MANUFACTURE OF WOOD-CEMENT COMPOSITES FROM *ACACIA MANGIUM*. Part II. USE OF ACCELERATORS IN THE MANUFACTURE OF WOOD-WOOL CEMENT BOARDS FROM *A. MANGIUM*

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ABSTRACT

In the second paper in this series, we test the hypothesis that cement-setting accelerators with the ability to chelate phenolic extractives will be more effective at improving the physical properties of wood-wool cement boards made from the heartwood of *Acacia mangium* than conventional accelerators. Furthermore, we assess whether the use of chelating accelerators will allow boards with acceptable properties to be manufactured from *A. mangium* wood-wool that has not been subjected to preliminary aqueous extraction to remove phenolic extractives. Batches of wood-wool from *A. mangium* containing approximately 75% heartwood were either soaked in water or used in their native form. The batches were then treated with an aqueous solution containing an inorganic compound (generally 0.05 or 0.1 M) selected for its ability to accelerate the hydration of Portland cement, and in the case of 5 of the 11 compounds tested, chelate phenolic extractives. Individual wood-wool cement boards were manufactured from each treated batch of wood-wool and tested for their dry and wet bending strength (MOR), stiffness (MOE), and water absorption properties. Boards made from untreated or water-soaked wood-wool acted as controls. The MOR and MOE of boards made from unsoaked *A. mangium* wood-wool and treated with the chelating accelerators tin or ferric chloride at 0.1 M concentration were 10.8 and 10.9 MPa and 2256 and 2178 MPa, respectively. These same boards showed less than 5% thickness swelling after 24-h immersion in water. In contrast most of the boards containing a conventional non-chelating accelerator had no structural integrity. The combination of a chelating accelerator and a conventional accelerator was particularly effective at improving the physical properties of boards made from unsoaked wood-wool. We conclude that wood-wool cement boards with acceptable physical properties can be manufactured from *A. mangium* heartwood by treating wood-wool with inorganic compounds that have the ability to chelate phenolic extractives and accelerate the hydration of Portland cement. Our findings could eliminate the need to pre-soak *A. mangium* wood-wool in water during the manufacture of wood-wool cement boards and may have broader relevance to the manufacture of wood-wool cement boards from other hardwood species containing phenolic extractives.

Keywords: Wood-wool cement boards, *Acacia mangium,* accelerators, physical properties, chelation, phenolic extractives.

INTRODUCTION

Brown salwood (*Acacia mangium* Willd.) is a commercially important tropical plantation species that is grown extensively throughout South East Asia, where it is mainly used for pulp and paper and sawn timber (Gunn and Midgley 1991; Awang and Taylor 1993). *Acacia mangium* is suitable for the manufacture of reconstituted wood composites (Abdul-Kader and Sahri

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1993a, b), but its heartwood inhibits the setting of Portland cement so strongly that it cannot be used to manufacture wood-cement composites such as wood-wool cement boards unless its extractive content is reduced, by soaking wood-wool in water for 6 to 12 h, and using a cement-setting accelerator to ameliorate the inhibitory effects of residual extractives on the hydration of cement (Rahim and Ong 1983; Jegasethwaran 1989; Tachi et al. 1988, 1989).

The pre-soaking of wood-wool in water adds an additional time-consuming step to the manufacture of wood-wool cement boards and creates large volumes of waste water containing phenolic extractives that need to be disposed of. Furthermore, it is sometimes difficult for commercial wood-wool cement board plants to obtain sufficient quantities of water to treat wood-wool, particularly during the dry season that precedes the monsoon in the wet humid tropics. For these reasons, it would be desirable to eliminate the pre-soaking of wood-wool during the manufacture of wood-wool cement boards from *A. mangium* by finding cement-setting accelerators that are highly effective at blocking the inhibitory effects of *A. mangium* heartwood extractives on the hydration of cement, thereby allowing boards with acceptable properties to be manufactured from unsoaked wood-wool.

In Part I of this research (Semple et al. 2004) it was hypothesized that inorganic compounds capable of both chelating phenolic extractives in *A. mangium* and accelerating the hydration of cement would be more effective at blocking the inhibitory effect of *A. mangium* heartwood on the setting of cement than conventional accelerators that simply increased the rate of cement hydration. Our findings supported this hypothesis since compounds such as tin chloride ($SnCl_4$) and ferric chloride ($FeCl_3$) capable of chelating phenolic extractives and accelerating cement hydration were much more effective at increasing the hydration rate and temperature in cement paste containing *A. mangium* heartwood than conventional cement-setting accelerators such as calcium chloride ($CaCl_2$). We further hypothesized that accelerators with the ability to chelate phenolic extractives would be more effective at improving the properties of wood-wool cement boards made from *A. mangium* than conventional accelerators (Semple et al. 2004). In this paper we test this hypothesis and assess whether the use of chelating accelerators used alone or in combination with a conventional accelerator will allow boards with acceptable properties to be made from unsoaked *A. mangium* wood-wool.

