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Manufacture and properties of oil palm frond cement-bonded board

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Abstract This study was designed to reveal the role of the cement/wood ratio in a hydration test of wood-cement mixtures. The compatibility of oil palm (*Elaeis guineensis* Jacq) fronds–cement mixtures was tested in the hydration test, with the addition of magnesium chloride as an accelerator at different water/cement ratios. To prove the findings on the hydration behavior of components, the cement-bonded boards were manufactured using a conventional cold-pressing method at different cement/wood ratios. Results indicated that the optimum weight ration of cement/wood increased with decreasing wood powder size based on the equal specific surface area ratio of cement/wood in the hydration test and board manufacturing. The addition of magnesium chloride improved the compatibility of oil palm fronds with cement; the compatibility factor (C_A) increased by more than 90% with the addition of 5% magnesium chloride. The C_A factor increased proportionally with a higher magnesium chloride content and a higher water/cement ratio. The addition of magnesium chloride also enhanced the cement hydration and ultimate board strength properties. However, the addition of 5% magnesium chloride did not improve the properties of boards sufficiently at a cement/wood ratio of 2.2:1.0.

Key words Cement-bonded particleboard · Oil palm fronds · Accelerator

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Introduction

During the cultivation and production of oil palm, the industry generates a number of by-products and residues, which are neither recycled nor converted to value-added products at present. Studies have shown the possibilities of the effective utilization of oil palm vascular bundles from empty fruit bunch (EFB) and fronds as cellulosic raw materials in the production of cement-bonded board.[1,2] Additional research, however, is necessary to improve the compatibility of such materials with cement because of the highly species-sensitivity of the wood–cement–water system.[3–10]

Hydration characteristics of cement have been commonly used to assess the compatibility of cement with potential lignocellulosic materials. It is known that in the presence of water the cement compound (i.e., silicates and aluminates) form products of hydration, which in time produce a firm, hard mass: hardened cement paste. This hydration process is an exothermic reaction.[11] When using portland cement as a binder, the exothermic behavior depends on the species being tested. Therefore, such compatibility can be expressed in terms of the cement hydration data when mixed with a given wood species. It is clear that the more compatible a given species is with cement, the more similar is the hydration of the wood–cement–water mixture to that of neat cement (cement without wood particles). Research has demonstrated that the cement/wood weight ratio and the particle size of wood have a significant effect on the hydration data and on the bending and compressive strength of wood–cement particleboard.[3,12]

The objective of this study was to develop a manufacturing technology of cement-bonded board using fronds of oil palm. For the purpose of this study, basic analyses of cement hydration and the compatibility of fronds with cement were conducted. The mechanical and dimensional properties of oil palm cement-bonded board manufactured by a conventional cold-pressing method were then investigated under various conditions.

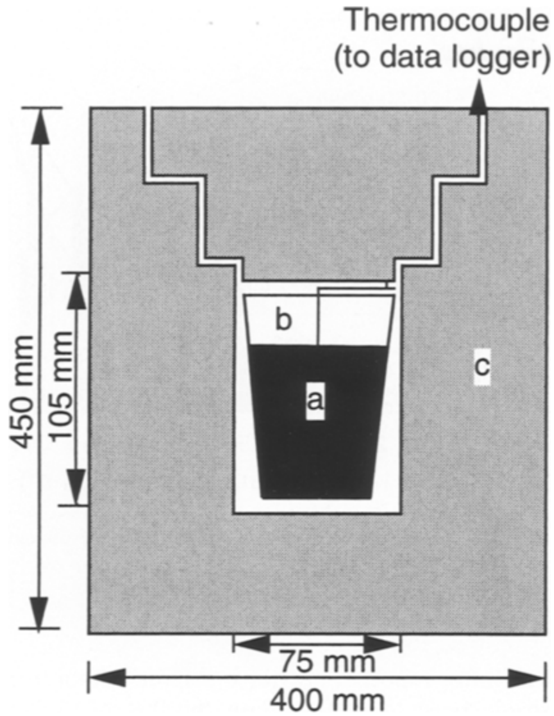

Fig. 1. Apparatus for measuring the hydration temperature. *a*, cement mixture paste; *b*, polyethylene cup; *c*, styrene foam

