/RF	1/4		0.25	1100	2.4	0.3	0.25	0.06	0.20	0.06	23.0
	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<sub>2</sub> 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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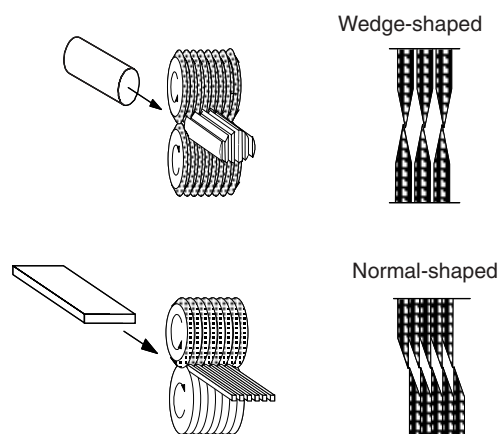
# Manufacture of Wood Strand–Cement Composite for Structural Use

Atsushi Miyatake<sup>1</sup>, Tsuyoshi Fujii<sup>1</sup>, Yasushi Hiramatsu<sup>1</sup>,  
Hisashi Abe<sup>1</sup> and Mario Tonosaki<sup>1</sup>

## Abstract

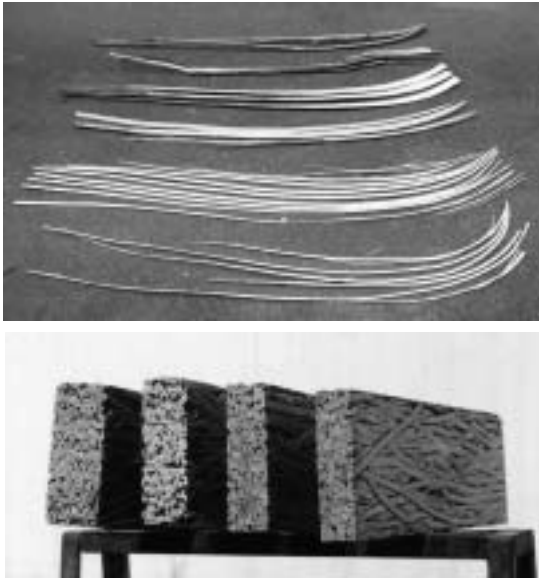
A new composite composed of wood strands and a cement-based matrix named Cement Strand Slab (CSS), was developed and the influence of manufacturing conditions on its strength properties was examined. Wood strands were produced by splitting slabs of sugi (*Cryptomeria japonica*) using a roll press-slitter 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.



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Figure 1. Diagram of a roll press-slitter



**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<sub>2</sub> (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 <sub>2</sub>	Strand	Cement	Sand	Water	Total
—	—	—	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 dipping (Cd)	1900	500	5000	4500	2500	50	1200	5500	4500	4400	15600
	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<sub>2</sub> 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 cut into test specimens and tested for bending properties.

The MOE was measured by the flexural vibration method and calculated using the following equation:

$$MOE = \frac{48\pi^2 f^2 \ell^4 P}{m^4 h^2},$$

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.

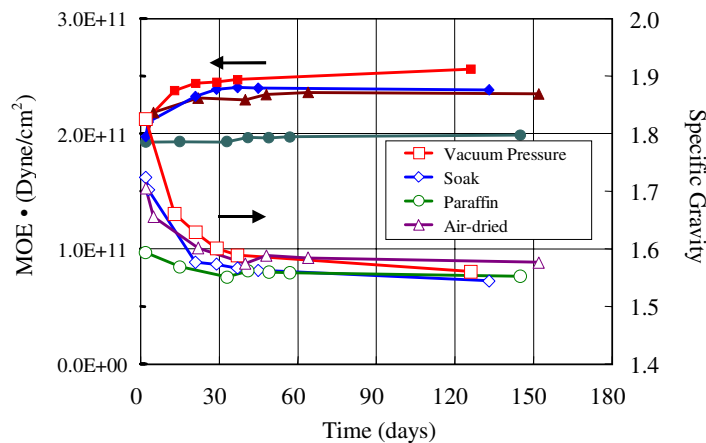
### Effect of treatment of strands on bending properties