MATERIALS AND METHODS

Experimental design and statistical analysis

An experiment was designed to compare the effects of two factors: (a) pre-soaking or not pre-soaking wood-wool in water prior to manufacture of wood-wool cement boards (2 levels); and (b) additive type/concentration combination (34 levels) on the mechanical properties of wood-wool cement boards. One or more different concentrations (generally 0.05 or 0.1 M) were used for each of the 16 additives tested. These concentrations were selected because they are similar to the concentrations of the inorganic accelerators that are added to wood-wool cement boards manufactured commercially. Furthermore, previous research had shown that at a concentration of 0.1 M the inorganic compounds were capable of accelerating the hydration of cement and chelating phenolic extractives (Semple et al. 2004).

Wood-wool was obtained from two *A. mangium* trees. Boards covering the 34 additive/concentration combinations for wood-wool from Tree 1 (unsoaked) were made first (in a randomized order) followed by all 34 randomized combinations for Tree 2 (soaked), Tree 2 (unsoaked), and finally Tree 1 (soaked). One board was made for each additive/concentration combination from each tree/soaking combination. The resulting split plot design accounted for random variation at 3 levels: variation between tree/soaking groups, variation between boards, and variation between test pieces.

Mixed linear models were used to analyze the effects of pre-soaking the wood-wool and addition of accelerators on board properties. Board density was treated as a covariate and the three levels of variation (above) as random effects. Computation was performed using Genstat 5 (Lawes Agricultural Trust 2001). Before the final analysis, diagnostic checks were performed to determine whether results conformed to the assumptions of analysis of variance, i.e. normality with constant variance. Results from the statistical analyses that were significant at the 5% ($p \leq 0.05$), 1% ($p \leq 0.01$), or 0.1% ($p \leq 0.001$) levels are plotted graphically. A bar representing the least significant difference (LSD) at the 5% level ($p \leq 0.05$) is included on each graph to facilitate comparison of individual means.

Preparation of wood-wool from billets

Two *A. mangium* trees measuring approximately 12 m in height were obtained from a 12-year-old provenance trial located at Kuranda in North Queensland, Australia. Both trees contained approximately 75% heartwood. The trees were felled and cut into logs measuring 1 m or 50 cm in length, color-coded (by tree), debarked, and cross-cut into 46-cm-long billets. The green billets were shredded using a van Elten reciprocating shredder to produce 'coarse' wood-wool measuring 3 × 0.5 mm in cross-section. The wood-wool was passed through a 3- × 1-m diameter rotating slatted drum to sift out short pieces; and the wood-wool was then air-dried under cover for 2 weeks.

Half of the wood-wool was then soaked in water at ambient temperature to remove soluble inhibitory constituents from the wood. This was done by filling 70-L plastic bins with approximately 2 kg of air-dry wood-wool and adding water (25–30°C) to the wood-wool to completely submerge it. The leachate was poured off after 24 h and the wood-wool rinsed once with clean water, drained, and spread out to dry under cover for 2 weeks. Prior to the manufacture of boards, the wood-wool was screened by passing it through a mesh measuring 40 × 50 mm to remove fines shorter than 10 mm in length. Screened wood-wool was then weighed into batches of 504 g (sufficient for one board) and stored in open bags.

Accelerators used and their preparation

The 32 different accelerator/concentration treatments used to make wood-wool cement boards from unsoaked and soaked *A. mangium* wood-wool are indicated by small circles in Table 1. In most cases, two concentrations, 0.05 M and 0.1 M, were used in combination with unsoaked wood. Exceptions to this were compounds known from previous studies to have no effect at 0.05 M, including $CaCl_2$, $MgCl_2$, Na_2SiO_3, and $SrCl_2$. For other accelerators such as $SnCl_4$ and $FeCl_3$, concentrations of 0.1 M were too high for use with pre-soaked wood-wool. In cases where a particular compound and concentration was not used a hyphen is inserted into the relevant field in Table 1.

Manufacture and testing of wood-wool cement boards

Medium-density wood-wool cement boards (target density of 700–900 kg/m^3) were manufactured using a wood-cement ratio of just under 1:1, as recommended by Soriano et al. (1997). Each board contained 504 g of wood-wool, 508 g of Portland cement ASTM Type 1 (Blue Circle Southern Cement Batch No. 23MA01), and 523 g of water to which each additive was added at a specified concentration. The solution containing the dissolved accelerator was sprayed onto the wood-wool to wet all strands. The treated wood-wool was then left for 2 to 3 minutes to allow inorganic compounds to react with heartwood polyphenols. The cement powder was then sprinkled through the wet wood-wool in stages interspersed with hand mixing to evenly coat all strands with cement. The mix was then transferred to a formply mold measuring 300 × 380 mm placed on a rectangular sheet of melamine-coated formply measuring 340 × 420 × 17 mm. The mix was evenly spread and manually flattened using a wooden block to form a mat, after which the mold was removed and another piece of formply placed on top of the mat. Two wooden spacer rods measuring 12 × 12 × 300 mm were placed at either end between the formply sheets to ensure that final pressed board

TABLE 1. *Accelerators used in the manufacture of wood-wool cement boards from A. mangium.*

