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Autoclaved Bamboo Pulp Fibre Reinforced Cement

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Abstract

This paper reports the use of bamboo fibre as a potential reinforcement for autoclaved cement building materials. At a fibre loading of 14% by mass, the autoclaved bamboo fibre reinforced cement composites have a flexural strength greater than 18 MPa and a density of about 1·3 g cm^{-3}. However, the fracture toughness value is low, being less than 0·50 kJ m^{-2}, due to short fibre length and high 'fines' content of the bamboo pulp. By screening out 'fines' contained in the original bamboo pulp the flexural strength values can be improved to greater than 20 MPa while fracture toughness exceeds 1·0 kJ m^{-2}. Beaten bamboo fibre reinforced cement composites do not vary greatly in flexural strength and fracture toughness values from those of the unbeaten fibre reinforced composites. This behaviour contrasts that of cement composites reinforced with beaten and unbeaten P. radiata *fibres.*

Keywords: Natural fibres, bamboo fibre, building materials, bamboo pulp, flexural strength, fracture toughness, bamboo fibre reinforced cement.

INTRODUCTION

The fibre cement industry has moved towards autoclaved wood fibre reinforced cement mortars as the most commercially viable product to replace asbestos cement products. In those countries without adequate forest resources, alternative fibre sources are being researched.

In Australia, wood fibre (*Pinus radiata*) has replaced asbestos fibre as a reinforcement in commercial cement products since 1981. This fibre has a reasonably high market price. Thus, considerable research effort has gone into the study of fast growing, cheap agricultural crops and crop residues, especially for those countries with limited forest resources.

Bamboo is a rapidly grown agricultural crop, which has good fibre qualities and is widely employed in the paper industry throughout the Asian region. Although bamboo has also been used in various forms in the construction industry, there is limited information in the scientific literature concerning the use of bamboo pulp fibre. Sinha *et al.*[1] and Pakotiprapha *et al.*[2] investigated the flexural strength of air-cured bamboo fibre reinforced cement (BFRC) composites; Coutts *et al.*[3] reported air-cured BFRC composites' properties for both flexural strength and fracture toughness.

The Hatschek process followed by curing in a high pressure steam autoclave has been commercially applied to the production of wood fibre reinforced cement (WFRC) products.[4] Steam curing at temperatures close to 180°C enables the replacement of between 40 and 60% of ordinary Portland cement by less expensive silica; the latter reacts with the cement to form a calcium silicate matrix of acceptable strength. The reaction is completed within 6–8 h, instead of three–four weeks, as required with air-cured products. In an earlier study, it was found that beating *P. radiata* fibres improved fibre to cement bonding, thus, resulting in improved WFRC composite flexural strength.[5] However, there was no evidence that beating improved the flexural strength of products reinforced with bamboo[3] (air-cured) or flax[6] (autoclaved). When studying short fibre (wood and non-wood) behaviour, it was also noticed that composites needed high fibre loadings (12–14% by mass) to reach their maximum strength,[3,7] rather than 8–10% as in WFRC composites.[5]

This current study investigates the preparation and the mechanical and physical properties of autoclaved BFRC composites to establish their suitability as an alternative to wood pulp fibre for asbestos replacement in fibre cement building products. At the same time this study also investigates the effect of fibre length with respect to the composite's mechanical performance.

EXPERIMENTAL

Figure 1 shows the flow chart of experimental work and includes fibre treatment, specimen preparation and composites testing.

Materials

The bamboo fibre was unbleached kraft pulp of Kappa No. 26, and was prepared from commercial packaging paper. The bamboo species was *Sinocalamus affinis* (Rendle) McClue. The matrix was prepared from equal proportions of ordinary Portland cement and finely ground silica (Steetly brand, 200 mesh, washed quartz).

Fibre modification

The fibres used in the composites were obtained by soaking the commercial packaging paper overnight followed by disintegration, in a Cadet Frame B56, for 10 min at a speed of 2850 rpm. After disintegration, the fibres were subjected to three different treatments:

(1) vacuum-dewatering and crumbling (unbeaten bamboo pulp–400 Canadian Standard Freeness (CSF));
(2) beating in a Valley Beater to 100 CSF, then vacuum-dewatering and crumbling (beaten bamboo pulp (100 CSF));
(3) disintegrating original pulp with hot water (90–95°C) for 2 min in a 3 litre Noram disintegrator, followed by screening on 0·83 mm hole size Somerville screen (yield 46%) and then dewatering and crumbling (screened bamboo pulp (550 CSF)).

