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Bamboo and wood fibre cement composites for sustainable infrastructure regeneration

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Abstract This paper describes the development of eco-friendly bamboo and wood fibre cement composites from agriculture wastes for applications in the housing and building industries, and for sustainable infrastructure regeneration. Bamboo flakes and fibres from oil palm tree fronds were produced and tested for their sugar content and effect on the setting and strength development of the portland cement matrix. To counteract the adverse effects on cement hydration, chemical accelerators, cement replacement materials or a combination of both were used in the manufacture of the composite boards. With the bamboo, the composition of the particleboard was optimized in terms of bamboo–cement ratio and the type and amount of chemical admixture to produce a composite with satisfactory strength and dimensional stability. For the production of wood fibre cement composites, cement replacement materials such as fly ash, rice husk ash and latex were used in conjunction with chemical admixtures to counteract the adverse effect on the hydration characteristics of the cement matrix. Tests were then carried out to optimize the amount and type of cement replacement material and chemical admixtures to produce boards with adequate strength and dimensional stability. All the strength and dimensional stability tests reported in the paper were carried out according to Malaysian Standard MS 934. The paper emphasizes the need for holistic design combining chemical admixtures, cement replacement materials and modern production technology to produce a wide range of cement-bonded composite boards, which will satisfy international standards and can be widely used for infrastructure regeneration.

Introduction

Fibre reinforcement of cementitious materials still remains an exciting and innovative technology because of the basic engineering properties of crack resistance, ductility and energy absorption that it imparts to concrete—properties that ensure long, trouble-free service life to many of the infrastructure constructions that enhance the quality of life [1]. Natural fibre cement composites occupy a special place in this development of fibre reinforced cement and concrete, because of the luxurious abundance and availability of natural fibres in many parts of the world, and also because they lead directly to energy savings, conservation of a country's scarce resources and reduction in environmental pollution. The fact that one of the most easily and readily replenishable earth's resources can be used to solve one of the most acute forms of human deprivation, is just as challenging not only to the basic human instinct of fellow feeling, but also to the science and engineering skills of advanced technologies [2–4].

Bamboo and wood fibre cement composites are exceptional in this respect, not only because of their eco-friendly nature but also because they provide the most economic and socially useful outlet for bamboo chips, wood residues and agricultural wastes. The combination of bamboo/wood

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particles and an inorganic cementitious binder can produce a new class of building products that can reflect the good characteristics of wood and concrete. Cement-bonded particleboards (CBP), as they are generally called, can be designed to possess good engineering properties for a wide range of applications in the building, housing and other commercial/infrastructure projects. The cementitious binder encapsulates the wood/bamboo particles, fibre and aggregates, and the composite can be designed to have high resistance to fire, termites, fungus and other bio-degrading agents. Further, their high weather resistance and low sound transmission properties combined with the ability to accept a wide range of surface treatments make these products highly attractive for a variety of applications such as partitions, internal and external walls, roof elements and permanent formwork.

Two major challenges face the development of durable wood/bamboo fibre cement composites. The first is the many inherent weaknesses of the wood/bamboo particles themselves such as their low elastic modulus, high water absorption, susceptibility to fungal and insect attack, and lack of durability in an alkaline environment. Secondly wood/bamboo particles and fibre contain a wide range of carbohydrates such as hemi-cellulose, starch, sugar, tannins, phenols and lignins, all of which are known to inhibit normal setting and strength development properties of the cement matrix [5, 6]. Extensive research, however, shows that a combination of low alkali cementitious materials, chemical admixtures and modern production processes under controlled compaction and temperature conditions can lead to a wide range of CBP with excellent durability properties and with very satisfactory levels of long-term performance under internal and external exposure conditions [2–13].

