Manufacture of Bamboo-Cement Particleboard

by

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Abstract

The hydration temperature and hardness of mixtures of bamboo (*Phyllostachys heterocycla* Mitf. var. *pubescens* Ohwi) powders and cement were examined. The inhibitory index **I** and compatibility factor C_A were determined. Extraction of bamboo chips by cold water, hot-water and 1% NaOH solution can moderate the inhibitory effects in the hydration reaction of bamboo-cement mixture.

The hydration rates of cement in bamboo-cement particleboards produced by cold pressing, steam injection pressing or hot pressing method were investigated by TG-DTA and X-ray powder diffractometry XRD, scanning electron microscope SEM. Board properties were tested according to the Japan Industrial Standards JIS A 5908. The effects of some additives on the hydration of bamboo cement mixture and the hardness of the cured paste were studied. The additives were, sodium hydrogen carbonate, sodium silicate, calcium chloride, and magnesium chloride. The rise in hydration temperature with respect to time varied depending on the additive used. Larger amounts of additives resulted to higher values of hydration temperature peaks T_{max}. Based on the hydration temperature, magnesium chloride and calcium chloride improved the compatibility of bamboo powder and cement. High correlations between Tmax or the compatibility factor C_A and the modulus of rupture MOR of bamboo-cement Particleboard (CBC) were observed.

The yields of $Ca(OH)_2$ resulting from the hydration of cement clinkers were estimated from the XRD and TG-DTA analyses. There were high correlations between the mechanical properties of CBC and the XRD intensity of the cement clinker and C_3S, the weight losses at 200°C and 900°C under TG-DTA, and the estimated yield of $Ca(OH)_2$. From these relationships, the mechanical properties of CBC using carbonates as additives might be predicted.

Where the flexural properties were concerned, the optimum bamboo/cement ratio was estimated to be 2.6 at the water cement ratio of 0.6 when the steam injection pressing method was employed. Hot pressing time affected the hydration of cement. In the range of 3 min to 21 min, long hot pressing times resulted in the improvements of CBC properties. CBC properties were markedly improved at 100°C heat treatment temperature than at 60°C or 80°C. The final properties of CBC were related with their initial strength and hydration degree (strength and hydration degree, respectively, immediately after hot pressing). The optimum conditions of manufacture of CBC by hot pressing were: addition of 15% Na_2SiO_3 based on cement weight, substitution of 5% cement with silica fume, 11 min hot pressing at 110°C, 24hr heat treatment at 100°C.

Keywords: Bamboo, *Phyllostachys heterocycla*, cement-bonded Particleboard, cement hydration, steam injection press

1. Introduction

China has an abundant stock of economic or commercial tree species, but the forest area and growing stock of wood *per capita* is less than one third of the world average. The contradiction of a country with wide forest area but less forest is brought about by its great population. Its imperative, therefore, to develop new sources of materials as alternative to wood. Bamboo is one the major non-wood forest resources in China. Of the more than 50 genera of bamboo in the world, about 26 genera and over 300 species grows in three dispersal and growing regions.[1] Although there are some plants manufacturing bamboo plywood and other construction materials in the country, the consumption is relatively low and new technologies and/or products are needed.

Inorganic bonded Particleboard, especially cement-bonded Particleboard CBC is one possible application of bamboo as raw material. Rapid curing of CBC can be achieved with the steam injection pressing method.[2] However, too fast curing or abrupt formation of carbonates and silicates have certain problems. Complete cement hydration can not take place and the long term strengths of the resulting boards are low. The mechanism of cement hydration in relation to time, temperature and raw material ratios should be clarified to determine the optimum economical conditions of manufacture of CBC. In this report various studies on the manufacture of CBC using bamboo as raw materials are presented. The effect of bamboo extractives, pre-treatment method, pressing methods (cold press, hot press, steam injection press), pressing (time, temperature) conditions, additive type and amount, and post treatments on the hydration of cement and the properties of bamboo CBC are summarized. The tools used were X-ray diffraction XRD, Thermo-gravimetric differential thermal analysis TG-DTA, scanning electron microscope SEM, and property test following the Japanese Industrial Standards.