	Relative concentrations		Tree/soaking			
Compound formula	Conc. (M)	% w/w cem.	1	1 (s)	2	2 (s)
$CaCl_2$	0.05	0.76	—	•	—	•
	0.1	1.52	•	•	•	•
	0.2	3.06	•	—	•	—
$MgCl_2$ (MC)	0.05	1.05	—	•	—	•
	0.1	2.11	•	•	•	•
$SrCl_2$	0.05	1.38	—	•	—	•
	0.1	2.77	•	•	•	•
$FeCl_3$ (FC)	0.025	0.70	•	—	•	—
	0.05	1.40	•	•	•	•
	0.1	2.81	•	—	•	—
$SnCl_4$ (SC)	0.025	0.91	•	•	•	•
	0.05	1.82	•	•	•	•
	0.1	3.65	•	—	•	—
$AlCl_3$	0.05	1.25	•	•	•	•
	0.1	2.51	•	—	•	—
$Al_2(SO_4)_3$ (AS)	0.05	1.78	•	•	•	•
	0.1	3.55	•	—	•	—
$Al(NO_3)_3$ (AN)	0.05	1.90	•	•	•	•
	0.1	3.79	•	—	•	—
Na_2SiO_3	0.1	2.10	•	•	•	•
	0.2	4.21	•	—	•	—
	0.4	8.43	•	—	•	—
	0.6	12.64	•	—	•	—
$Ca(NO_2)_2$	0.05	0.68	•	•	•	•
	0.1	1.37	•	—	•	—
Pozzolith*	10 mL	—	•	•	•	•
Water		—	•	•	•	•
SC + MC	0.05 + 0.05	1.82/1.05	•	•	•	•
FC + MC	0.05 + 0.05	1.40/1.05	•	•	•	•
AS + MC	0.05 + 0.05	1.78/1.05	•	•	•	•
AN + MC	0.05 + 0.05	1.90/1.05	•	•	•	•
SC + MC	0.025 + 0.05	0.91/1.05	•		•	
FC + MC	0.025 + 0.05	0.70/1.05	•		•	

* Pozzolith is a $CaCl_2$-based commercially available additive containing polymers to enhance cement strength. (s) denotes soaked wood-wool.

thickness was 12 mm. The resulting assemblage was pre-pressed while the mat for the next board was mixed, and the process was repeated to produce a sandwich of two mats between three sheets of formply. This stack of mats was then placed between two steel plates measuring 340 × 470 × 15 mm and pressed at ambient temperature at 140 kPa using a PHI hydraulic press. The compressed mats were kept under pressure for 24 h by bolting the two steel plates together using four 8-mm-thick bolts, an assemblage that could then be removed from the press. After 24 h the boards were de-clamped, stacked, and conditioned for 10 weeks at 20 ± 1°C and 65 ± 5% r.h. to allow the cement to cure and gain strength. Between 2 and 4 boards were manufactured per day, with a total of 100 boards manufactured over a period of about 50 days.

Conditioned boards measuring 340 × 320 × 12 mm were sawn into 5 test samples measuring 230 × 50 mm using a large bandsaw. Samples 1 and 3 were tested for bending strength (MOR) and stiffness (MOE) in the dry conditioned state. Samples 2 and 4 were tested for MOR and MOE in the wet condition, after they had been immersed in water at ambient temperature (20°C) for a period of 24 h. Prior to soaking, the samples were weighed, and their thickness was measured at three points along their length using a Mitutoyo digital caliper. These measurements were used to determine the basic density of pieces 2 and 4. After soaking, samples were drained on paper towels for 20 minutes to remove excess water. The thickness and weight of each sample were re-measured and the percentage absorption of water and thickness swelling of samples were calculated and expressed as percentages of original weight and thickness, respectively. Three-point flexural bending tests were carried out using an Instron 4505 Universal Testing Machine, using a span of 18 mm, cross-head and bearer diameter of 25 mm and loading speed of 5 mm/min.

RESULTS AND DISCUSSION

Accelerator type/concentration and whether the wood-wool was pre-soaked in water had highly significant effects ($p < 0.001$) on the density and strength properties of wood-wool cement boards. Only two accelerators produced wood-wool cement boards of acceptable quality (meeting international and country-specific standards) when unsoaked wood-wool was used. These accelerators ($SnCl_4$ and $FeCl_3$) were a subset of those identified previously as being the most effective at ameliorating the inhibitory effects of *A. mangium* heartwood on the hydration of cement (Semple et al. 2004).

Effects of accelerators on the properties of wood-wool cement boards made from unsoaked wood-wool

The strength and dimensional stability of wood-wool cement boards containing the different accelerators are shown in Figs. 1 to 4 for MOR, MOE, wet MOR, and thickness swell, respectively; in which the results for boards made from unsoaked wood-wool are denoted by the black bars. Part (a) of each figure shows the results for the addition of each compound at 0.05 M and part (b) for 0.1 M. There are no test results for most of the accelerators tested in boards containing unsoaked wood-wool since these failed to consolidate. For the 0.05 M concentration, the only boards of adequate strength (average MOR = 11.6 MPa) were those containing $SnCl_4$ at equivalent to 1.8% of cement weight.