Research significance

Bamboo is the fastest-growing and highest-yielding renewable natural construction material available to mankind. Oil palm trees, on the other hand, are a national economic asset in the production of palm oil. However, once the useful life of the oil palm tree is over, the tree becomes a waste material often left to decay or be burnt adding considerably to environmental pollution. The focus of this paper is to show that flakes derived from the bamboo and fibres processed from the fronds of the oil palm tree can be utilized in the production of cement-bonded particleboards with satisfactory engineering properties and dimensional stability to satisfy international standards. The utilisation of residues and wastes from living plants in the construction industry poses two major challenges. One relates to the highly variable and generally lower engineering properties of the plant residues themselves. The second, and more important, is the presence of sugars, starch and phenolic compounds all of which have a profoundly adverse effect on the setting and strength development of the portland cement matrices. This paper shows that a holistic approach combining cement replacement materials, chemical accelerators and modern production processes can lead to a wide range of cement-bonded particleboards for applications in the housing, building and infrastructure sectors.

Cement-bonded boards from bamboo

Bamboo is probably the fastest-growing and highest-yielding natural resource and construction material available to mankind. Its uses are unlimited [14–19] but the level of sophistication and the degree of utilisation of its structural efficiency is far from satisfactory. The focus of this paper is to offer another possible use of bamboo for the building industry in the form of bamboo cement-bonded boards (BCB) [20]. The type of bamboo used in this study was *Bambusa vulgaris* from Malaysia.

Particle size analysis

Initially, about 2 m length of the bamboo was chipped, and the chips were screened through a 20 × 20 mm screen. The chips were then flaked before being further screened to various particle sizes. The bamboo flakes retained on the 0.50 mm screen were used as fine material while those retained at 1.0 mm screen were utilized as core material for manufacturing the BCB. The particle size distribution of the fibres was carried out on random samples through a laboratory siever with screen size ranging from 0.85 to 3.35 mm. The sieve analysis showed that some 80% of the particles were retained in sieve sizes ranging from 0.5 to 2.0 mm; particles larger than 3.35 mm were recycled to produce smaller particles suitable for BCB manufacture. The average thickness and length of the flakes, based on at least 100 samples, were 0.39–0.61 mm and 14.0–17.1 mm, respectively.

Sugar content analysis

The sugar content analysis was determined on random samples of the bamboo flakes ground to about 200-mesh size; 12 separate tests were carried out. The major sugar components of the freshly felled bamboo species used in these tests were found to consist of fructose, glucose and smaller amounts of sucrose. The average total sugar content was 4.92% of dry weight of wood which is about 2–4 times higher than that in rubberwood [5] and about half of that in oil palm trunk [21]. In general, the level of sugar content considered allowable in wood aggregates for the manufacture of CBP and BCB is less than 0.5% of the dry mass of wood [22].

Various tests were carried out to investigate the influence of *B. vulgaris* particles on the hydration time and hydration temperature of the portland cement matrix. These tests confirmed that the incorporation of particles of *B. vulgaris* in the cement matrix had set-retarding effects—it was observed that the hydration time of bamboo–cement mixes was prolonged to about 10 h compared to about 8 h of the neat cement paste.

Manufacture of bamboo cement boards

The main variables in the study reported here were the bamboo–cement ratio and the type of chemical admixture/mineralising fluid incorporated in the mix. Three bamboo–cement ratios, viz, 1:2.50, 1:2.75 and 1:3.00, and four chemical admixtures as shown in Table 1 were used. The chemical admixtures were used at a dosage of 2% by mass of cement, primarily to counteract the retardation effect of the bamboo particles, accelerate the hydration process, and also to enhance the strength development of the BCB. The chemical admixtures used were calcium chloride, magnesium chloride, aluminium sulphate, and a mixture of aluminium sulphate and sodium silicate.

Several series of three-layered BCB were made, and for each series, five test samples of boards, with a specimen size of 450 × 450 × 10 mm thick, were produced. The target density of the boards was 1,250 kg/m^3. The bamboo–cement mixes were mat formed on a caul plate inside a wooden mould; each mat was then stacked on top of the other, pressed up to the required thickness, and clamped overnight in a hardening chamber at a temperature of 60–65 °C. The pressure was released after 24 h, and the boards then cured further at room temperature, for 28 days and tested.