1. Hydration characteristics of bamboo-cement mixtures

The hydration temperature and hardness of mixtures of bamboo and cement were examined. The bamboo splices were divided into three parts along the thickness direction (outer, middle and inner layers) after the nodes were removed. These were then cut to chips and ground to powder. Those passing #40 mesh screen were used in the measurement of hydration temperature and Brunell hardness. Neat cement paste or bamboo powder-cement mixtures were mixed thoroughly in a polyethelyne cup then enclosed in an insulated container. The weight ratio of cement/water/bamboo was 200/100/15. The temperatures at the core of the mixtures were measured continuously for 50 hrs with a thermocouple. The hardnesses (Brunell) of the mixtures after 28 days were tested in a universal testing machine. The inhibitory index[3] and compatibility factor[4,5] for each mixture were determined. The inhibitory characteristics of the different parts of bamboo to cement were evaluated.

The hydration temperatures of neat cement pastes and cement mixed with ground powders from different parts of bamboo are graphed against time in Fig. 1. The presence of inhibitors to cement setting is indicated by the lower hydration temperature peaks of bamboo-cement mixtures compared to neat cement peaks. The inhibitors are mostly contained in the inner or middle layers and in the node. Although the total heat releases in neat cement pastes and cement-inner layer mixtures are almost the same, the hydration rate was slower in the later. Results in the hardness tests of the mixtures after 28 days confirmed the incomplete hydration on bamboo-cement mixtures. The hardness of cement-inner layer mixture (5.8 kgf/cm^2) was only 1/2 of that of neat cement paste (11.6 kgf/cm^2) while those of the rest of mixtures containing bamboo were less than 1 kgf/cm^2.

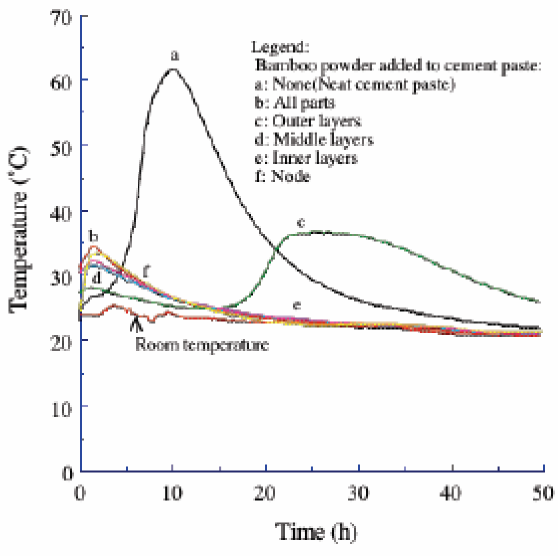

Fig. 1. Hydration temperature of neat cement paste and cement pastes mixed with powders ground from different parts of bamboo.

Bio-treatment (3day-, 30day-mold exposure; 30day fermentation) possibly degraded some of the inhibitors since the hydration peak temperatures increased although these were still much lower and the hydration rate was slower than that of neat cement paste. The hardnesses of 28-day cured mixtures were also higher (6 - 10 kgf/cm^2) compared to mixtures of cement and untreated bamboo powder. Eight-hour extraction with cold water, hot (boiling) water, or 1% aqueous solution of NaOH (boiling) showed the same improved results. However the hardnesses were less at 3 -

5.8kgf/cm^2. [5)]

The compatibility factors of outer (18%), middle (13%), and inner (14%) layers of bamboo, increased to 42% after 30-day fermentation, to 45% after 30-day mold exposure, and to 55%, 65% and 66% after extraction with 1%NaOH, cold water, and hot water resp., (Note: C_A of neat cement paste = 100%). The inhibitory indices of untreated bamboo outer layer was 31 (I of neat cement paste = 0), and it decreased to 6, 9 and 11 after extraction with hot water, cold water and 1% NaOH, respectively.

Cold pressed (20h, 25°C) bamboo-cement Particleboard manufactured using particles (L=25mm, W=1mm, t=0.5mm) from untreated whole or inner layers of bamboo, and those exposed to mold for three days resulted to unstable boards. Thirty day fermentation or exposure to mold resulted to better boards whose MOR were 162 kgf/cm^2 and 91kgf/cm^2, MOE were 2.75 tf/cm^2 and 1.96 tf/cm^2, and IB were 4.5kgf/cm^2 and 2.3 kgf/cm^2, respectively.[5)]

2. Effects of additives on hydration of bamboo-cement mixtures

The effects of some additives on the hydration temperature and hardness of mixtures of bamboo and cement with some additives were studied. The additives were sodium hydrogen carbonate ($NaHCO_3$), sodium carbonate (Na_2CO_3), sodium silicate (Na_2SiO_3), calcium chloride ($CaCl_2$), and magnesium chloride ($MgCl_2$). The values of compatibility factor and inhibitory indices were also calculated. The properties of cold pressed (20h press time, 25°C) bamboo-cement Particleboard were tested. Raw materials were portland cement, bamboo semiflakes (L=25mm, W=3mm, t=0.4mm) prepared with a ring flaker, and the additives mentioned above.