When the treatment solution concentration was doubled to 0.1 M, both $SnCl_4$ and $FeCl_3$ were effective at improving the properties of boards made from unsoaked wood-wool. In fact

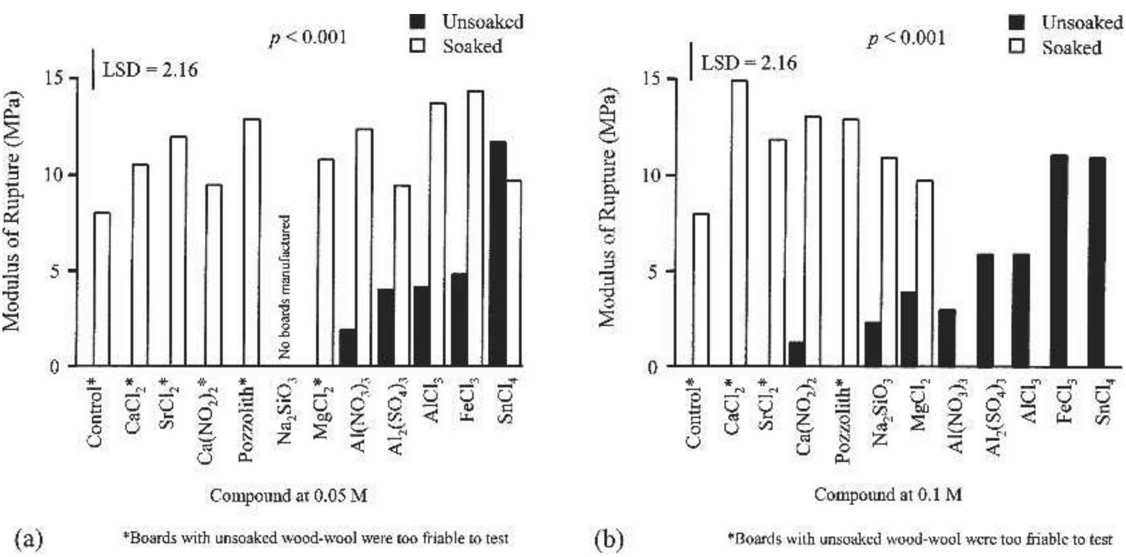

FIG. 1. Average MOR of wood-wool cement boards manufactured from unsoaked and soaked *A. mangium* wood-wool with accelerators applied at (a) 0.05 M and (b) 0.1 M concentration.

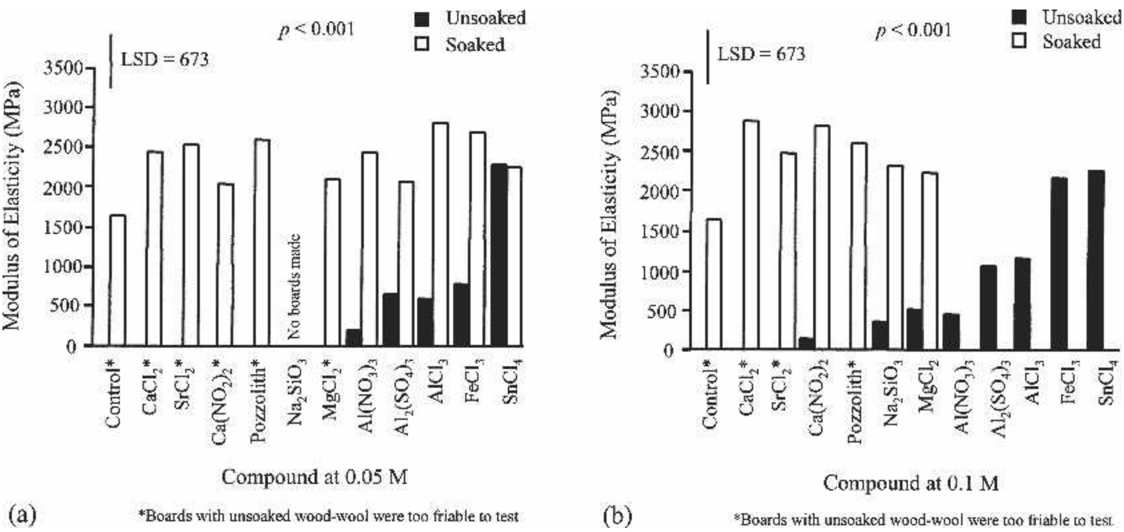

FIG. 2. Average MOE of wood-wool cement boards manufactured from unsoaked and soaked *A. mangium* wood-wool with accelerators applied at (a) 0.05 M and (b) 0.1 M concentration.