Specimen fabrication

Specimens were fabricated in the laboratory from modified fibres and matrix material (consisting of equal weight of cement and silica), and were mixed in a slurry of approximately 20% solids. The fibre mass fraction (oven-dried) ranged from 2 to 22% for unbeaten and beaten BFRC composites and from 2 to 14% for screened BFRC composite. The mixture was stirred for 5 min, and was poured into an evacuable casting box 125 × 125 mm and evenly distributed over the screen. Vacuum (90 kPa) was applied and water was drawn off until the sheet appeared dry on the surface. Samples were lightly pressed with a tamper.

The sheet and screen were removed from the vacuum box, then stored between two steel plates and the procedure repeated until a stack of six sheets had been prepared. The stack of sheets was then pressed for 5 min at a pressure of 3·2 MPa. Initially, the load was applied slowly to prevent damage to sheets. After pressing, the sheets were stacked flat in a sealed plastic bag overnight then

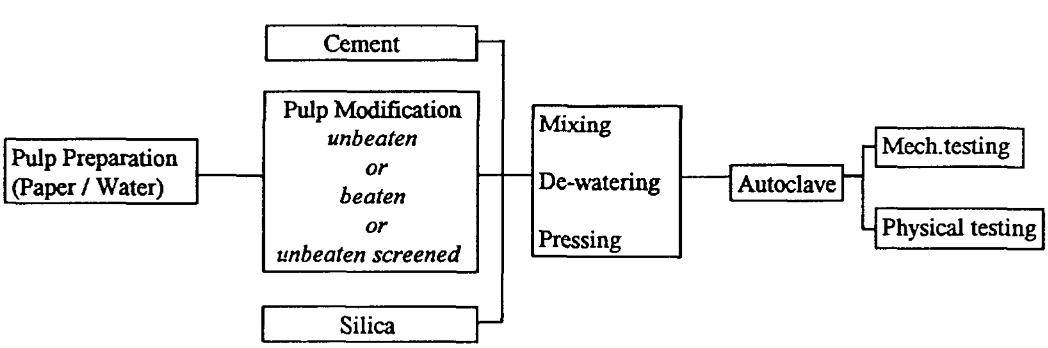

Fig. 1. Flow chart of BFRC composites fabrication and characterisation.

finally cured in an autoclave for 7·5 h at 0·86 MPa steam pressure (175°C).

Test methods

Specimens were cut with a diamond saw to specified dimensions and stored under a controlled atmosphere of 50 ± 5% relative humidity and 22 ± 2°C for seven days before testing.

Specimens measuring 125 × 40 mm and of varying thickness (about 6 mm) were tested for values of flexural strength and fracture toughness. The modulus of rupture (MOR) was measured in three point bending as $2Pl/3bd^2$, where P = maximum load recorded during test, l = specimen width, and d = specimen depth. A span of 100 mm and a deflection rate of 0·5 mm min^{-1} was used on an Instron testing machine (Model 1114).

The fracture energy was calculated from the area under the load/deflection curve when the failed specimen reached 50% maximum load. The fracture toughness is defined in this study as fracture energy divided by the specimen cross-sectional area. The comparison of fracture energy or fracture toughness is strictly only valid for samples of the same thickness.

Water absorption values, void volume and density measurements were obtained by the methods laid down in ASTM-C220-75.

In all cases, at least six samples were tested for MOR, fracture toughness, density, void volume and water absorption (Tables 1 and 2). Standard deviations have been included for all properties measured.

Fibre length weighted average was measured on a Kajaani FS-200 fibre length analyser. The fibre length mass distribution was converted from the reported fibre length population distribution (Table 3).

The Canadian Standard Freeness test method (Australian Standard AS 1301·2065-88) is a measurement of pulp drainage. The freeness test used in this study was to indicate the degree of beating.

RESULTS AND DISCUSSION

Results of the various tests are reported in Tables 1–5 and Figs 2–6. Some data from an earlier study of *P. radiata* reinforced autoclaved cement products[5] are reported in Figs 2–4 as reference data.