Materials and methods

Hydration temperature of cement mixed with oil palm fronds

The materials used were frond vascular bundles of oil palm (*Elaeis guineensis* Jacq), ordinary portland cement (Osaka Sumitomo Co.), and magnesium chloride ($MgCl_2$). Frond vascular bundles were cut at average lengths, diameters, and weights of 15.0mm, 0.78mm, and 4.06 10^{-3}g, respectively. The frond particles were then hammer-milled and subsequently screened using different mesh sizes: 20 pass/30 on; 30 pass/50 on; 50 pass/80 on; 80 pass/100 on; and 100 pass. The distributions of particle diameters on the various meshes were measured following a light-dispersion method using particle size analysis of Nikkiso MK II.

Magnesium chloride was added to each mixture in the range of 0%–15% based on cement weight. The mass water/cement ratios were 0.4, 0.5, and 0.6, respectively.

The hydration temperature was measured in an insulated box, as shown in Fig. 1. A thermocouple wire was inserted approximately at the center core of the cement paste and connected to a data logger. All the experiments were conducted at ambient room temperature.

The compatibility of oil palm fronds with cement was evaluated using the C_A factor calculation method.[8]

Manufacturing cement-bonded board

Frond vascular bundles of oil palm cut to an average length of 15.0mm with ordinary portland cement as a binder and $MgCl_2$ as an accelerator were used to manufacture cement-bonded board. Boards with a target density of 1.2 g/cm^3 were manufactured at cement/oven-dried particles/water weight ratios of 2.2:1.0:1.32 and 2.7:1.0:1.62, respectively. The 300 $\times$ 300mm hand-formed mats were cold-pressed to a target thickness of 12mm and kept in an oven for 24h at 60°C. Boards were then wrapped with polyvinylchloride (PVC) sheet immediately after clamping and left for 2 weeks at room temperature followed by placing then in an oven for 10h at 80°C. They were then conditioned at ambient temperature prior to further testing. Three replications were made for the bending test with samples of 210 $\times$ 50 $\times$ 12mm. Five replicates were made for internal bonding and thickness swelling tests at a size of 50 $\times$ 50 $\times$ 12mm. The mechanical and dimensional properties of the boards were tested in accordance with the Japan Industrial Standard JIS A 5908.

Results and discussion

Hydration temperature of cement mixed with oil palm fronds

Taking into account the clear definition of the cement/wood weight ratio, a new calculation method was developed based on the weight of cement as a binder per unit surface area of wood powder in the hydration test equal to that of wood particled during board manufacture. Because the size of the wood powder is much smaller than that of wood particles, the specific surface area of wood powder (S_{pw}) is larger than the specific surface area of wood particles (S_p). Therefore, the relation between the cement/wood weight ratios in the hydration test (WR_1) and during board manufacture (WR_2) is determined by the following equation:

$$WR_1 = WR_2\left[\frac{S_{pw}}{S_p}\right] \tag{1}$$

$$WR_1 = WR_2\left[\frac{A_{pw}}{A_p}\right]\left[\frac{W_{up}}{W_{upw}}\right] \tag{2}$$

where, S_{pw} is the specific surface area of wood powder in the hydration test; S_p is the specific surface area of the wood particles during board manufacture; A_{pw} is the surface area of the wood powder; A_p is the surface area of the wood particles; W_{upw} is the weight of a unit of wood powder; and W_{up} is the weight of a unit of wood particles.

For the oil palm fronds, in which the area of wood powder and wood particle are assumed to be spherical and cylindrical, respectively, the developed formula can be modified as follows:

$$WR_1 = WR_2\left[\frac{4\pi r^2{}_{pw}}{2\pi r_p l + 2\pi r_p^2}\right]\left[\frac{W_{up}}{W_{upw}}\right] \tag{3}$$

where r_p is the radius of the particles; r_{pw} is the radius of the powder; and l is the length of the particles.