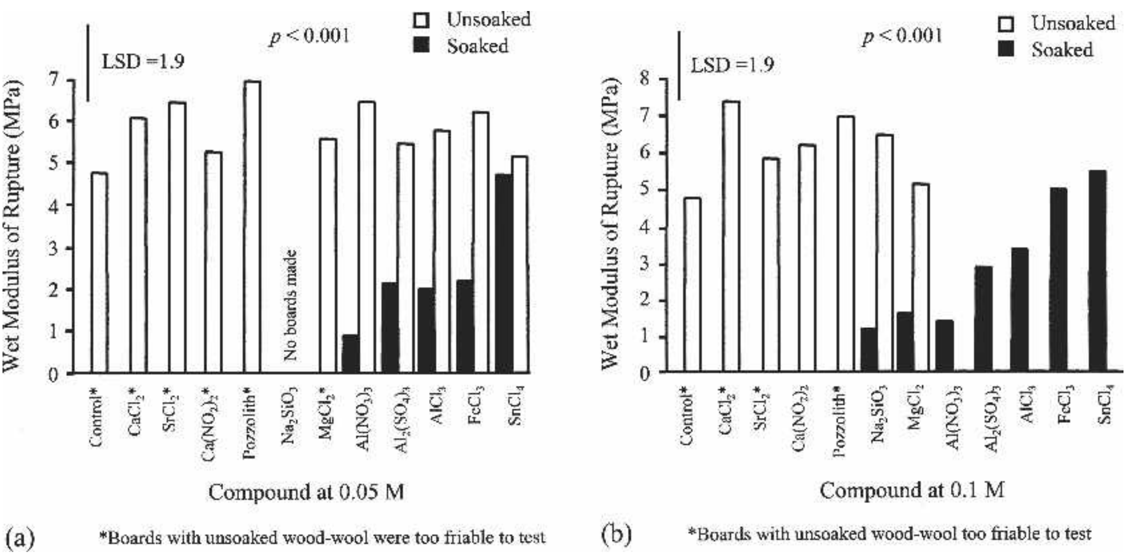

FIG. 3. Average wet MOR of wood-wool cement boards manufactured from unsoaked and soaked *A. mangium* wood-wool with accelerators applied at (a) 0.05 M and (b) 0.1 M concentration.

only boards made with these compounds exceeded the PNS/CTP 07 (1990) standard for non-structural 12-mm-thick wood-wool cement board of 6.75 MPa, and the more stringent ISO 8335 (1987) for cement-bonded particleboard of 9 MPa in bending strength. Wood-wool cement boards made from unsoaked wood-wool and containing $SnCl_4$ and $FeCl_3$ at 0.1 M strength had average MOR values of 10.8 and 10.9 MPa, respectively (Fig. 1 (b)). Wood-wool cement boards containing $SnCl_4$ had the highest MOE, i.e. 2284 MPa for 0.05 M, and 2256 MPa for 0.1 M addition, as shown in Figs. 2 (a) and (b), respectively. At 0.1 M concentration, the MOE of boards containing $FeCl_3$ was 2178 MPa. The MOE of wood-wool cement boards containing

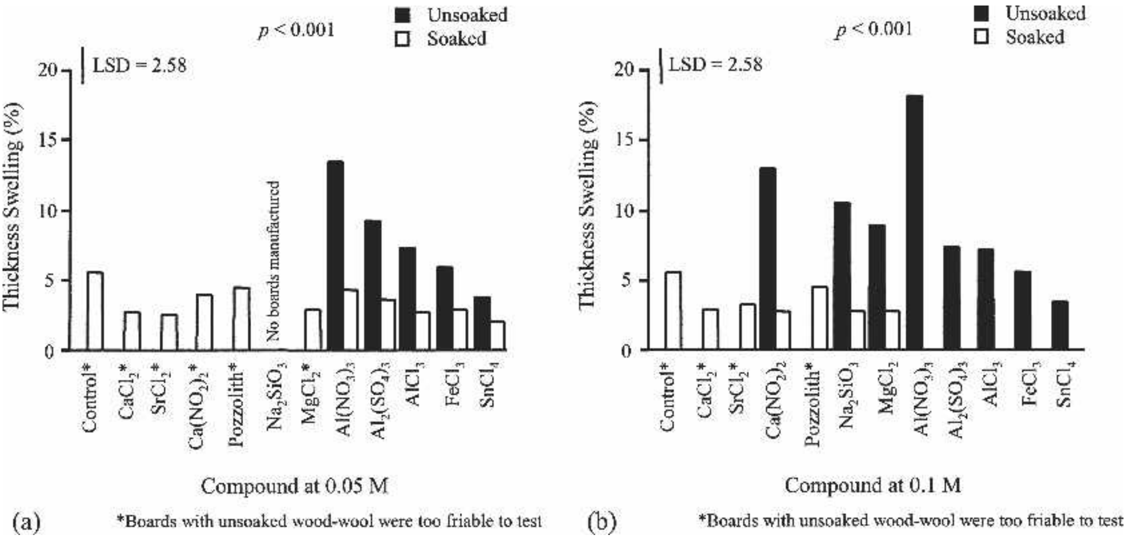

FIG. 4. Average thickness swell of wood-wool cement boards manufactured from unsoaked and soaked *A. mangium* wood-wool with accelerators applied at (a) 0.05 M and (b) 0.1 M concentration.

other accelerators was significantly ($p < 0.001$) lower, i.e. below 800 MPa at 0.05 M and below 1200 MPa at 0.1 M. The majority of compounds added at 0.1 M strength (other than $SnCl_4$ or $FeCl_3$) failed to produce boards of acceptable strength from unsoaked wood-wool even though the boards (in particular $AlCl_3$ and $Al_2(SO_4)_3$) appeared to be well consolidated, with average densities of between 690 and 700 kg/m^3. This suggests that for these accelerators, the strength of the hydrated cement binder was lower than in boards containing $SnCl_4$ or $FeCl_3$.