Table 1. Properties of autoclaved bamboo fibre reinforced cement

Fibre (wt%)	*MOR (MPa)*	*Frac. tough. (kJ m^{-2})*	*Void volume (%)*	*Water abs. (%)*	*Density (g cm^{-3})*
Unbeaten pulp					
2	13·3 ± 0·5	0·08 ± 0·01	35·7 ± 0·5	22·1 ± 0·5	1·62 ± 0·02
4	13·2 ± 1·8	0·13 ± 0·01	38·0 ± 0·9	24·9 ± 0·9	1·52 ± 0·03
6	13·8 ± 0·9	0·20 ± 0·02	39·1 ± 1·0	26·7 ± 1·0	1·46 ± 0·02
8	15·5 ± 1·0	0·29 ± 0·05	43·1 ± 2·2	30·7 ± 1·1	1·41 ± 0·04
10	16·0 ± 0·8	0·39 ± 0·04	45·1 ± 1·7	33·9 ± 1·5	1·33 ± 0·02
12	16·5 ± 1·2	0·49 ± 0·05	45·7 ± 0·9	35·9 ± 1·3	1·27 ± 0·02
14	18·3 ± 1·6	0·62 ± 0·01	45·4 ± 4·9	36·6 ± 6·5	1·26 ± 0·11
16	17·2 ± 1·5	0·77 ± 0·07	48·6 ± 1·4	41·1 ± 2·3	1·18 ± 0·03
18	17·7 ± 1·0	0·96 ± 0·14	49·2 ± 1·2	42·8 ± 2·3	1·15 ± 0·03
20	16·1 ± 0·6	1·08 ± 0·11	50·8 ± 0·8	45·1 ± 2·1	1·13 ± 0·05
22	14·9 ± 1·3	1·20 ± 0·31	50·9 ± 0·6	49·0 ± 2·3	1·00 ± 0·05
Beaten pulp					
2	12·1 ± 0·5	0·10 ± 0·01	34·2 ± 0·6	21·0 ± 0·6	1·63 ± 0·02
4	12·2 ± 1·0	0·13 ± 0·02	37·7 ± 1·1	24·8 ± 1·0	1·52 ± 0·02
6	14·6 ± 1·3	0·22 ± 0·03	39·8 ± 1·5	27·6 ± 1·4	1·44 ± 0·02
8	14·9 ± 1·2	0·29 ± 0·04	41·1 ± 1·1	29·1 ± 1·1	1·41 ± 0·02
10	16·1 ± 0·9	0·40 ± 0·04	44·2 ± 1·3	33·1 ± 1·6	1·34 ± 0·03
12	17·1 ± 1·4	0·50 ± 0·02	44·3 ± 1·4	34·1 ± 1·6	1·30 ± 0·03
14	18·2 ± 1·3	0·50 ± 0·01	42·8 ± 0·8	32·5 ± 1·2	1·32 ± 0·03
16	18·2 ± 1·4	0·56 ± 0·06	44·7 ± 1·5	35·9 ± 2·0	1·25 ± 0·03
18	16·4 ± 0·9	0·82 ± 0·08	46·9 ± 1·1	40·6 ± 1·8	1·16 ± 0·04
20	17·1 ± 1·5	0·97 ± 0·08	47·0 ± 0·8	40·9 ± 1·1	1·15 ± 0·01
22	16·7 ± 1·2	1·03 ± 0·11	47·4 ± 1·0	42·2 ± 1·4	1·12 ± 0·02

BFRC composites were fabricated using Portland cement and silica at the ratio of 1 : 1, auto-claved at 0·86 MPa steam pressure for 7·5 h, and tested at 50 ± 5% RH and 22 ± 2°C. BFRC composites maximum flexural strength at 14% by mass.

Table 2. Properties of autoclaved screened long bamboo reinforced cement

Fibre (wt%)	*MOR (MPa)*	*Frac. tough. (kJ m^{-2})*	*Void volume (%)*	*Water abs. (%)*	*Density (g cm^{-3})*
Unbeaten pulp					
2	13·3 ± 1·4	0·10 ± 0·01	39·1 ± 0·8	24·7 ± 0·8	1·59 ± 0·02
4	14·8 ± 1·5	0·23 ± 0·02	41·2 ± 1·0	27·7 ± 1·1	1·49 ± 0·02
6	16·3 ± 2·2	0·37 ± 0·06	42·6 ± 1·0	30·0 ± 1·3	1·42 ± 0·03
8	18·8 ± 1·2	0·54 ± 0·12	42·6 ± 0·9	30·1 ± 0·9	1·42 ± 0·07
10	21·6 ± 2·2	0·71 ± 0·13	42·7 ± 1·4	32·0 ± 1·4	1·33 ± 0·02
12	19·5 ± 1·5	0·79 ± 0·06	46·6 ± 0·6	37·8 ± 1·4	1·23 ± 0·03
14	18·9 ± 1·9	1·09 ± 0·14	47·0 ± 0·9	39·8 ± 1·7	1·18 ± 0·03