Table 1. Average diameter of frond powder and cement requirement for hydration test

No.	Powder size (mesh)	Average diameter (μm)	WR_1	
			WR_2 (2.2)	WR_2 (2.7)
1	20 pass/30 on	420	5.6	6.9
2	30 pass/50 on	421	5.6	6.9
3	50 pass/80 on	316	7.5	9.2
4	80 pass/100 on	178	13.3	16.4
5	100 pass	122	19.3	23.8

WR_1, cement/wood weight ratio in hydration test; WR_2, cement/wood weight ratio during board manufacturing

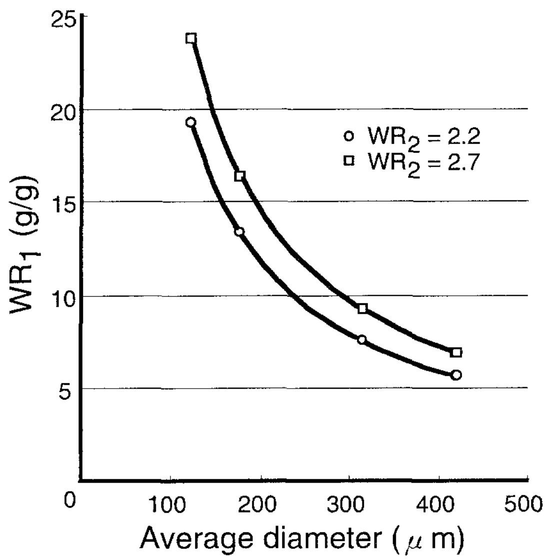

Fig. 2. Effect of varying wood powder size on the mixing ratio. WR_1, WR_2, weight ratios of cement/wood in hydration test and board manufacturing, respectively

Table 1 shows the optimum WR_1 with various wood powder sizes. The WR_1 increased with the decreasing wood powder size, as is true for the inhibitory index (I) of wood materials shown by Weatherwax and Tarkov.[3] A strong correlation appeared to exist between the average diameter of wood powder and WR_1, as shown in Fig. 2. To confirm the validity of the data obtained, the cement/wood weight ratio in the hydration test should be adjusted to the wood powder size and cement/wood weight ratio during board manufacturing.

The powder size of 80 pass/100 on mesh was chosen to calculate the WR_1 in the hydration test of the frond–cement mixtures. WR_1 has also been calculated based on the average length and diameter of frond fibers of 15 mm and 0.78 mm, respectively, and a WR_2 of 2.2 based on the previous research on cement-bonded particleboard manufacturing.[13] The 80 pass/100 on mesh had a uniform volume distribution of the average-diameter frond powders, as shown in Fig. 3.

A WR_1 of 13.3 was an explicable ratio in the hydration test method of the cement-frond mixtures, especially with a frond powder size of 80 pass/100 on, which is in the mesh

