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Potential of alternative fibre cements as building materials for developing areas

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Abstract

This project evaluated the performance of thin fibre-cement elements produced from alternative raw materials using the Hatschek process, with a view to their use in low-cost housing. Sisal and banana fibres were prepared using mechanical and kraft pulping procedures while residual *Eucalyptus grandis* pulp was obtained from a commercial pulp mill. Granulated blast furnace slag (BFS) was used as the major component of an alternative hydraulic binder and ordinary Portland cement as a control. Composites were prepared using a slurry vacuum de-watering process, pressing and air-curing. At fibre contents of 8–12% by mass, moduli of rupture (MOR) up to 23 MPa and fracture toughness (FT) values in the range of 0.6–1.7 kJ/m^2 were obtained at 28 days. After 12 months of exposure under temperate and tropical conditions, the MOR of the BFS-based composites had decreased to values in the range of 6.6–10.1 MPa. FT values remained stable or even increased with the weathering exposure. The results indicate that the mechanical performance of the composites being studied is currently satisfactory, but further optimisation of formulation and processing parameters should be investigated.

Keywords: Fibre-cement; Construction materials; Blast furnace slag; *Eucalyptus grandis* pulp; Sisal pulp; Banana pulp; Microstructure

1. Introduction

In several developed countries, cellulose fibres derived from hardwoods or softwoods are used for the production of cement composites by adaptation of the former asbestos-cement production processes [1]. Asbestos cement still represents around 74% of the 190 million m^2 of fibre-cement composites produced yearly in Central and South America, mostly as corrugated roofing elements as noted by Heinricks et al. [2]. As increasing health concerns [3,4] are leading to chrysotile asbestos bans in Latin American countries (e.g. Brazil and Chile), new products utilising available raw materials and production systems are necessary to fit consumer requirements in each application area. Research toward this end has been in progress for some time.

Tropical and equatorial countries are known for their plant fibre production [5] and the consequent generation of by-products from commercial, agricultural and industrial activities. With the low cost of raw material and simplified pulping methods, the resulting cellulose has considerable potential for fibre-cement production at significantly lower costs than those associated with the use of conventional kraft wood pulps produced for the paper market.

Granulated blast furnace slag (BFS) can provide advantages when used as a substitute for ordinary Portland cement (OPC). These may include energy savings, lower CO_2 emissions, cost reductions and an abundant availability in steel producing areas [6]. However, the hydration rate of BFS-based cement is known to be lower than that of OPC and to be strongly dependent on the degree of fineness and cure procedures employed [7].

The main objective of this collaborative work undertaken by the Commonwealth Science and Industry Research Organisation (CSIRO), Division of Forestry and Forest Products, Australia, and the University of São Paulo, Brazil, is to evaluate the production of thin alternative fibre-cement elements by the Hatschek process for use in low-cost housing. This paper presents

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an overview of the performances of clinker free cements reinforced with several waste-based pulps. The short term properties of these materials and the effects of ageing under three different environmental conditions are discussed.

2. Raw materials and preparation

Basic granulated iron BFS provided by Companhia Siderúrgica Tubarão (CST), Brazil, and fully characterised by Oliveira et al. [8], was ground to an average Blaine fineness of 500 m^2/kg and employed as the main component of an alternative binder. Ground agricultural gypsum and construction grade hydrated lime were used as activators in proportions varying from 0.88:0.10:0.02 to 0.92:0.06:0.02 (BFS:gypsum:lime) by mass. These formulations are identified as BFS 10G2L and BFS 6G2L respectively working this paper. Adelaide Brighton brand OPC, Type GP (Australian Standard AS 3972-1991), was used as the reference matrix.

Three different types of Brazilian fibrous residue were selected on the basis of their availability and relatively low levels of contamination: waste *Eucalyptus grandis* kraft pulp, with an estimated availability of 30,000 tonnes/year; sisal (*Agave sisalana*) field by-product, with an estimated 100,000 tonnes/year available; and banana (*Musa cavendishii*, nanicão variety) pseudo-stem fibres, with a potential production of 95,000 tonnes/year in Ribeira Valley, the main producing area in Sao Paulo state.

The waste *E. grandis* pulp was used as received after a 2 min disintegration and washing in hot (90 °C) water. The sisal and banana strands were subjected to kraft pulping as detailed by Savastano et al. [9]. Each pulp produced was passed through a 0.23 mm Packer screen, vacuum de-watered, pressed, crumbed and stored in a sealed plastic bag under refrigeration. The kraft-pulped banana fibre was refined in a laboratory valley beater for 20 min with the standard 5.5 kg weight applied, after first having been circulated for a period of 20 min, following the approach of Zhu et al. [10].