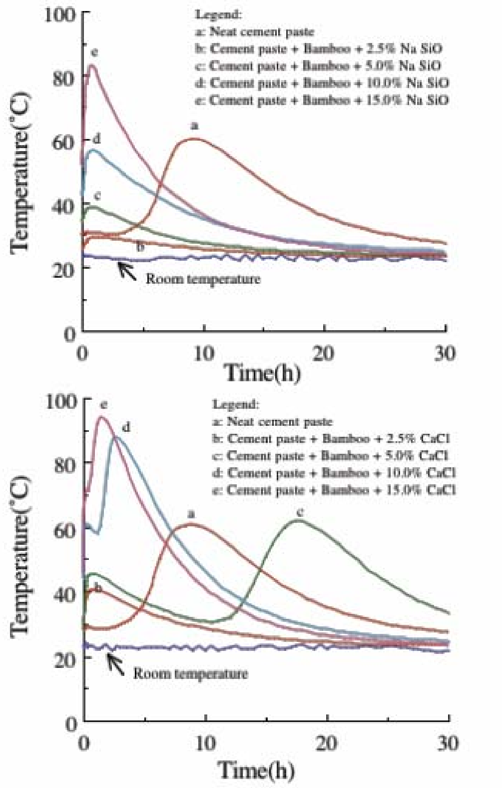

Fig. 2. The effect of Na SiO or CaCl addition on the hardness and hydration temperature of cement/bamboo mixtures.

The rise in the hydration temperature with respect to time varied depending on the additive used. In general, larger amounts of additives resulted to higher values of hydration temperature peaks (Tmax). Fig. 2 is an example of the relationship between the amount of additive and the hydration temperature of the mixtures or the hardness of 28-day cured pastes, in this figure the additives were sodium silicate or calcium chloride. The same trends were exhibited in the bamboo cement mixtures with sodium hydrogen carbonate and sodium carbonate additives although the peak temperatures and 28-day hardness varied depending on the amount and type of additive. Based on the hydration temperature, magnesium chloride and calcium chloride improved the compatibility of bamboo powder and cement. Higher peak temperatures and hardness values were observed when $CaCl_2$ or $MgCl_2$ were used as additives.

The properties of the bamboo-cement pastes (hardness, Tmax, C_A-value, I-value) and of the cold pressed bamboo-cement Particleboard (board density, MOR, MOE, and IB) are summarized in Table 1. There were high correlations between the peak temperature Tmax or the compatibility factor C_A and the modulus of rupture MOR of cement-bonded bamboo Particleboard as shown in Fig. 3.

3. Hydration characteristics and properties of bamboo-cement Particleboard manufactured by Steam Injection Pressing

Bamboo-cement Particleboard (300 x 300 x 9mm) were manufactured from ordinary portland cement and 6-year old mousou bamboo grown in a bamboo plantation in Uji-shi, Kyoto, Japan. Semiflakes were prepared with average dimensions of L=25mm, W=3mm, and t=0.4mm using a ring flaker. Additives used were sodium carbonates ($NaHCO_3$, Na_2CO_3) or their combinations with $MgCl_2$. The boards were pressed using the steam injection pressing technique[7)] in a sealed-system steam injection press at the Institute of Wood Technology, APCA. Unsaturated steam was injected on both surfaces of the

Table 1. Effects of various additives on the properties of cold pressed bamboo-cement Particleboards and values of I, CA, and Tmax. (cement:bamboo:water = 2.2:1.0:1.32)