Unbeaten Sichuan bamboo pulp was screened on 0·83 mm hole size Sommerville screen (yield 46%); fibre length weighted average (Kajanni FS200 fibre analyser) was 1·3 mm and the freeness was 550CSF. BFRC maximum flexural strength was at 10% by mass fibre loading, which was similar fibre loading to WFRC.

Table 3. Fibre weighted average length (mm)

Beaten P. radiata	*Unbeaten bamboo*	*Beaten bamboo*	*Screened bamboo*
2·4	1·0	0·8	1·3

Kajanni FS-200 fibre length weighted average calculated as $\S n_i l_i^2 / \S n_i l_i$ (mm), where $l_i = 0{\cdot}05i - 0{\cdot}04$ (mm), $i = 1$ 1/4 144 class i average length, n_i = number of fibres within the i range of length.

Table 4. Fibre length mass distribution percentage

Length (mm) longer than	*Beaten* P. radiata	*Unbeaten bamboo*	*Beaten bamboo*	*Screened bamboo*
0·05	100	99·7	99·7	100
0·4	95·6	71·2	67·3	94·8
0·8	90·0	51·6	42·1	74·3
1·2	81·8	32·2	22·6	51·1
1·6	72·1	19·2	11·4	30·3
2·0	61·3	10·9	5·3	15·4
2·4	48·9	5·9	2·5	7·6
2·8	36·8	3·1	1·3	3·6
3·2	28·0	1·7	0·6	1·6

Fibre length mass distribution percentage was analysed on Kajanni FS-200 fibre length analyser. More than 15 000 fibres were measured and analysed. Length longer than 0·4 mm fibre mass distribution percentage for *P. radiata*, unbeaten bamboo, beaten bamboo and screened long bamboo pulp was 95·6, 71·2, 67·3 and 94·8%, respectively.

Flexural strength

Unbeaten fibre reinforced composites

Table 1 and Figure 2 show the variation in flexural strength of BFRC composites, as the fibre content increased from 2 and 22% in steps of 2%. Figure 2 contains reference data for autoclaved WFRC composites reinforced with kraft pulped *P. radiata* fibres.[5] Flexural strength values for autoclaved BFRC composites increased from about 12 MPa up to 18 MPa, as the fibre content was increased from 2 to 14%, at which point the strength of the composite products decreased,

Table 5. Properties of short *P. radiata* fibre reinforced cement[8]

Fibre (wt%)	*MOR (MPa)*	*Frac. tough. (kJ m^{-2})*
Length 0·3 mm		
2	13·6 ± 1·0	0·07 ± 0·01
4	14·3 ± 0·5	0·09 ± 0·01
6	14·1 ± 0·7	0·13 ± 0·02
8	14·3 ± 1·3	0·18 ± 0·01
Length 1·6 mm		
2	16·2 ± 1·1	0·22 ± 0·02
4	18·1 ± 2·1	0·59 ± 0·07
6	20·9 ± 1·8	0·89 ± 0·11
8	22·3 ± 0·7	1·37 ± 0·17

Air-cured WFRC composites were tested at 50 ± 5% RH and 22 ± 2°C. *P. radiata* original fibre length (weighted av.) was 2·4 mm. Different lengths of fibre (e.g. 0·3 and 1·6 mm) were obtained from Wiley Mill and guillotining *P. radiata* laboratory made handsheets.

with increasing fibre content, due to poor fibre distribution throughout the matrix material. This behaviour was in general agreement with the change in flexural strength observed with autoclaved WFRC composites.

Beaten fibre reinforced composites

Beaten (100 CSF) and unbeaten (400 CSF) BFRC materials gave similar flexural strength values of approximately 18 MPa at 14% fibre (Table 1). With the WFRC composites it was found that beaten *P. radiata* (550 CSF) gave a maximum flexural strength of 24·3 MPa at 10% fibre loading.[5] This was an improvement over products reinforced with unbeaten fibres.