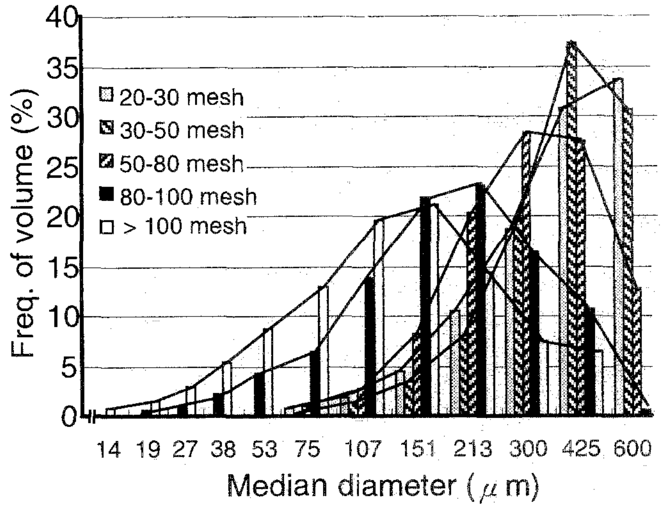

Fig. 3. Volume distribution of average (median) diameter of wood powder

size range reported previously.[3] Even with a frond powder size increase to 50 pass/80 on, the WR_1 of 13.3 remained at reasonable levels, as the maximum hydration temperature was negligible, with cement/wood ratios of 13:1 and 7:1. It was drastically reduced when the cement/wood ratio decreased to 4:1.[12] In contrast, the effect of species and treatment on hydration behavior can be overshadowed, particularly when an effective agent is added to the mixture at a higher cement/wood ratio.[14]

Compatibility of oil palm fronds with cement

The hydration temperatures of the cement–frond mixtures with addition of $MgCl_2$ at different water/cement ratios are shown in Fig. 4. The hydration temperature curve for cement without $MgCl_2$ indicates that cement hydration is retarded when the fronds are present. The maximum hydration temperature (T_{max}) was less than 40°C, and the compatibility factor (C_A) was less than 31%, as shown in Table 2. The exothermic reaction of the cement mixtures did not occur at water/cement ratios of 0.4 and 0.6 when $MgCl_2$ was not added. This showed that oil palm frond could not be used solely as the raw material for cement-bonded board owing to its inhibitory effect on cement hydration due to the inherent extractives of the materials. In addition, cement needs an optimum volume of water for hydration. A small amount of water would produce a stiff material that is not easy to mix, and excess water would dilute the cement constituents, resulting in a maximum temperature decrease. The retardation of cement hydration became more pronounced at the highest water/cement ratio. The T_{max} was about 25°C and less than 2% of the C_A factor. Water- and alkali-soluble extractives have been suggested for lowering the hydration temperature of the cement–water system.[15]

Addition of $MgCl_2$ accelerates the hydration reaction of mixtures and subsequent increases the compatibility of fronds with portland cement. The addition of 5.0% $MgCl_2$

Table 2. Effect of $MgCl_2$ on hydration characteristics of frond–cement mixtures at three water/cement ratios

No.	$MgCl_2$ (%)	T_{max} (°C)			Time (h)			C_A factor (%)		
		0.4	0.5	0.6	0.4	0.5	0.6	0.4	0.5	0.6
1	0	27.5	39.3	25.1	1.25	0.50	0.50	10.1	30.9	1.6
2	5.0	71.7	75.4	68.5	3.25	4.50	5.75	90.4	113.8	121.7
3	7.5	75.4	85.7	82.8	2.75	2.00	3.25	106.9	103.0	137.7
4	10.0	73.6	89.2	91.5	1.50	1.75	2.00	95.4	105.6	145.0
5	15.0	69.0	86.5	92.3	1.00	1.00	1.25	72.8	84.7	110.9

The 0.4, 0.5, and 0.6 represent water/cement ratios
T_{max}, maximum temperature; Time, time to reach T_{max}; C_A, compatibility (%)