Additive	Additive content %	Cement-bonded composite				Cement/bamboo paste			
		Ovendry density kg/m^3	MOR kgf/cm^2	MOE kgf/cm^2	IB kgf/cm^2	I-value %	C_A-value %	Tmax °C	Hardness kgf/mm^2
$NaHCO_3$	2.5	Unstable board					10	29.9	0
	5	Unstable board					17	31.6	0
	10	903	26.2				30	40.6	3.7
	15	1,026	40.2				51	50.8	4.9
	20	1,155	97.8	21,318	1.5		81	73.9	1.8
Na_2CO_3	2.5	Unstable board				13	24	35	0.3
	5	Unstable board				48	25	30.1	5.8
	10	889	11.4				28	37.6	4.9
	15	910	12.2				33	45.1	3.8
	20	1,111	56.8				72	51.7	3.8
Na_2SiO_3	2.5	Unstable board					10	29.4	0.1
	5	Unstable board					26	38.5	4.7
	10	1,100	44.6				52	56.4	5.9
	15	1,295	147.6	34,427	5.6		64	83.1	2
$CaCl_2$	2.5	Unstable board					22	40.7	9.7
	5	963	27.4			-0.2	99	61.8	9.9
	10	1,095	135.6	39,025	4.1	-49	107	88	9.9
	15	1,250	172.4	44,385	6.6	-95	88	94.3	6.4
$MgCl_2$	2.5	952	24.6			0.1	83	61.3	9.7
	5	1,029	57.2			-0.2	120	73	11.2
	10	1,212	138	42,234	4.4		115	90.7	5.9
	15	1,165	87.2	28,258	2.6		88	88.3	7.6

formed mats. Total press time was 11 minutes at 110°C hot press temperature, including 5-second steam injection at 1.5kgf/cm² steam pressure. The boards were immersed in water (20°C) for 14 days after pressing, dried at 80°C for 6hrs until the moisture content was reduced to 10-15%, then conditioned for one week at 20°C, 65%RH. Board properties were tested according to JIS A 5908.

Powdered samples passing 125*mm* taken from bending test specimens were examined by X-ray diffraction XRD (MO3X-HF). Step scan measurements were done using X-ray (Cu-Kα) at 40kV and 20 mA, 2θ ranged from 5.0 to 60.0 deg, at 0.02 deg scanning steps and 4 deg/min. Comparisons of the amounts unreacted clinker taken at 2θ = 32.3, 32.7, and 34.5 deg[8]; $Ca(OH)_2$ at 2θ=18.2 deg[9]; and C_2S at 2θ=51.7 deg[10], were determined.

Thermo-gravimetric differential thermal analysis TG-DTA (WS002, TG-DTA2000s) were done on 22g samples from the bending test specimens using α-Al_2O_3 as standard sample, 20°C/min heating rate and nitrogen flow at 200ml/min. The amount of $Ca(OH)_2$ and $CaCO_3$ generated were determined.[11] Observations by scanning electron microscope (SEM) were done using JSM-5310LV.

Fig. 4 shows the effect of additive addition on the mechanical properties of bamboo-cement Particleboard. The initial setting of cement is accelerated by the addition of sodium carbonates. Although there were not much differences between the additions of $NaHCO_3$ and Na_2CO_3, there were some improvements in the hydration rates and the board properties

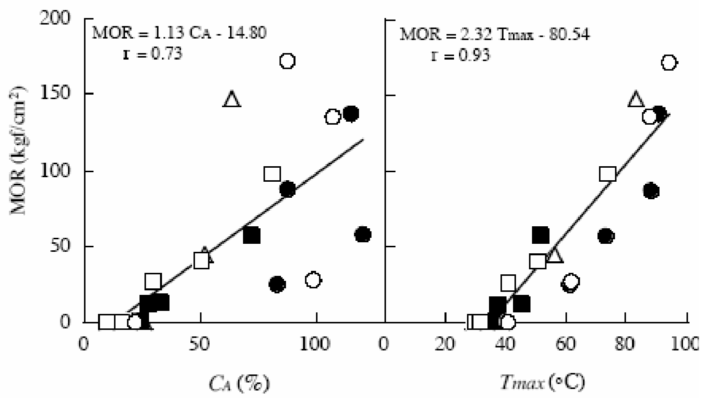

Fig. 3. Effects of C_A and *Tmax* on MORs of cement-bonded bamboo composites.
Legend: ○: $CaCl_2$ □ $NaHCO_3$ △: Na_2SiO_3
● $MgCl_2$ ■ Na_2CO_3

with increases in additive contents. However, these are not significant enough. Cement hydration was not improved during water soaking because the $Ca(OH)_2$ and CO_2 generated from the cement clinker and the sodium carbonates, respectively may have reacted to form $CaCO_3$ that covered the cement clinker and prevented further hydration. The hydration of cement under water soaked condition was also accelerated