Bamboo has a fibre length about half that of *P. radiata* (Table 3). The bamboo fibre used in this study was separated from commercial packing paper and there was a higher fines content in both the beaten and unbeaten pulps. The beaten and unbeaten bamboo pulp fines (lengths < 0·4 mm) accounted for 32·7 and 28·8% of the mass,

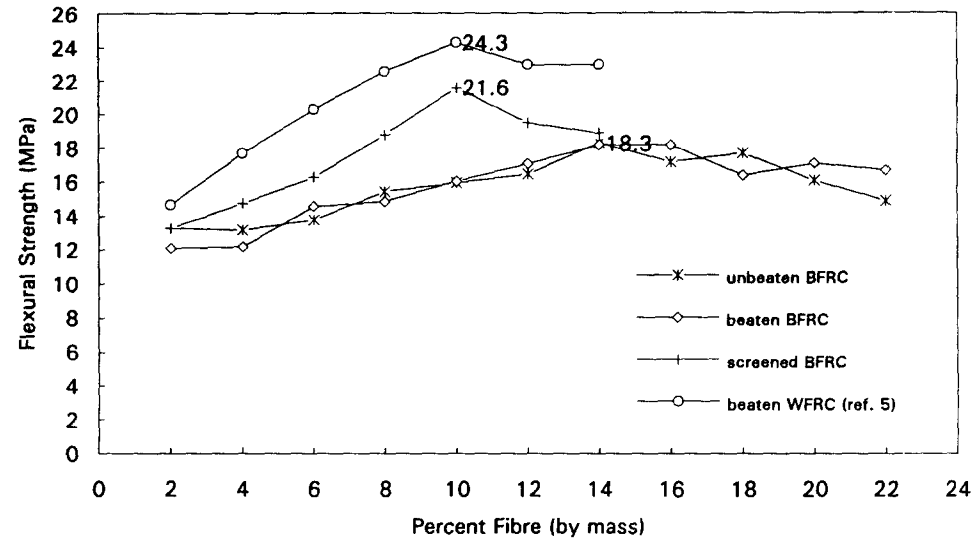

Fig. 2. Flexural strength as a function of percentage fibre loading for autoclaved BFRC and WFRC composites.

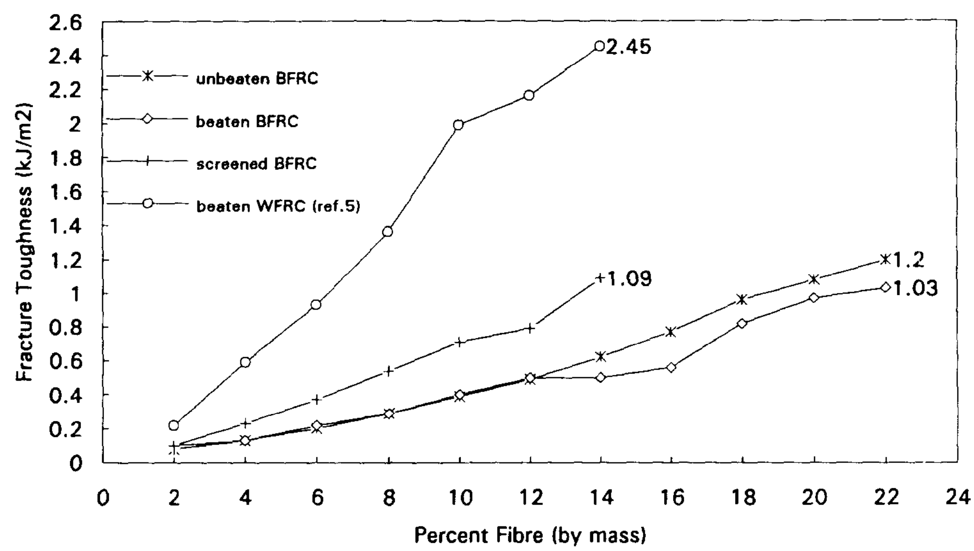

Fig. 3. Fracture toughness as a function of percentage fibre loading for autoclaved BFRC and WFRC composites.