The strength properties of wood-wool cement boards made from unsoaked *A. mangium* wood-wool and small amounts of $SnCl_4$ and $FeCl_3$ are higher than those of typical wood-wool cement boards made commercially in the Philippines, mostly from pre-soaked Gamhar (*Gmelina arborea* Linn., Roxb.) wood-wool. The average strength and stiffness of such boards are 4.7 MPa and 1333 MPa, respectively. Strength data are available from previous laboratory studies of the manufacture of wood-wool cement boards from pre-soaked *A. mangium* wood. MOR values for boards containing 3% $CaCl_2$ or $Al_2(SO_4)_3$ are quoted at 8 MPa (Eusebio et al. 2002), 6 MPa (Soriano et al. 1997), and between 1.5 and 2 MPa (Cabangon et al. 1998). The MOE of wood-wool cement boards made in these studies was less than 1500 MPa.

The compounds that allowed adequate strength development in boards made from unsoaked *A. mangium* wood-wool were $SnCl_4$ and $FeCl_3$. Both of these compounds are strong metal oxidants capable of catalyzing the radical induced coupling of mono- and polyhydric phenols (Sheldon and Kochi 1981). In Part 1 of this research (Semple et al. 2004), we suggested that the formation of complex amorphous matrices consisting of co-ordinated polyphenols formed through the reaction of $SnCl_4$ or $FeCl_3$ with *A. mangium* heartwood extractives, would limit the ability of the polyphenols to diffuse into the cement gel and inhibit cement hydration. We further suggested that precipitated phenolic complexes with fewer hydroxyl groups might be less able to chemically interfere with the diffusion of Ca^{2+} ions, $Ca(OH)_2$ formation, and the hydration of calcium silicates in cement pastes. These effects were used to explain why inorganic compounds with the ability to complex polyphenols were much more effective than conventional accelerators at accelerating the hydration of cement containing *A. mangium* heartwood. The same effects may explain observations here that compounds such as $SnCl_4$ and $FeCl_3$ were far more effective at low concentrations at improving the properties of wood-wool cement boards made from *A. mangium* than conventional accelerators. Wood-wool cement boards that contained accelerators with no 'complexing' capacity, such as $SrCl_2$, $CaCl_2$, and Pozzolith, failed to consolidate even after the solution concentration was doubled to 0.2 M. These observations may help explain why Lee and Short (1989) found that the ability of $CaCl_2$ to improve the properties of wood-wool cement boards was extremely variable depending on the species of wood used. $CaCl_2$ was effective in the case of sweetgum (*Liquidambar styraciflua* L.), but ineffective in the case of southern red oak (*Quercus falcata* Michx.) where oak tannin (dihydroquercetin) was the primary cause of low cement compatibility. Tachi et al. (1988, 1989) and Subiyanto and Firmanti (1998) also found that $CaCl_2$ was ineffective in countering the inhibitory effects of heartwood polyphenols during the manufacture of wood-cement composites from untreated *A. mangium* wood.

Thickness swelling and loss of mechanical properties of wood-wool cement boards after exposure to water

The effects of different accelerators on the water resistance of wood-wool cement boards (reflected in wet MOR and thickness swell) are shown in Figs. 3 and 4, respectively. Boards containing unsoaked wood-wool and the different accelerators were all below the minimum 5.5 MPa residual MOR required by ISO 8335 after exposure to water for 24 h (no minimum wet MOE is specified; nor are any minimum wet strength values specified in JIS-A 5404 or PNS/CTP 07 for wood-wool cement boards). The strength losses of boards containing different accelerators after exposure to water are shown in Table 2. Most boards containing unsoaked wood-wool and an accelerator showed losses in MOR of between about 45 and 60%. Surprisingly, the pre-soaking of wood-wool prior to board manufacture had relatively little effect on strength losses after wetting if compounds were used at 0.05 M. Na_2SiO_3 and $MgCl_2$ were common to boards containing unsoaked and soaked wood-wool, and in these cases the reduction in MOR was much lower if soaked wood-wool was used in board fabrication, as would be expected.

The moisture-induced swelling of wood cement composites containing high levels of cement such as cement bonded particleboard can be predicted based on the response of their individual components to moisture (Fan et al. 2004b). For these composites the contribution of wood to dimensional stability is greater than that of cement, despite their relatively high cement content (Fan et al. 2004a). Hence, the moisture-induced swelling of wood-wool cement boards,

TABLE 2. *Percentage strength losses of wood-wool cement boards containing soaked or unsoaked wood-wool and different accelerators at 0.05 M or 0.1 M concentration.*

	0.05 M		0.1 M	
Compound	Unsoaked ww	Soaked ww	Unsoaked ww	Soaked ww
Control	—	41	—	—
$CaCl_2$	—	42	—	50
$SrCl_2$	—	51	—	46
$Ca(NO_2)_2$	—	44	53	—
Pozzolith	—	46	—	46
Na_2SiO_3	—	—	51	40
$MgCl_2$	—	48	100	47
$Al(NO_3)_3$	54	48	53	—
$Al_2(SO_4)_3$	47	42	51	—
$AlCl_3$	53	58	43	—
$FeCl_3$	55	57	55	—
$SnCl_4$	59	47	50	—

— denotes instances were boards were unconsolidated or manufacture was not necessary.

which have a high wood to cement ratio, is likely to be dominated by the response of its wood component to water. Nevertheless, effective cure of its cement component can be expected to enhance dimensional stability by increasing the interfacial strength of inter-strand bonds and their resistance to stresses generated by moisture-induced swelling of wood. Accordingly, the addition of accelerators at 0.1 M concentration generally increased the dimensional stability of boards, but only the addition of $SnCl_4$ and $FeCl_3$ reduced thickness swelling to 5% or below (Figs. 4 (a) and (b)). In the absence of any maximum thickness swelling specified for wood-wool cement boards, 5% could be regarded as a maximum target value since it is the maximum allowed for 12-mm-thick particleboard by JIS A 5908 (1994). The thickness swelling of boards containing $SnCl_4$ at 0.05 M were also below 5%. Boards containing $SnCl_2$ absorbed the lowest quantity of water during immersion, less than 35% of their weight. ISO 8335 specifies a maximum thickness swelling of 2% after immersion in water for 24 h; however, this specification is for composites with much higher cement content and may not be appropriate for the low cement-content wood-wool cement boards manufactured here.