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 <sup>2</sup>	MOR edge <sup>3</sup>	MOR flat <sup>4</sup>
—	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 <sup>1</sup> (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 dipping (Cd)	0.95 : 1	0.50 : 1	0.82 : 1	0.80 : 1	1.53	32.7	—
	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	—

<sup>1</sup>V-P = vacuum and pressure treatment; <sup>2</sup>SG = specific gravity; <sup>3</sup>MOR edge = modulus of rupture under loading perpendicular to laminated direction (MPa); <sup>4</sup>MOR flat = modulus of rupture under loading parallel to laminated direction (MPa)

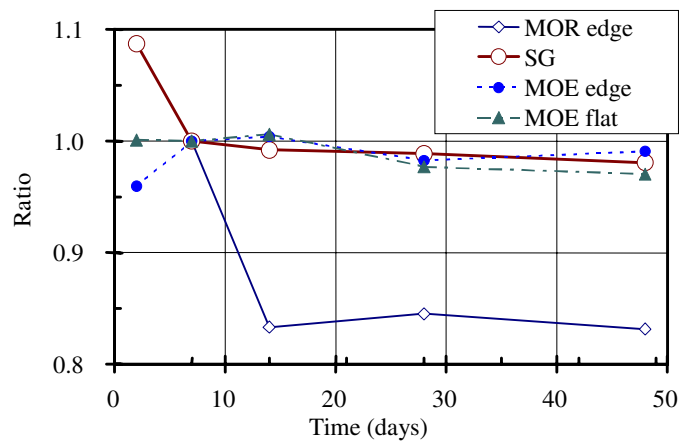


**Figure 2.** Relationships between changes in specific gravity and MOE during post-curing in response to manufacturing conditions

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.

### References

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# Application of Wood-Wool Cement Boards for Shop-fabricated Emergency Shelters in the Philippines

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## *Abstract*

The Forest Products Research and Development Institute (FPRDI) recently developed the 'F shelter'<sup>2</sup> — a fast-to-build, firm and foldaway 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<sup>2</sup> 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

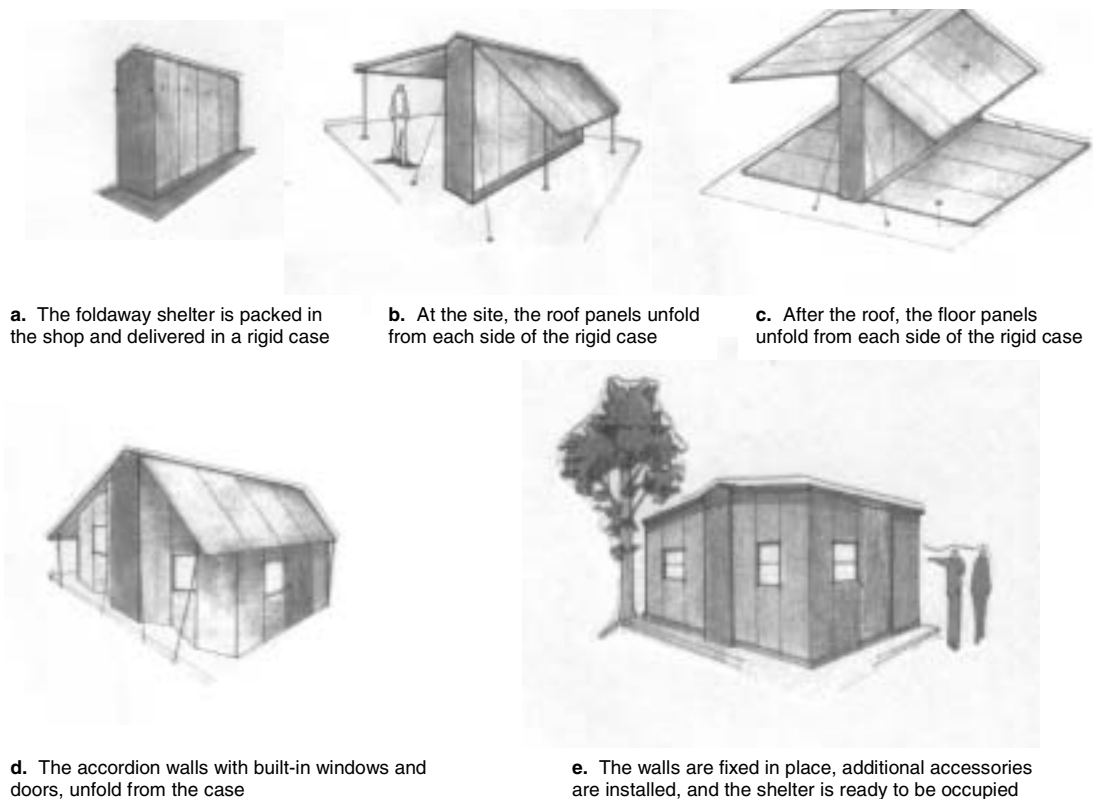
(Balana 1999). Prolonged use of schools, gymnasiums, churches and other public buildings as evacuation centres may cause further disruption to the normal livelihoods and activities of people, including those who have not been directly affected by a disaster.