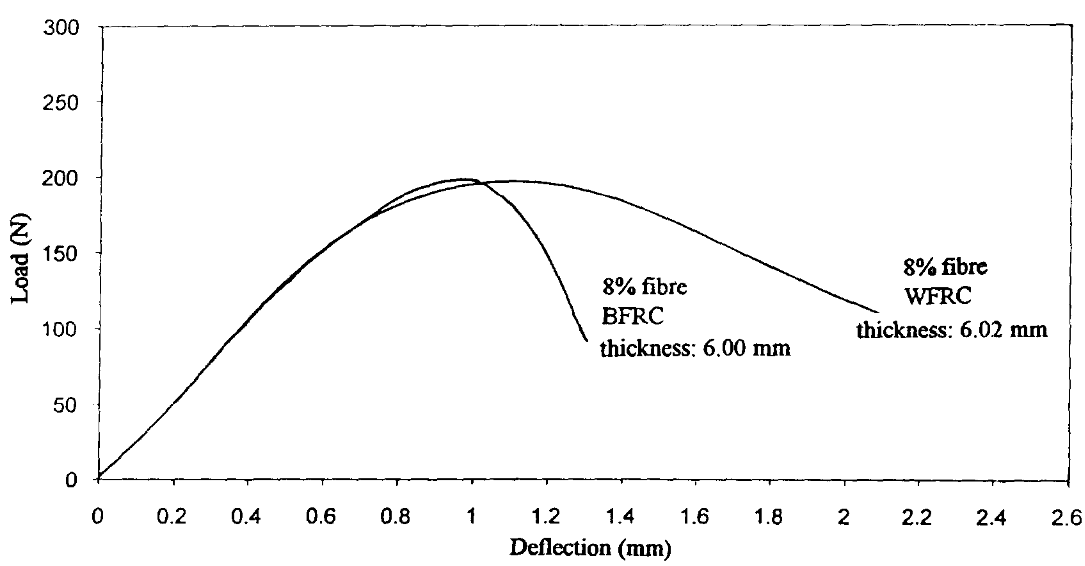

Fig. 4. Typical load/deflection graph for autoclaved WFRC and BFRC specimens.

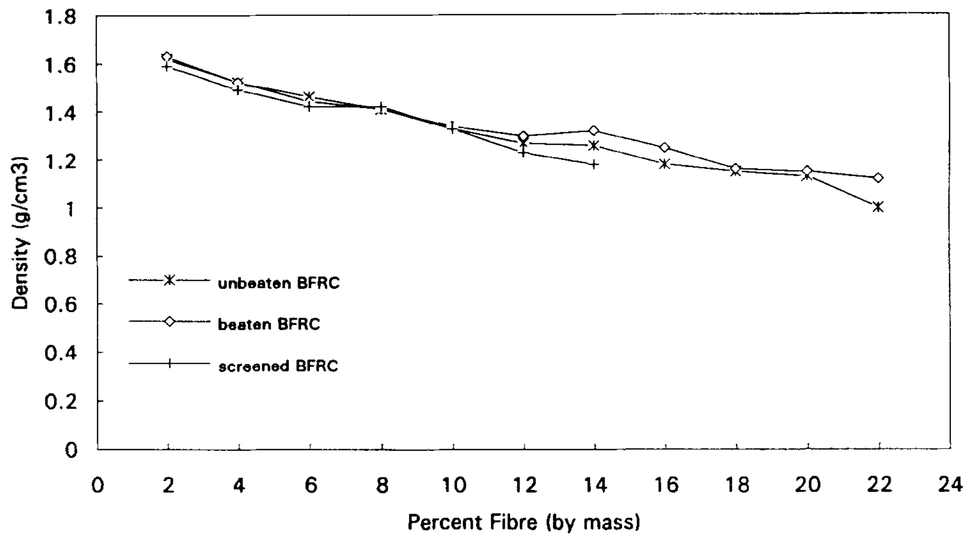

Fig. 5. Density as a function of percentage fibre loading for autoclaved BFRC and WFRC composites.