Engineering properties of BCB

Table 1 summarizes the modulus of rupture (MOR), internal bond (IB), water absorption (WA) and thickness swelling (TS) of cement boards manufactured from *B. vulgaris*. The test samples were all cut from the 400 × 400 × 10 mm boards, and all the tests were carried out according to the Malaysian Standard specifications for Wood Cement Board, MS 934:1986. The testing specifications according to this standard are almost identical to the International Specification for CBP, ISO 8335:1987. The minimum requirements of MS 934 are given in the last line of Table 1. All the test data were analysed by the statistical analytical system for ANOVA and Duncan's Multiple Range *t*-test to examine the influence of the bamboo–cement ratio and the chemical additives on the properties of the BCB. The results shown in Table 1 represent the average of 18 and 16 replications, respectively, for the effects of bamboo–cement ratio and chemical admixtures.

The test results of Table 1 confirm, as expected, that a bamboo–cement ratio of 1:3 gave the best board properties, but the modulus of rupture was well below the minimum specified by MS 934. Of all the chemical additives, aluminium sulphate gave the best results, all well above the MS minimum requirements. The mixture of aluminium sulphate and sodium silicate, on the other hand, gave marginal improvements to those with aluminium sulphate alone. But the overall test results are very clear that bamboo cement boards with a bamboo–cement ratio of 1:2.75 and incorporating 2% aluminium sulphate can be produced to meet the requirements of MS 934.

Table 1 Strength and dimensional stability properties of BCB

Bamboo cement ratio	Chemical additives	MOR (MPa)	IB (MPa)	WA (%)	TS (5)
1:2.50	–	2.43	0.07	29.00	2.15
1:2.75	–	3.87	0.12	26.10	1.17
1:3.00	–	5.04	0.23	20.40	1.26
1:2.75	$CaCl_2$	5.48	0.19	24.64	2.26
1:2.75	$MgCl_2$	6.93	0.43	15.97	1.11
1:2.75	$Al_2(SO_4)_3$	9.25	0.63	14.40	0.76
1:2.75	$Al_2(SO_4)_3$+ Na_2SiO_3	9.41	0.77	12.57	0.82
MS 934	–	9.00	0.50	–	< 2.00

Cement boards from oil palm frond fibres

The oil palm tree is a major perennial agricultural crop in Malaysia, abundantly rich in lignocellulose, and readily replenished in the natural eco system. It is a uniquely resourceful and sustainable national asset in being not only economically valuable and productive but also that the trunks, crown, fronds, and the empty fruit bunches all provide the most useful source of raw material for a range of wood-based industries. Extensive studies have shown that fibres extracted from oil palm trunks and fronds can be used as wood aggregate in the manufacture of wood fibre cement composites [23, 24]. Fibres extracted from the fronds are particularly attractive for commercial exploitation as they are readily available in large quantities during replanting, pruning of the trees, harvesting of the fruit bunches and felling of the trees. These economic benefits are strengthened by the environmental benefits derived from the utilisation of agricultural residues and wastes which are otherwise left to decay or being burnt leading to considerable soil deterioration and environmental pollution.

The focus of this paper is to examine the role of oil palm frond fibres and cement replacement materials in the production of wood fibre cement composites. Previous studies had shown that oil palm trunk fibres not only needed pretreatment but also chemical additives for their proper utilisation [23]. The fronds on the other hand, are not only readily available throughout the year without felling the tree, but they are also easier to process by the oil palm fractionator. In addition, since both the wood fibre and pozzolanic cement replacement materials such as fly ash and rice husk ash have a retardation effect on the early hydration process of the cement, it was necessary to establish an optimum amount of cement replacement consistent with the development of engineering properties to establish oil palm fibre cement boards as a viable construction material.

Materials and board manufacture

Oil palm fibres

The freshly felled oil palm fronds were first of all disintegrated in the plantation using an oil palm fractionator. Under this process, the oil palm fronds were shredded, hammered and mechanically treated to separate the fibres from the parenchyma tissue. The fibres were then collected, air-dried under the sun, and transported to the laboratory. The frond fibres were then further disintegrated using a Pallmann knife-ring flaker into a particle size suitable for the manufacture of the CBP. The fibres were then stored in a cold room prior to board manufacture.