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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<sup>2</sup>Patent pending



**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 lightweight 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 lightweight 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 ( $750 \text{ kg m}^{-3}$ ) and high-density ( $900 \text{ kg m}^{-3}$ ) WWCB panels were used as floor, wall and roofing boards in both prototypes. The dimensions of structural members and jointing details were structurally designed.

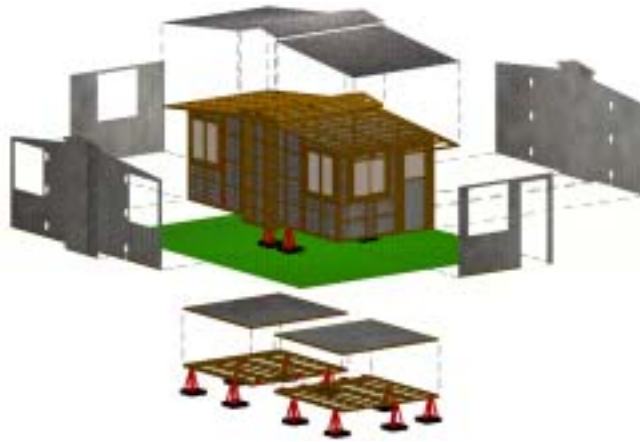
Construction materials were purchased within the Laguna and Metro-Manila areas. The use of materials, equipment and tools and the worker requirements were monitored and recorded and these were used in estimating production cost. Time and motion studies were conducted to determine the time and effort 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

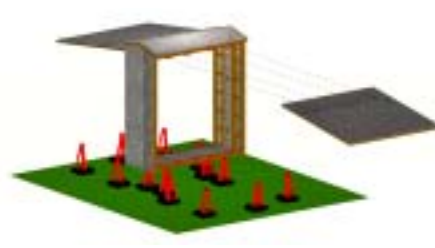
From the initial concept and plans all the technical specifications and guidelines in shop fabricating the roof, wall, floor components and the rigid