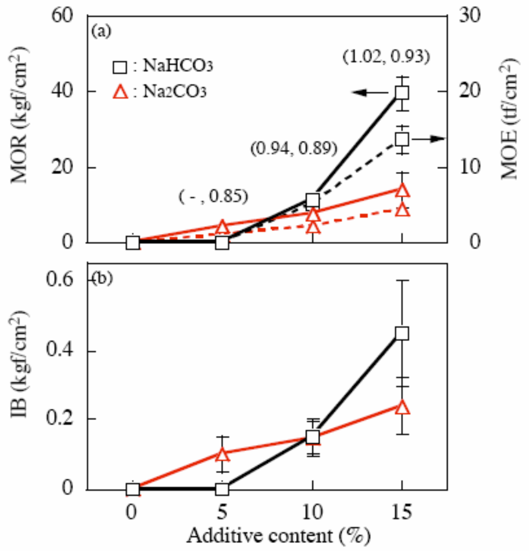

Fig. 4. Effect of $NaHCO_3$ or Na_2CO_3 addition on the properties of steam injection pressed bamboo-cement composites. (bamboo/cement/water: 1.0/2.6/1.3)

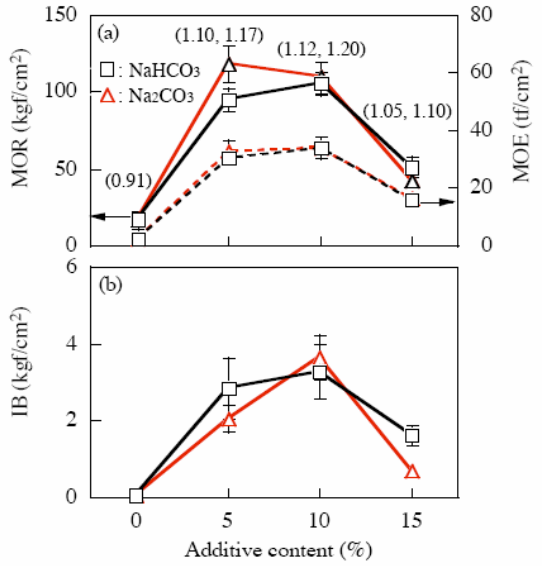

Fig. 5. Effect of the combinations of $MgCl_2$ and $NaHCO_3$ or Na_2CO_3 addition on the properties of steam injection pressed bamboo-cement composites. ($MgCl_2$ = 5%)

by the addition of sodium carbonates in combination with $MgCl_2$. The effects of these additive combinations on the properties of CBC are shown in Fig. 5. The MOR of CBC exceeded 100 kgf/cm^2 with the addition of 10% carbonates of sodium and 5% $MgCl_2$. CBC manufactured at 2.6 cement/bamboo ratio have better mechanical properties than those at 2.2 ratio.

Figs. 6 & 7 are examples of the XRD patterns and the TG-DTA curves, respectively, of samples from bamboo-cement Particleboard while Fig. 8 are SEM photographs of the fractured surfaces. The yields of $Ca(OH)_2$ resulting from the hydration of cement clinkers were estimated from the XRD and TG-DTA analyses.[12] As shown in Fig. 9, there were high correlations between the mechanical properties of CBC and the XRD intensity of the cement clinker and C_3S, the weight losses at 200°C and 900°C under TG-DTA, and the estimated yield of $Ca(OH)_2$. From these relationships, the mechanical properties of bamboo CBC using carbonates as additives might be predicted.

At the same manufacturing conditions, the effects of the additions of sodium silicate (Na_2SiO_3) or its combination with $MgCl_2$ on the degree of cement hydration and on the properties of cement-bonded bamboo Particleboard were also studied. Results showed that the cement hydration was accelerated and the properties of CBC were improved by the addition of less than 15% Na_2SiO_3. Under water soaked condition the combination of Na_2SiO_3 and $MgCl_2$ was more effective than that of Na_2SiO_3 alone and the mechanical properties of CBC were improved. The mechanical properties of CBC made with these additives were much higher than those of CBC made with sodium carbonate additives. The optimum additive content was found to be 15% Na_2SiO_3 or a combination of