The fibres from the trunks and fronds processed by the fractionator and the knife-ring flaker were found to have slight differences both in terms of size and bulk density. The average thickness and length of the frond fibres were generally lower than those of the trunk fibres produced under similar processing methods. More importantly, the bulk density of the frond fibres was about a third of that of the trunk fibres. These studies showed that the frond fibres were generally much easier to disintegrate into smaller sizes than the trunk fibres. The tensile strength of the frond fibres varied from 41 to 260 MPa compared to 176–489 MPa of the trunk fibres.

Cementitious materials and latex

In the tests reported here, ordinary portland cement was used alone as well as in conjunction with fly ash (FA), rice husk ash (RHA) and natural latex. The FA, RHA and latex were used as cement replacement materials at 10, 20, 30 and 40% by mass of cement. The chemical composition of the cement, FA and RHA are shown in Table 2. The portland cement complied with the Malaysian standard and the Bogue composition consisted of C_3S = 47.7%, C_2S = 23.4%, C_3A = 9.5% and C_4AF = 19.4%. The FA used was a low calcium type F Malaysian fly ash with low alkali content, a specific surface of 394 m^2/kg and a specific gravity of 2.15. The RHA used in the tests was a white RHA obtained from the open burning of rice husk. The white colour is an indication of complete oxidation of carbon in the ash as shown by the LOI in Table 2. The ash from the field was dried in an oven at 105 °C, and then ground in a rotary ball mill for about 30 min to pass through a 200-mesh sieve size. Like the FA, the RHA had also a low alkali content which is an advantage in reducing the higher alkalinity of the portland cement.

The latex used in the mixes was a natural rubber latex in liquid form with about 60% solids and 40% water. It was preserved from degradation by adding a small percentage of ammonia as preservative, and chemical stabilizers. The cement replacement by latex was based on the latex solid content.

The hydration test

The hydration test was carried out primarily to determine the effect of the cement replacement material used in this study on the early hydration behaviour of portland cement. In particular, it was also important to evaluate the pozzolanic properties of the white RHA used, and the retardation effects of the latex. The test was carried out in accordance

Table 2 Chemical composition of OPC, FA AND RHA

Chemical components	Composition (% w/w)		
	OPC	FA	RHA
CaO	64.8	2.8	0.8
SiO_2	20.6	65.4	94.7
Al_2O_3	5.8	21.3	0.7
Fe_2O_3	3.5	4.2	0.3
MgO	0.6	1.2	0.8
SO_3	2.4	0.2	–
K_2O	0.6	0.5	–
Na_2O	0.1	0.1	–
IR	0.8	–	–
LOI	1.3	4.1	0.7
LSF	0.96	–	–
Free lime	2.2	–	–

IR, insoluble residues; LSF, lime saturation factor with ASTM C 186-83 (1983). Three replications were made for each variable studied.

The results of the hydration test are shown in Figs. 1, 2, 3 for FA, RHA and latex, respectively. With FA, the maximum hydration temperature (MHT) was reduced from 77 to 63 °C at 10% replacement level, although the maximum hydration time to reach MHT still remained within 10–11 h. At 20% replacement, the MHT was reduced to below 54 °C, and the hydration time to MHT was prolonged to about 14 h. Further replacement of cement by FA affected the cement reactivity adversely as shown by the hydration curves of 30 and 40% FA in Fig. 1.

The results of the hydration test for RHA shown in Fig. 2 confirmed good reactivity between portland cement and the white RHA used in this study. At 10% replacement level, the MHT was reduced to 70 °C, but the time to MHT remained at 10 h, and this was also the case when the replacement level was raised to 20%, although the MHT was then reduced slightly to about 66 °C. Further additions to RHA to 30 and 40% replacement levels reduced the MHT but in both cases the time to MHT was not significantly affected as it remained between 12 and 13 h. Figure 2 shows that the white RHA fulfilled the requirement to reduce the hydration temperature of the cementitious matrix without significantly affecting its hydration time to reach MHT.

The effect of natural latex on the hydration characteristics of portland cement is shown in Fig. 3. The results show that in the presence of 10 and 20% latex, the MHT was reduced to 68–69 °C, and the time to MHT was prolonged to 11 and 13 h, respectively. At 30 and 40% replacement levels, the MHT was reduced further, and the time to MHT was delayed to more than 16 h.