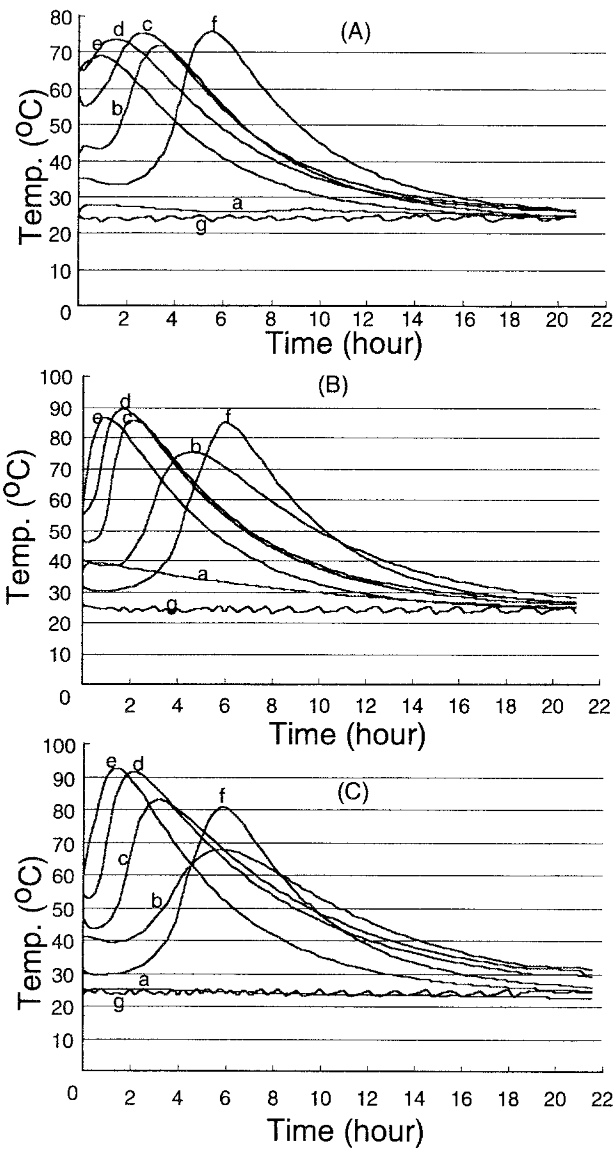

Fig. 4. Hydration temperature of cement mixed with fronds using accelerator $MgCl_2$. **A** Water/cement ratio is 0.4. **B** Water/cement ratio is 0.5. **C** Water/cement ratio is 0.6. *a*, no $MgCl_2$; *b*, 5.0% $MgCl_2$; *c*, 7.5% $MgCl_2$; *d*, 10.0% $MgCl_2$; *e*, 15.0% $MgCl_2$; *f*, neat cement; and *g*, room temperature

improved the C_A factor to 90.43% within 3.25h with a T_{max} of 71.7°C at a water/cement ratio of 0.4. The highest C_A factor was achieved at 7.5% $MgCl_2$ addition within 2.75h with a T_{max} of 75.4°C. The amount of $MgCl_2$ increased from 7.5% to 15.0% as the C_A factor decreased.

The C_A factor was increased to 113.8% at a water/cement ratio of 0.5 when 5.0% of $MgCl_2$ was added. However, the C_A factor decreased at this water/cement ratio when the amount of $MgCl_2$ increased to 15.0%. The highest T_{max} (89.2%) was recorded at 1.75h and 10.0% $MgCl_2$ addition.

The C_A factor increased with increasing amount of $MgCl_2$ at a water/cement ratio of 0.6 when up to 10.0% of $MgCl_2$ was added. Meanwhile, the C_A factor was decreased when 15.0% $MgCl_2$ was added. The T_{max} reached a high level with increasing amounts of $MgCl_2$.

At the same level of $MgCl_2$ addition, the C_A factor increased proportionally with higher water/cement ratios. For instance, the addition of 5.0% $MgCl_2$ improved the C_A factor up to 90.43%, 113.80%, and 121.67% at water/cement ratios of 0.4, 0.5, and 0.6, respectively; and T_{max} values were 71.7°, 75.4°, and 68.5°C, respectively. The highest T_{max} was reached when $MgCl_2$ concentrations of 7.5%, 10.0%, and 15.0% were added at water/cement ratios of 0.4, 0.5, and 0.6, respectively.

In general, it took longer to reach T_{max} at high water/cement ratios at the same level of $MgCl_2$ addition. In contrast, the time to reach T_{max} shortened with increasing amounts of $MgCl_2$ at the same water/cement ratio.