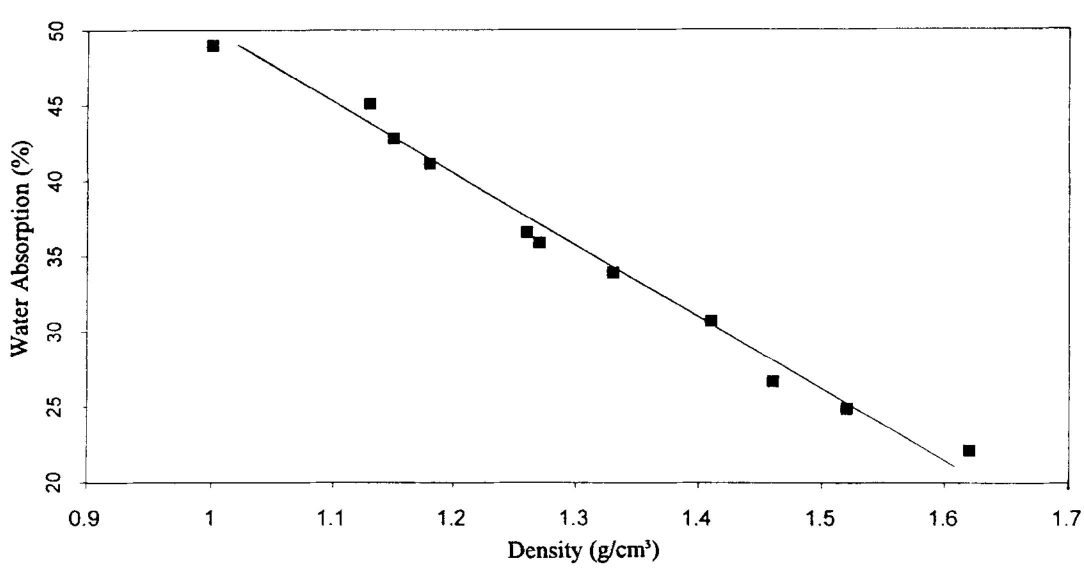

Fig. 6. The relationship between density and water absorption for autoclaved BFRC composites.

respectively (Table 4). This suggests little damage occurred during beating.

Screened fibre reinforced composites

Bamboo pulp was screened to remove fines and to obtain the longer fibres for use as reinforcement. Compared with unscreened unbeaten fibre the screened fibre showed improved composite flexural strength at the same fibre loading. The maximum flexural strength of screened BFRC was 21·6 MPa at 10% fibre loading (Table 2).

Fibre length can make a significant contribution to the composite's flexural strength. Softwood *P. radiata* fibre, and screened and unscreened unbeaten bamboo fibres, had fibre lengths (length weighted average) of 2·4, 1·3 and 1·0 mm, respectively (Table 3). The flexural strengths of materials reinforced with wood fibre, and screened and unscreened unbeaten bamboo fibres were 24·3, 21·6 and 16·0 MPa, respectively, at 10% fibre by mass (Fig. 2).

The flexural strength of unscreened BFRC materials (beaten and unbeaten) increased up to 14% fibre before the maximum value was reached. This could be due to the fact that the fine material (length < 0·4 mm) offers little reinforcement to the composite and so a greater mass of pulp was needed to have sufficient numbers of long fibres. When fines (lengths < 0·4 mm) were removed, maximum strength was achieved with fibre loadings between 8 and 10%, which is in keeping with the early study of WFRC composites.[5] The percentage of screened bamboo pulp fibre lengths longer than 0·4 mm was 94·8% of its mass. This is similar to the data for *P. radiata* pulp (Table 4).

A fibre length fractionation study of *P. radiata* wood pulp[8] confirms the belief that fragments with length less than 0·3 mm act more as a filler-diluent than as a reinforcing fibre when used to make WFRC products (Table 5). A similar behaviour regarding the maximum flexural strength value with respect to fibre mass content (about 12%) was noted for waste paper fibre reinforced cement products.[7] In that instance, the high fibre content was required to provide sufficient mass of the longer reinforcing fibres. This was due to the high fines content generated (lengths $< 0{\cdot}6$ mm constituted 21·2% by mass) during processing and recycling.[7]

There is little difference between beaten and unbeaten BFRC composites with respect to flexural strength, which contrasts with the observations reported in the earlier research on beaten and unbeaten *P. radiata* WRFC composites.[5] Similar behaviour to that of autoclaved BFRC was found in the case of autoclaved New Zealand (NZ) flax reinforced cement composites[6] and air-cured bamboo reinforced cement products.[3] This might be associated with the fact that the round and small diameter NZ flax and bamboo fibres do not have lumens and, hence, are unable to collapse, as can softwood fibres, which form flat ribbons. Alternatively, it may be due to the beating, generating fines which do not contribute to the composites strength. This behaviour is currently under investigation and will be reported at a later date.