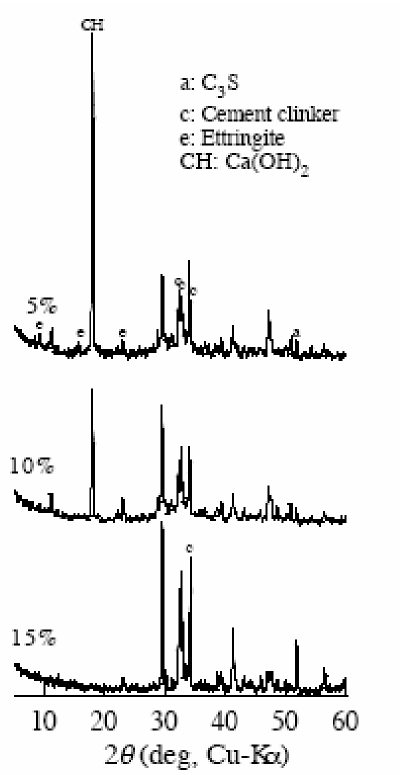

Fig. 6. XRD patterns of samples of bamboo-cement composites with Na_2CO_3 and 5%$MgCl_2$.

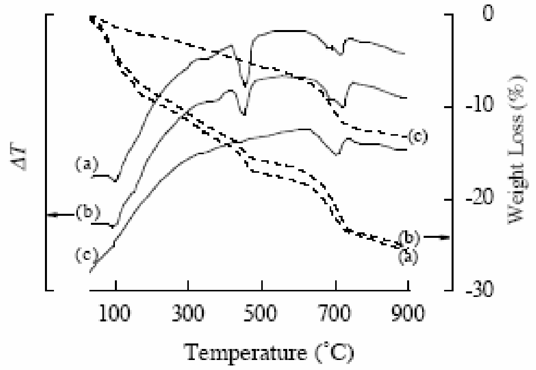

Fig. 7. TG-DTA curves of samples of steam injection pressed bamboo-cement composites using combinations of $MgCl_2$ and Na_2CO_3.
Legend: (a): Na_2CO_3 5% + $MgCl_2$ 5%, (b): Na_2CO_3 10% + $MgCl_2$ 5%, (c): Na_2CO_3 15% + $MgCl_2$ 5%.

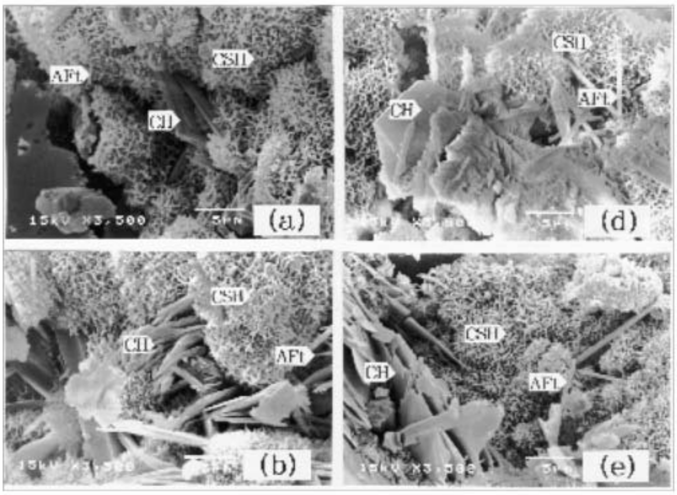

Fig. 8. SEM photographs of fractured surfaces of steam injection pressed of bamboo-cement composites.
Legend: (a): Na_2CO_3 5%, (b): Na_2CO_3 10%, (d): Na_2CO_3 5% + $MgCl_2$ 5%, (e): Na_2CO_3 10% + $MgCl_2$ 5%.
CSH: Calcium silicate hydrate, CH: Calcium hydroxide, AFt: Ettringite.

10%Na_2SiO_3 and 5% $MgCl_2$. There were high correlations between the flexural properties of bamboo-cement Particleboard and the XRD peak intensity or weight loss at 900°C. It is difficult to estimate the yield of $Ca(OH)_2$ in the case of Na_2SiO_3 addition because the $Ca(OH)_2$ generated during cement hydration reacts with SiO_2 from the additive. Where the flexural properties were concerned, the optimum bamboo/cement ratio was estimated to be 2.6 at the water cement ratio of 0.6.[13)]

4. Hydration characteristics and properties of bamboo- cement Particleboard manufactured by Hot Pressing

Hot pressing was also applied in the manufacture of CBC using similar raw materials as above, except that only Na_2SiO_3 at 5% to 20% levels (based on cement weight) was used as additive. The effects of pressing temperature, pressing time and the additive content (Na_2SiO_3) on the degrees of cement hydration and on the board properties were determined.