A preliminary study indicated that the addition of sodium hydrocarbonate ($NaHCO_3$) or its combination with various amounts (0%–7.5%) of $MgCl_2$ did not improve sufficiently the C_A factor of frond–cement mixtures. A similar trend was also observed when combining $MgCl_2$ with sodium silicate (Na_2SiO_3). However, the hydration reaction rate appeared to be accelerated effectively by $MgCl_2$, as the addition of 5.0% $MgCl_2$ resulted in a T_{max} of 75.4°C within 4.5h at a water/cement ratio of 0.5. It is known that chlorides react with tricalcium aluminate in cement, forming calcium hydrochloroaluminate ($3CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O$).[16,17] The suitability of hydrochloroaluminate in water is greater than that of ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_20$). Moreover, the grains of minerals in cement are surrounded by a more permeable layer than that in neat cement, and the reactions at the beginning are intensified.[15–17] These reactions liberate a large amount of heat.

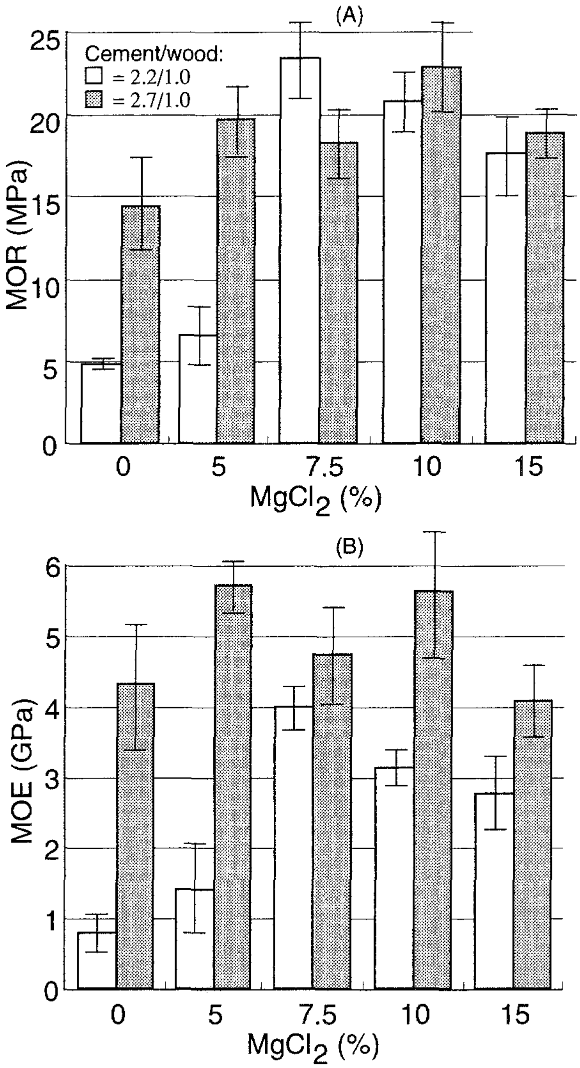

Fig. 5. Bending properties of various boards. **A** Modulus of rupture (MOR). **B** Modulus of elasticity (MOE). Bars show the standard deviation in Figs. 5–7

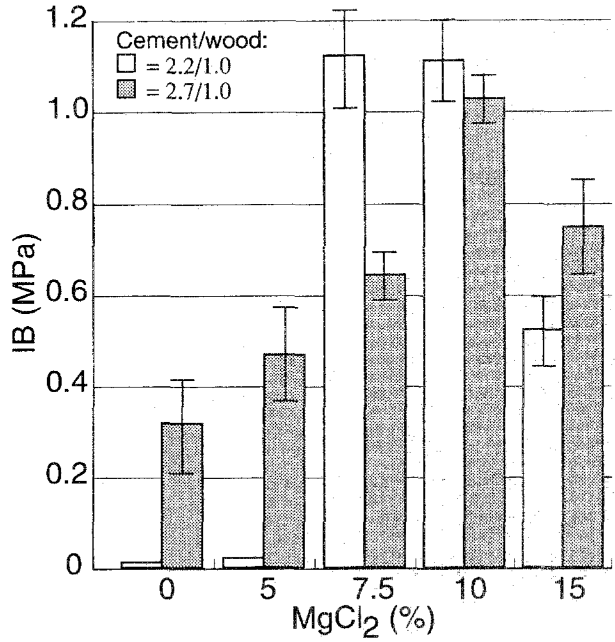

Fig. 6. Internal bond (*IB*) strengths of various boards

Properties of cement-bonded board from oil palm fronds

The results showed that the bending properties of boards improved significantly after adding $MgCl_2$. The moduli of rupture (MOR) and elasticity (MOE) increased with increasing amounts of $MgCl_2$ to a maximum, followed by a decline, as shown in Fig. 5.