The results shown in Figs. 1–3 confirm that FA, RHA and latex have some retardation effects on the hydration of portland cement. In general terms the MHT decreased and the time to reach MHT increased as the cement replacement level increased. Bearing in mind that the fibres themselves have some retardation effect on the hydration of cement, these results indicate that cement replacements

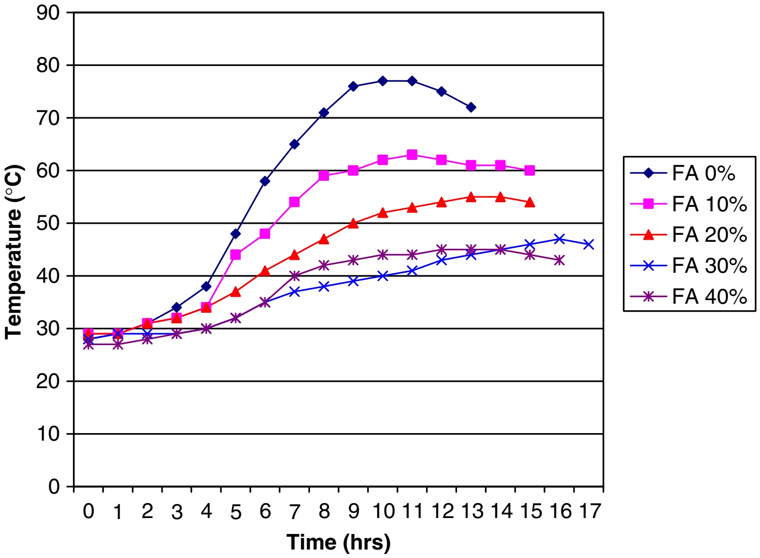

Fig. 1 Effect of FA on cement hydration

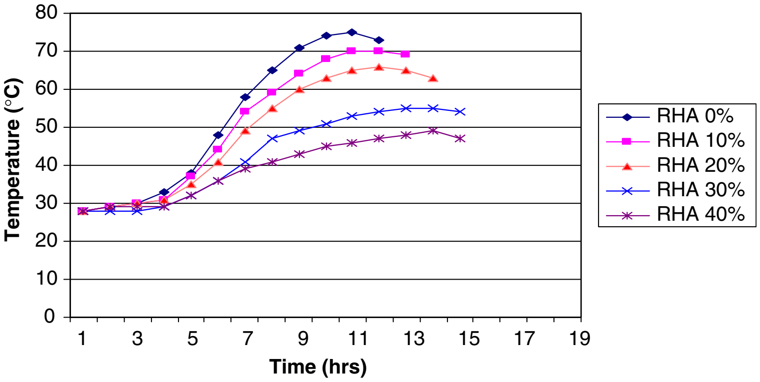

Fig. 2 Effect of RHA on cement hydration

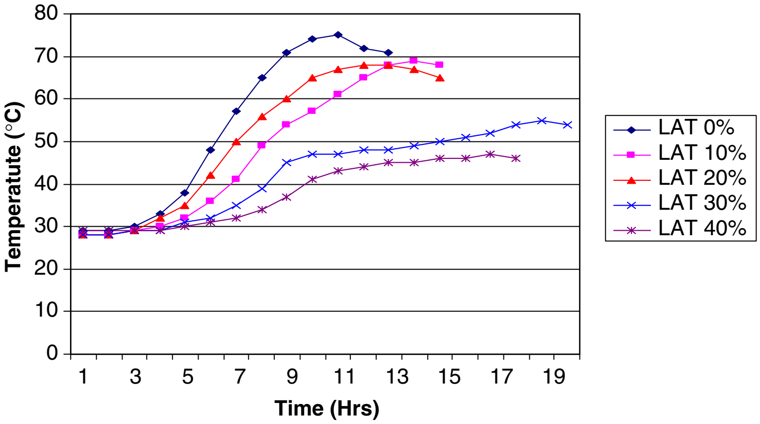

Fig. 3 Effect of natural latex on cement hydration

above 20–30% may affect adversely the binding properties between the oil palm fibre and the cementitious matrix in the production of composite boards.