Results showed that the initial setting of cement was accelerated by hot pressing and the addition of Na_2SiO_3, i.e., rapid curing of CBC was also achieved. Cement hydration was accelerated and the properties of CBC

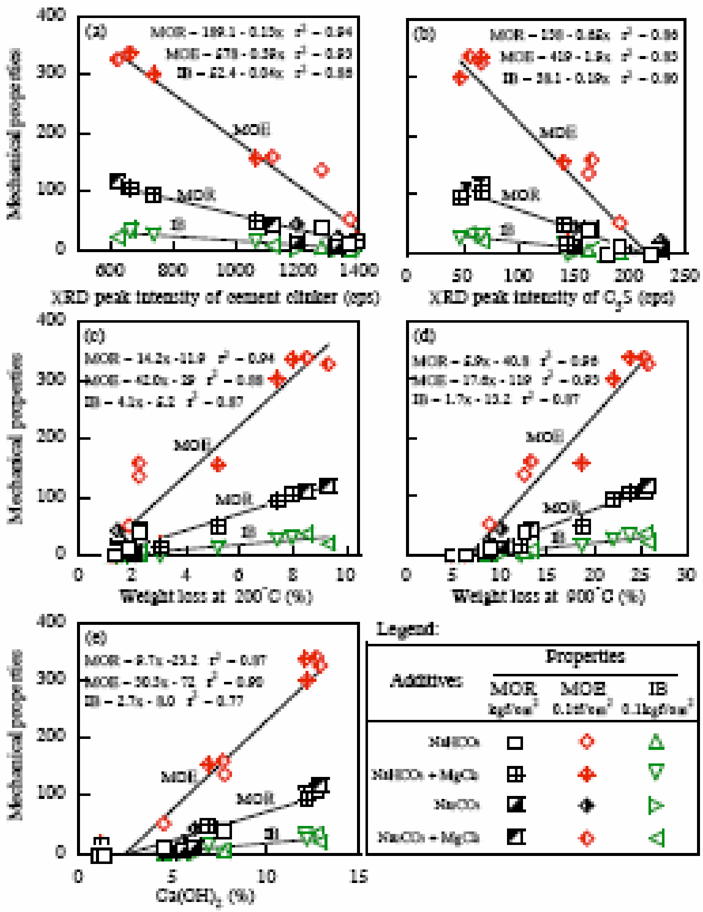

Fig. 9. Mechanical properties of steam injection pressed bamboo-cement composites as functions of XRD peak intensity of cement clinker or C_3S, weight loss at 200 °C or 900 °C, and estimated amount of $Ca(OH)_2$.

were improved by the addition of Na_2SiO_3 as shown in Fig. 10. The optimum additive content was found to be 15% to 20% Na_2SiO_3 based on cement weight. Hot press temperature affected the hydration of cement, and the values of the mechanical properties of CBC pressed at high temperature were higher than those pressed at low temperature. XRD and TG-DTA analysis showed that the initial setting of cement was slow at low temperature, therefore the thickness direction springback of CBC after pressing was not controlled. Although the hydration of cement was improved by curing under water-soaked condition, the mechanical properties of CBC were not enhanced. In the case of CBC pressed at more than 100°C, the springback was suppressed since the initial setting of cement was accelerated but curing under water soaked condition barely improved the hydration of cement. SEM analysis also showed better structure of CBC pressed at higher temperature. Hot pressing time affected the hydration of cement. In the range of 3 min to 21 min, long hot pressing times resulted in the improvements of CBC properties.[14]

In order to improve the properties of boards, silica fume was added to the raw materials and the manufactured boards were post-cured by heat treatment. Properties of hot pressed CBC were improved after additional heat treatments, especially with the combination of the addition of silica fume and heat treatment. Fig. 11 shows the effect of silica fume substitution of cement content on the properties of the