Fracture toughness

The mechanism that takes place when a fibre composite is loaded to failure include fibre fracture and fibre pull-out. The latter can have considerable influence on the value of fracture toughness. If the fibre is short then the energy required to pull the fibre through the matrix, after the fibre to matrix bond is broken, is low and can contribute little to the dissipation of energy contained in the advancing crack. Therefore the crack continues through the sample and the material appears brittle.

Figure 3 shows the increment in fracture toughness values of beaten and unbeaten BFRC composites (from 0·10 kJ m^{-2} to 1·03 kJ m^{-2} and from 0·08 kJ m^{-2} to 1·20 kJ m^{-2}, respectively) for fibre loading from 2 to 22%. The same graph has reference data for WFRC composite fracture toughness, which are seen to have higher values.[5] Screened BFRC composites, which contain more long fibres, are tougher (from 0·10 kJ m^{-2} to 1·09 kJ m^{-2} for fibre loadings from 2 to 14% (Fig. 3)) than unscreened composites. Unbeaten BFRC composites are slightly better than beaten ones at the high fibre loadings.

WFRC composites indicated better properties of fracture toughness than BFRC composites in the three point bending load/deflection curve, as shown in Fig. 4. After reaching the maximum load, the curve for WFRC composites went through a gradual 'tailing off' which indicated that a greater amount of energy was needed to pull the long fibres through the matrix. The curve for the BFRC composites did not show such behaviour and they were more brittle. This is indicated by a sharp 'drop off' of load carrying capacity in the load/deflection curve. Fracture toughness behaviour is related to fibre length and fibre morphology, and comparison is only valid for specimens of the same thickness.[8,9]

Beaten BFRC composites did not vary greatly in fracture toughness values from those of the unbeaten BFRC composites. At high fibre loadings the beaten BFRC composites showed slightly lower values due probably to the increased amount of fines present in the formulation (Table 4). As stated above, the presence of fines provides less opportunity for fibre pull-out being a major component in the mechanism of failure, and hence lower fracture toughness values are observed. The observed failure mechanisms taking place in WFRC composites have been studied by Coutts and Kightly and reported at length.[9,10]

The above argument is strengthened by the data shown in Table 5, which shows the reinforcement properties of different fractions of fibre length generated from a single pulp made from kraft *P. radiata*. When short fragments of fibres (length weighted average 0·30 mm) are used to make WFRC composites and are compared with composites made using longer fibres (length weighted average 1·60 mm), a drastic reduction in fracture toughness is observed. For example, at 8% by mass the short fibre samples show a sevenfold decrease in fracture toughness.

Physical properties

The changing proportions of the constituent fibres and matrix affect void volume, density and water absorption (Tables 1 and 2). There is little difference in the density of the composites when the bamboo fibre was beaten compared with the materials containing unbeaten bamboo fibre (Fig. 5). However, the same graph shows a slight decrease in density, at a given fibre content, when the pulp has been screened to remove the fines. This effect is possibly due to the increase in fines, present in the unscreened pulps, which allows closer packing of the fibres and matrix, and hence less void volume in the composite.

The relationship between water absorption and density is depicted in Fig. 6. The amount of water absorbed by the cellulose fibre reinforced cement composites depends on their void volume and the amount of cellulose material present; both these parameters have an effect upon density. Thus, one would expect the density to decrease and the water absorption to increase as the fibre content is increased, due to the nature of the hydrophilic, low density bamboo fibres. At the same time the packing of fibres and matrix becomes less efficient as the fibre content is increased, and so void volume increases accompanied by decreased density and increased water absorption.

CONCLUSIONS

Bamboo fibre is a satisfactory fibre for incorporation into the cement matrix.

Autoclaved BFRC products have flexural strength values of about 18 MPa at fibre loading of 14% by mass. However, the fracture toughness is low due to short fibre length and high fines content of the bamboo pulp.

By screening out 'fines' contained in the original bamboo pulp the flexural strength values can be improved to greater than 20 MPa while fracture toughness exceeds 1·0 kJ m^{-2} at a loading of 14% by mass of fibre.

In contrast to softwood fibre reinforced cement composites, beaten bamboo fibre composites did not vary greatly in flexural strength and fracture toughness values from those of the unbeaten fibre composites.

It would be expected in some countries such as China, India, and within the South East Asia region, where there is a lack of softwood fibre, but which have an abundance of bamboo plantations as ready fibre sources, that bamboo fibre has potential for commercial application in the building materials industry.

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