The improvement effect of $MgCl_2$ was more prominent at a cement/wood ratio of 2.2:1.0 than at 2.7:1.0, especially when the $MgCl_2$ addition was increased from 5.0% to 7.5%. At this level of $MgCl_2$ addition, the MOR increased to 23.3MPa from 6.5MPa, coincident with an increase in the MOE to 4.0GPa from 1.4GPa. Even though the $MgCl_2$ was not added to the cement–wood mixtures, the bending properties at a cement/wood ratio of 2.7:1.0 were significantly higher than that at 2.2:1.0. This fact suggests that the potential inhibitory effect of wood extractives could be overshadowed at a high cement/wood ratio.

The improvement effect of $MgCl_2$ on the strength properties of boards might be due to the suitable alkalinity of $MgCl_2$. The alkalinity of $MgCl_2$ could not be expected to trigger dissolution of the inhibitory extractives but, rather, to enhance the hydration reaction of cement and the substantial strength development of board.

A similar trend was observed for internal bond (IB) strength, where the $MgCl_2$ had a favorable effect on the board. The acceleration effect of $MgCl_2$ could also produce high bondability of cement, as reflected in the high IB strength shown in Fig. 6. However, the addition of 5% $MgCl_2$ did not improve the IB strength at a low cement/wood ratio. Boards without accelerator and with 5% $MgCl_2$ showed properties inferior to those of other boards, implying that the inhibitory substances of the fronds adversely affected the strengthening of cement.

The IB value increased drastically to 1.1MPa when 7.5% $MgCl_2$ was added. In general, the addition of $MgCl_2$ up to 10% resulted in an optimum IB strength at both low and high cement/wood ratios. An adverse effect was observed after addition of 15% $MgCl_2$. Rapid acceleration of the hydration reaction led to improper mixing and forming of the mixtures. Thus, the wood particles were not completely covered with cement because part of the cement had already hardened during the mixing process, resulting in low IB strength.

The thickness swelling (TS) of the board after 24h of soaking in water is shown in Fig. 7. The boards, without accelerator and with 5% $MgCl_2$, had high TS values at a low cement/wood ratio. This characteristic might be due to the compounding effect of low IB strength. The TS was markedly improved when 7.5% $MgCl_2$ was added. In addition, the TS was further increased when the $MgCl_2$ addition was increased from 7.5% to 15.0% because of the swelling effect of magnesium and wood particles.

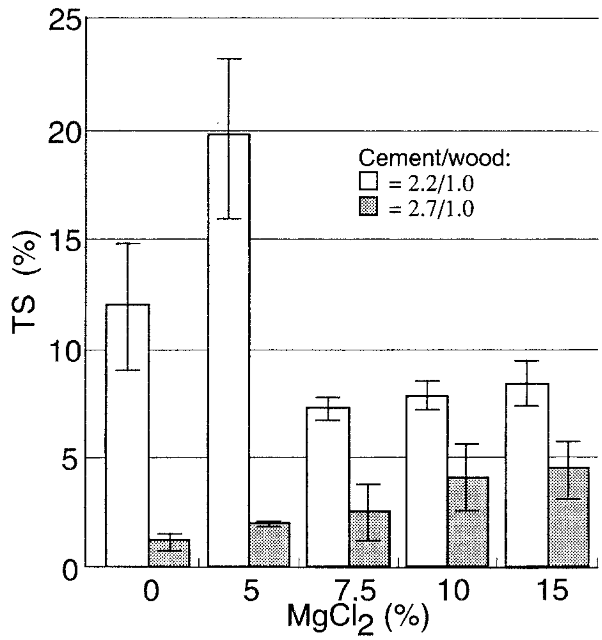

Fig. 7. Thickness swelling (*TS*) of various boards

Conclusions

The surface area ratio of cement and wood particles affects the hydration behavior of wood–cement mixtures. The smaller the size of wood powder, the higher are the values of the optimum cement/wood weight ratio.