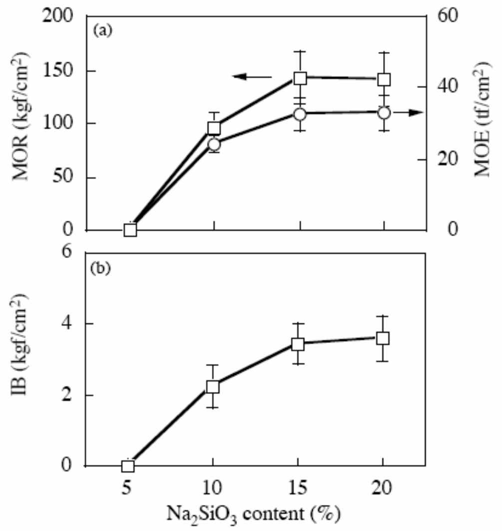

Fig. 10. Effect of Na2SiO3 on the properties of hot pressed bamboo-cement composites. (bamboo/cement/water: 1.0/2.6/1.3)

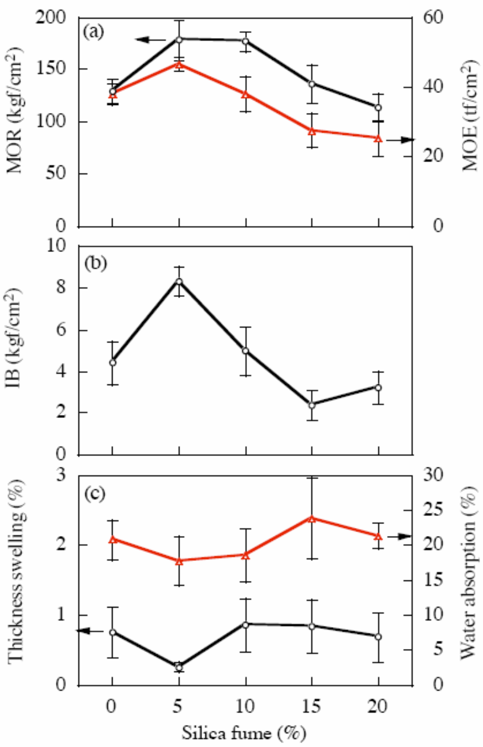

Fig. 11. Effect of silica fume addition on the properties of hot pressed bamboo-cement composites with 15%Na2SiO3.(100°C heat-treatment)

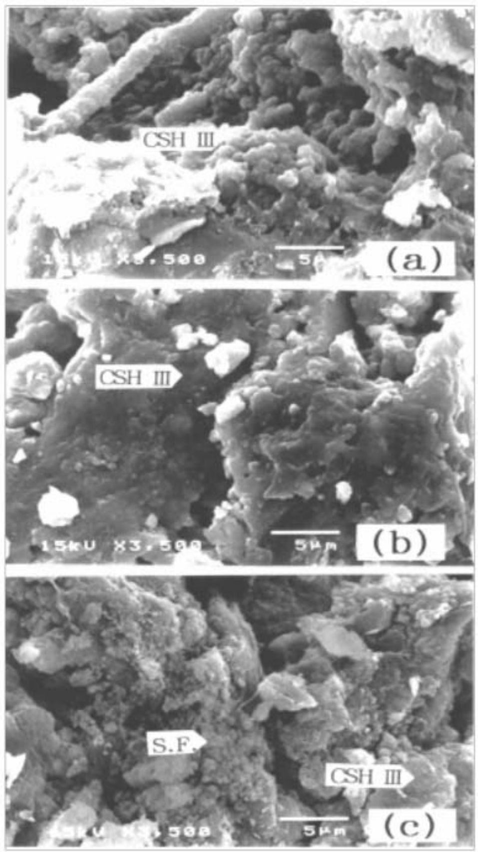

Fig. 12. SEM photographs of fractured surfaces of hot pressed bamboo-cement composites with (a) 0%, (b) 5%, and (c) 20% silica fume.(CSH III: Type III calcium silicate hydrate, S.F.: Silica fume)

CBC. With additional heat treatment, the optimum amount of silica fume was 5% substitution (that is 5% cement was replaced with silica fume). Based on SEM analysis, the cured structures were more compact at 5% silica fume substitution, hence the interfaces between bamboo and the cured cement might have been improved. Fig. 12 are SEM photographs of the fractured surfaces. CBC properties were markedly improved at 100°C heat treatment temperature than at 60°C or 80°C. Longer press time resulted in better mechanical properties of CBC. The final properties of CBC were related with their initial strength and hydration degree (strength and hydration degree, respectively, immediately after hot pressing). The optimum conditions of manufacture of CBC by hot pressing were: addition of 15% Na_2SiO_3 based on cement weight, substitution of 5% cement with silica fume, 11 min hot pressing at 110°C, 24hr heat treatment at 100°C. [15)]

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