An important purpose of cement-setting accelerators is to improve the resistance of wood-cement composites to moisture-induced swelling (Kayahara et al. 1979; Wei et al. 2000). Our results showed that wood-wool cement boards containing unsoaked wood-wool and accelerator were highly susceptible to water-induced losses in strength despite good initial board consolidation afforded by some of the accelerators. For example the moderately well-consolidated boards containing $Al(NO_3)_3$ and $Ca(NO_2)_2$ swelled by over 10% and absorbed over 50% of their weight in water, suggesting weak bonding between the wood and cement, resulting in poor water resistance. Irrespective of their dry strength, most boards also lost 50% of their MOR after exposure to water for 24 h. The possible migration of extractives to the wood-cement interface induced by wetting has been suggested by Eusebio et al. (2002) as a possible reason why exposure of wood-wool cement boards to water adversely affects their strength. In light of our findings, it would be advisable when using wood-wool cement boards for building construction to minimize direct exposure of the boards to water through appropriate building design, and the application of moisture-proof coatings or mortar rendering to board surfaces (Cabangon et al. 2003).

The effects of additive combinations on unsoaked wood-wool

The effects of using small amounts of four compounds; $Al_2(SO_4)_3$, $Al(NO_3)_3$, $FeCl_3$, and $SnCl_4$, either on their own or mixed with 0.05 M $MgCl_2$ (~1% w/w cement), on the mechanical properties of boards containing unsoaked wood-wool are shown in Fig. 5 (a) for MOR and (b) for MOE. Significant ($p < 0.001$) increases in the strength of wood-wool cement boards made from unsoaked wood-wool were achieved by combining 0.05 M $MgCl_2$ with either 0.05 M $Al_2(SO_4)_3$ or 0.025 M $SnCl_4$. These boards were stronger than those containing the same compounds used individually at the same concentrations. With $Al_2(SO_4)_3$ the average MOR increased from 4 MPa to 8.5 MPa, and with $SnCl_4$ from 3.5 MPa to 10.5 MPa. These results suggest that 0.025 M $SnCl_4$ (i.e. ~1%) may have been sufficient to neutralize enough inhibitory extractives from the wood-wool to enable a relatively small amount of supplementary $MgCl_2$ to further accelerate cement hydration and enhance the consolidation of the cement binder. Supplementing $Al_2(SO_4)_3$ with 0.05 M $MgCl_2$ also had a positive, but less pronounced effect.

The effect of using pre-soaked wood-wool on board properties

Pre-soaking wood-wool in water combined with the use of cement-setting accelerators is the method that has been used by industry to ameliorate the inhibitory effects of wood extractives on cement hydration during the manufacture of cement-bonded wood composites (Wei et al. 2000; Wei and Tomita 2001). Accordingly, as

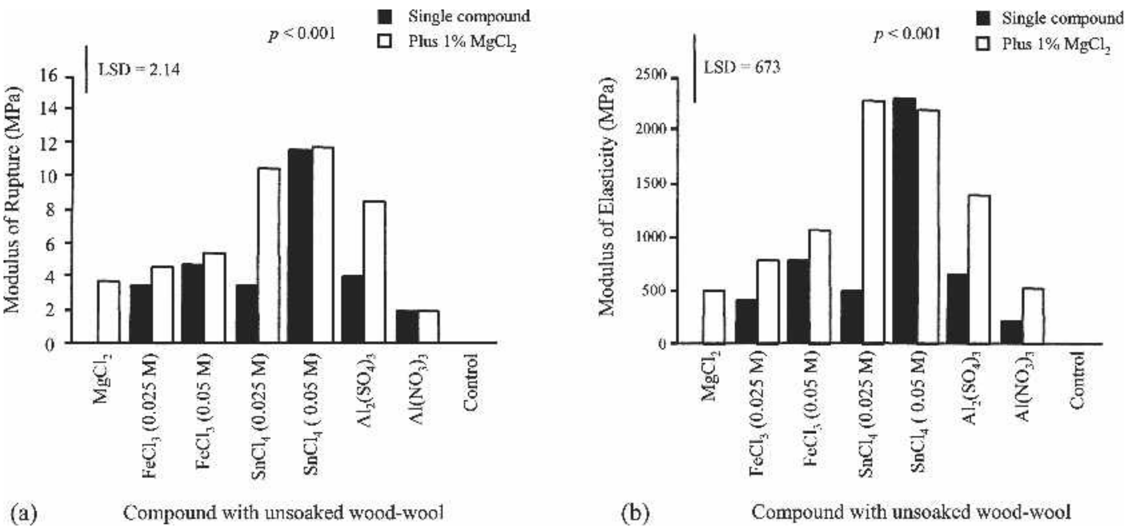

FIG. 5. The effect on (a) MOR and (b) MOE of combining selected accelerators with 0.05 M (1%) $MgCl_2$ compared to adding the accelerators on their own to wood-wool cement boards made from unsoaked wood-wool.