The hydration of cement paste was retarded by addition of oil palm fronds. This situation could be improved by adding $MgCl_2$ in a specific water/cement ratio. As the water/cement ratio increases, the amount of $MgCl_2$ to reach the maximum hydration temperature was increased; the highest T_{max} was achieved at 7.5%, 10.0%, and 15.0% $MgCl_2$ at water/cement ratios of 0.4, 0.5, and 0.6, respectively.

The mechanical and dimensional properties of cement-bonded board produced by a conventional method improved when $MgCl_2$ was added as an accelerator. The minimum requirement of an accelerator depends on the cement/wood ratio being applied. At a low cement/wood ratio, the addition of 5% $MgCl_2$ did not improve the properties of boards owing to the large amount of oil palm particles. The mechanical properties improved significantly when 7.5% $MgCl_2$ was added at both low and high cement/wood ratios. The addition of $MgCl_2$ has enhanced the hydration reaction of cement and hence the board strength properties.

References

1. Singh G (1994) Management and utilization of oil palm by-products. In: Proceeding 3rd national seminar on utilization of oil palm tree and other panels, Malaysia, September 27–29
2. Teck CL, Khoo KC, Rahim S, Kozirah S (1991) Oil palm stem utilization: review of research. FRIM Res Pamphlet 107:35–50
3. Weatherwax RC, Tarkov H (1964) Effect of wood on setting of portland cement. For Prod J 14:567–570
4. Weatherwax RC, Tarkov H (1967) Effect of wood on the setting of portland cement: decay wood as an inhibitor. For Prod J 17(7):30–32
5. Biblis EJ, Chen FL (1968) Sugar and other wood extractives; effect on the setting of southern pine-cement mixtures. For Prod J 18(8):28–34
6. Zhengtian L, Moslemi AA (1986) Effect of western larch extractives on cement setting. For Prod J 36(1):53–54
7. Hachmi MH, Moslemi AA (1989) Correlation between wood-cement compatibility and wood extractives. For Prod J 39(6):55–58
8. Hachmi MH, Moslemi AA, Chambell AG (1990) A new technique to classify the compatibility of wood with cement. Wood Sci Technol 24:345–354
9. Moslemi AA, Lim YT (1984) Compatibility of southern hard woods with portland cement. For Prod J 34(7):22–26
10. Hofstrand AD, Moslemi AA, Garcia JF (1984) Curing characteristics of wood particle from nine northern rocky mountain species mixed with portland cement. For Prod J 38:57–61
11. Neville AM (1981) Properties of concrete. Wiley, New York
12. Lee AWC, Hong Z, Phillips DR, Hse CY (1987) Effect of cement/wood ratio and wood storage condition on hydration temperature, hydration time, and compressive strength of wood-cement mixtures. Wood Fiber Sci 19:262–268
13. Nagadomi W, Kuroki Y, Kawai S, Sasaki H (1996) Rapid curing of cement-bonded particleboard with silica fume II. Mokuzai Gakkaishi 42:202–210
14. Lee AWC, Hong Z (1986) Compressive strength of cylindrical sample as an indicator of wood-cement compatibility. For Prod J 36(11/12):87–90
15. Eusebio DA, Yamauchi H, Sasaki H, Kawai S (1996) Bark-cement composites. In: Proceedings of the first international wood science seminar, Kyoto, December 6–7
16. Stein HN (1961) Influence of some additives on the hydration reaction of portland cement. J Appl Chem 11:474–482
17. Taylor HFW (1964) The chemistry of cement, vol 1. Academic, London