Cement composite board manufacture

Based on the above results, 10 series of oil palm fibre cement composite boards were made incorporating portland cement replacements of 10, 20 and 30% of FA, RHA and latex, respectively. Five test samples, 400 × 400 × 10 mm thick, were produced from each series. The target density of the boards was 1,300 kg/m^3, and an oil palm fibre/cementitious matrix ratio of 1:2.5 (based on oven dry weight) was used. Two chemical additives, namely aluminium sulphate and sodium silicate at 1.4 and 3.0%, respectively, by mass of cementitious matrix were separately added to the mixture. All the test boards were kept clamped at a pressure of 500 kg/cm^2 for 24 h overnight in a special chamber at 65 ± 3 °C. They were then declamped and cured in water for 7 days and in ambient temperature for 21 days until the weight of the cement composite remained practically constant. All the boards were tested after 28 days of curing according to the Malaysian Standard specification for wood cement boards MS 934:1986. As stated earlier, the MS specifications are almost identical to the International Standard specifications for Cement-Bonded Particleboards. All the test data presented in this paper were also analysed by the statistical analytical systems for ANOVA and Duncan's Multiple Range *t*-test to examine the influence of the variables involved.

Engineering properties

The engineering properties of oil palm fibre cement composites produced in this study with 10, 20 and 30% cement replacement by FA, RHA and latex are summarized in Table 3. The properties reported are density, modulus of rupture (MOR), modulus of elasticity (MOE) and internal bond (IB). The values presented are the mean of 20 tests, and the last line of Table 3 gives the minimum specified values according to the MS 934.

The data presented in Table 3 show that the engineering properties of oil palm fibre cement composites generally decrease as the proportion of cement replacement is increased. This reduction in engineering properties generally corresponds with the hydration test results presented in Figs. 1–3. The reduction in strength properties is obviously the result of retardation at early ages in the degree of cement hydration, and the resulting incomplete bonding of

Table 3 Engineering properties of composite boards from OPT fibres

Test series	Admixture	Cement replacement (%)	Board density (kg/m^3)	MOR (MPa)	MOE (MPa)	IB (MPa)
Control	–	–	1,366	12.81	3,909	1.087
FFA	FA	10	1,274	10.06	3,231	0.755
FFB	FA	20	1,292	10.25	3,365	0.713
FFC	FA	30	1,260	5.61	1,996	0.231
FRA	RHA	10	1,323	10.77	3,440	0.901
FRB	RHA	20	1,263	9.44	2,990	0.610
FRC	RHA	30	1,165	5.93	1,664	0.236
FLA	Latex	10	1,341	11.68	3,269	0.975
FLB	Latex	20	1,336	9.70	2,973	0.681
FLC	Latex	30	1,215	6.16	1,215	0.581
MS 934 (1986)			> 1,000	9	3,000	0.5

the fibres with the cement matrix. There is, however, considerable indication that the strength properties will increase with ageing and continued pozzolanic reaction. The results shown in Table 3 thus confirm that a cement replacement level of up to 20% can be tolerated without any serious loss in the early age engineering properties of oil palm fibre cement composites to satisfy the minimum requirements of national standards.

Dimensional stability

The water absorption and thickness swelling properties of the fibre cement composite due to soaking in water for 24 h are shown in Table 4. The minimum requirements to satisfy the MS 934 are also shown in the same Table. It is clear that all the test results shown in Table 4 are well above the minimum requirements. In general, RHA as cement replacement gave overall better performance than FA, but the incorporation of both FA and RHA appears to have produced higher water absorption properties of the composite compared to that of the control.

On the other hand, incorporation of 10 and 20% latex in the composite reduced their water absorption properties to below that of the control. This is not altogether surprising because of the well-established role of polymer modification in reducing penetration of water and aggressive ions into concrete [25].