expected, the pre-soaking of *A. mangium* wood-wool had a highly significant ($p < 0.001$) effect on the mechanical properties and dimensional stability of wood-wool cement boards, and allowed low concentrations (0.05 M) of cement accelerators to further improve board properties. Wood-wool cement boards made from pre-soaked wood-wool usually had basic densities above 750 kg/m^3, which exceeded the minimum of 600 kg/m^3 for 12-mm-thick boards specified in PNS/CTP 07 (1990). Boards containing no accelerator had an average MOR of 8 MPa while most of the accelerators, particularly $CaCl_2$ and the $CaCl_2$-based 'Pozzolith', further improved board strength as shown in Figs. 1 and 2. Boards containing 0.1 M $CaCl_2$ and manufactured from pre-soaked wood-wool attained an average MOR of almost 15 MPa, well above even the minimum of 9 MPa specified by ISO 8335 for higher density and higher cement-content composites such as cement-bonded particleboard. Some of the accelerators, including $CaCl_2$, Pozzolith, $FeCl_3$ and $AlCl_3$, increased MOR by up to 50% compared to boards containing no accelerator. However, no single compound either at 0.05 or 0.1 M concentration increased the MOE of boards to the level of 3000 MPa specified in ISO 8335 for cement-bonded particleboard. All accelerator types when used in combination with pre-soaked wood-wool reduced thickness swelling to below 5% (Fig. 5 (a)) and water absorption values were all below 35%.

The addition of accelerators or the use of pre-soaked wood-wool produced boards with MOR similar or higher than that of cement-bonded particleboard, but this was not the case for MOE as the stiffness of cement-bonded composites is more strongly affected by cement content than MOR (Sorfa 1984; Moslemi and Pfister 1987). The low cement content of wood-wool cement boards is likely to have limited the extent to which stiffness could be increased by the addition of cement-setting accelerators.

When using pre-soaked wood-wool for board manufacture the addition of many of the accelerators, including $SnCl_4$ and $Al_2(SO_4)_3$, became unnecessary and resulted in little improvement in board strength. In fact increasing the quantity of $SnCl_4$ added to pre-soaked wood-wool resulted in decreases in board strength possibly because this accelerator is highly acidic and may have adversely affected the tensile strength of wood-wool. Provided the wood is relatively free of inhibitory heartwood tannins, simple, inexpensive accelerators based on $CaCl_2$ can be among the most effective compounds at improving board strength properties. Cabangon et al. (1998) also found that pre-soaked *A. mangium* wood-wool responded particularly well to conventional cement-setting accelerators ($CaCl_2$, $Al_2(SO_4)_3$ and $FeCl_3$), producing stronger boards than those manufactured from eucalypt (*Eucalyptus pellita* F. Muell.) or poplar (*Populus euramericana* L.) wood.

An interesting and unexpected result that was not related to the original hypothesis of this study, was that certain combinations of accelerators used with pre-soaked wood-wool produced boards exceeding the minimum MOE of 3000 MPa specified in ISO 8335 for high cement-content cement bonded particleboard. This could not be achieved using soaked wood-wool in combination with any individual compound. The average MOE for boards made from soaked wood-wool and containing the combinations $SnCl_4$ 0.05 M + $MgCl_2$ (0.05 M) and $Al(NO_3)_3$ (0.5 M) + $MgCl_2$ (0.05 M) were 3178 and 3109 MPa, respectively. This is a noteworthy finding which supports the suggestion of Sorfa (1984) that small quantities of selected accelerators can greatly improve the mechanical properties of low-cement-containing composites such as wood-wool cement boards, potentially giving lower-density composites similar mechanical properties to those containing much higher quantities of cement, such as cement-bonded particleboard.

CONCLUSIONS

1. Wood-wool cement boards with enhanced physical properties can be made from the heartwood of *A. mangium* by pre-treating wood-wool with an inorganic compound such as tin chloride (3.65% w/w cement) or ferric chloride (2.8% w/w cement) that can chelate phenolic extractives and accelerate cement hydration.
2. The combination of an accelerator such as tin chloride (~1% w/w cement) with the ability to chelate phenolic extractives and a conventional accelerator (magnesium chloride, 1% w/w cement) was particularly effective at improving the strength properties of wood-wool cement boards made from the heartwood of *A. mangium*.
3. Conventional cement-setting accelerators such as calcium and magnesium chloride (~1.5 to 2.0 w/w cement) were very effective at improving the properties of wood-wool cement boards made from *A. mangium*, provided the wood-wool was pre-soaked in water to remove phenolic extractives.
4. Our findings have the potential to simplify the manufacture of wood-wool cement boards from *A. mangium* by eliminating the need to pre-soak the wood-wool in water prior to mixing it with cement, and may have broader relevance to the manufacture of wood-wool cement boards from other hardwood species containing phenolic extractives.

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