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



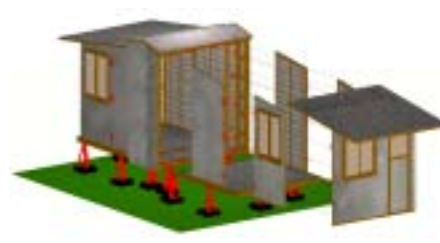
b. case-to-floor details



c. case-to-roof details



d. case-to-wall details



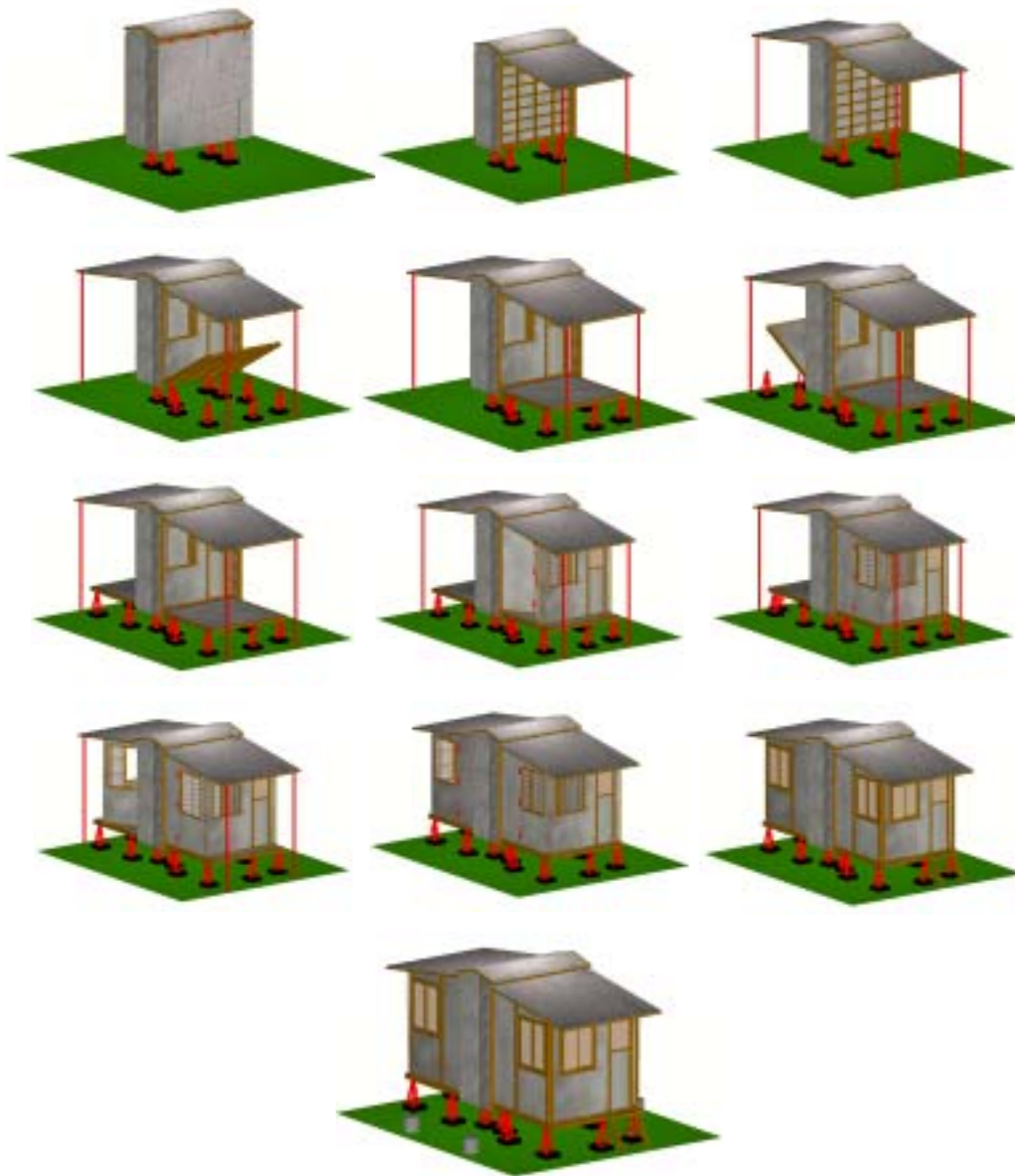
e. case-to-floor, wall and roof details

**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<sup>2</sup>), 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 fast-to-build, firm and foldaway 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 lightweight 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 <sup>2</sup>	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 <sup>2</sup>	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-wood 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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