General discussion

The sugar content analysis showed that *Bambusa vulgaris* culm possessed a very high amount of sugars, about 4.92%. This had a significant retardation effect on the setting and strength development of the portland cement matrix. This, in effect, meant that portland cement matrix alone will not enable a bamboo cement board to be produced with the necessary engineering properties. A bamboo–cement ratio of 1:3 was considered maximum; beyond this ratio, the boards were likely to become uneconomic, and it was felt that a higher ratio may also lead to brittle behaviour of the boards. The incorporation of chemical accelerators was thus found essential to enhance the strength properties of the BCB. And as shown in Table 1, a bamboo–cement ratio of 1:2.75 and the addition of 2% of aluminium sulphate by mass of cement or a combination of aluminium sulphate and sodium silicate produced an acceptable board that satisfied the strength properties and dimensional stability requirements of the Malaysian Standard MS 934. The results of this study confirm that bamboo flakes can be successfully incorporated in the manufacture of bamboo cement-bonded boards.

The results of the hydration tests shown in Figs. 1–3 confirm that FA, RHA and latex can all be successfully used as cement replacement materials in the production of oil palm frond fibre cement boards. These results, however, also confirmed that there is an optimum amount of cement replacement beyond which there was a significant reduction in bending strength and elastic modulus, and a progressive increase in water absorption and thickness swelling of the boards. The results also showed that locally burnt white RHA can be ground to have pozzolanic properties. At 10% replacement level, latex imparted better engineering properties to the particleboard compared to FA and RHA, and RHA gave better performance than FA. At 20% replacement level, FA gave better strength properties than RHA and latex. However, when dimensional stability is considered, the latex gave the best performance at 10 and 20% replacement levels. These results gain confirm that oil palm fibre cement boards can be successfully produced with 10–20% of cement replacement materials to satisfy the engineering properties and dimensional stability requirements of national standards.

Concluding remarks

The aim of this paper is to show that flakes produced from naturally occurring bamboo, and fibres extracted from agricultural wastes emanating from oil palm trees can be

Table 4 Dimensional stability properties of composite boards from OPT fibres

Test series	Admixture	Cement replacement (%)	Average density (kg/m^3)	Water abs (%)	Thickness swelling (%)
Control	–	–	1,359	12.54	0.97
FFA	FA	10	1,269	15.26	0.89
FFB	FA	20	1,298	15.30	1.08
FFC	FA	30	1,249	19.35	1.76
FRA	RHA	10	1,327	13.51	0.66
FBR	RHA	20	1,286	14.77	0.68
FRC	RHA	30	1,209	15.32	1.03
FLA	Latex	10	1,353	10.84	0.60
FLB	Latex	20	1,365	11.71	1.54
FLC	Latex	30	1,245	14.66	1.21
MS 934 (1986)			> 1,000	–	< 2.0

utilized to produce cement-bonded particleboards for applications in the housing and building industries and in infrastructure construction. The bamboo flakes contained a high amount, about 4.92%, of sugars which had a significant retarding effect on the setting and strength development of the portland cement matrix. It was found that the addition of chemical admixtures was necessary to counteract this adverse effect. With a bamboo–cement ratio of 1:2.75 and 2% aluminium sulphate alone or in combination with sodium silicate, it was possible to produce a board which satisfied the strength and dimensional stability requirements of international standards.

Fibres extracted from oil palm fronds were, on average, 0.40 mm thick and 19.3 mm long. Three cement replacement materials, namely, FA, RHA and a natural rubber latex and two chemical accelerators, namely, aluminium sulphate and sodium silicate were incorporated in the production of oil palm fibre cement boards. Hydration tests showed that the MHT decreased and the time to reach the MHT increased as the cement replacement level increased. The boards were produced with an oil palm fibre/cementitious materials ratio of 1:2.5 and a target density of 1,300 kg/m^3. The tests showed that with 10–20% of cement replacement material and the chemical admixtures, it was possible to produce boards that satisfied the strength and dimensional stability requirements of national standards.

Theses tests emphasize that with a holistic approach combining cement replacement materials, chemical admixtures and modern production processes, bamboo flakes and oil palm fibres can be successfully utilized to produce particleboards that will satisfy the strength and dimensional stability requirements of national standards and which can be used in a wide range of infrastructure construction applications.

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