Chemi-thermomechanical pulps (CTMPs) were also produced from the sisal and banana strands using procedures based on the recommendations of Higgins [11]. Slivers of by-product sisal and banana were initially chopped to 30 mm in length and soaked for at least 16 h in tap water. The chemical pre-treatment consisted of boiling the strands in a 10% lime (on strand mass) liquor for a period of 1 h on completion of the soak. The strands were then mechanically de-fibred in an Asplund Type D laboratory de-fibrator and post-refined using a 20 cm Bauer laboratory disc refiner fitted with straight-patterned “rubbing” plates.

Table 1
Pulp and fibre physical properties

Fibre	Freeness (ml)	Fines[a] (%)	Length[b] (mm)	Width[c] (μm)	Aspect ratio
E. grandis	685	7.01	0.66	10.9	61
Sisal kraft	650	3.31	1.66	13.5	123
Sisal CTMP	280	5.61	1.61	10.9	148
Banana beaten kraft	16	9.33	2.03	15.7	129
Banana CTMP	630	2.70	1.99	20.1	99

[a] Arithmetic basis.
[b] Length-weighted basis.
[c] Average of 20 determinations by SEM.

Both mechanical pulps were passed through a Packer screen (0.23 mm slots) to remove unseparated bundles of fibres. Banana CTMP was submitted to a further Somerville screening (0.180 mm mesh) to reduce the incidence of fines of length less than 0.2 mm. Fibre shortening and the generation of fines are typical, although undesirable, outcomes of refining procedures [11] and can be controlled by the application of appropriate energies to the stock during mechanical treatment. Finally, the pulps were vacuum de-watered, pressed, crumbed and stored in sealed plastic bags under refrigeration.

The main physical attributes of the pulps produced are summarised in Table 1. The Canadian Standard Freeness (CSF) of each pulp was determined in accordance with AS 1301.206s-88. CSF is an arbitrary measure of the drainage properties of pulp suspensions and relates well to the initial drainage rate of the wet pulp pad during the de-watering process [12]. Fibre length and fines content were determined using a Kajaani FS-200 automated optical analyser.

3. Composite preparation

Cement composite pads measuring 125 mm × 125 mm and reinforced with 4%, 8% and 12% by mass of the various pulps were prepared in the laboratory using a slurry vacuum de-watering technique previously described by Eusebio et al. [13]. The selection of fibre contents was based on the optimum levels found in a similar study [9]. Pads of each formulation were prepared in groups of three, pressed simultaneously at 3.2 MPa for 5 min, then sealed wet in a plastic bag to cure at room temperature for 7 days.

On completion of the initial saturated air-curing, pads destined for testing at a total age of 28 days were cut wet using a diamond saw into three 125 mm × 40 mm flexural test specimens. Specimen depth was the thickness of the pad, which was approximately 6 mm. The specimens were then allowed to air cure in a laboratory environment of 23 ± 2 °C and $50 \pm 5\%$ relative humidity prior to mechanical and physical testing.

4. Test methods

A three point bend configuration was employed in the determination of modulus of rupture (MOR), fracture toughness (FT) and modulus of elasticity (MOE). A span of 100 mm and a deflection rate of 0.5 mm/min were used for all tests in an Instron model 1185 universal testing machine. Fracture energy was calculated by integration of the load–deflection curve to the point corresponding to a reduction in load carrying capacity to 50% of the maximum observed. For the purpose of this study, the FT was measured as the fracture energy divided by specimen width and depth at the failure location. Nine flexural specimens were tested for each formulation and condition of exposure. The mechanical test procedures employed are described in greater detail by Savastano et al. [9].

Water absorption (WA) values were obtained from six tested flexural specimens following the procedures specified in ASTM C 948-81.

Fracture surfaces of composites were analysed using a Philips XL30 field emission gun scanning electron microscope (SEM). To facilitate fibre observation the images were taken after tilting the samples 75° in relation to the horizontal plane. Observation procedures were similar to those employed by Coutts and Kightly [14].

5. Weathering conditions

To determine the effect of weathering on the properties of the composites, some of the prepared samples were exposed to temperate and tropical weather conditions in Melbourne, Australia, and Pirassununga, Brazil, respectively. The samples were exposed 28 days after manufacture in racks inclined 45° and facing north in Melbourne (latitude 37°49′S) and Pirassununga (latitude 21°59′S). The exposure in Melbourne of composites reinforced with *E. grandis* pulp commenced in April 1999, while the exposure of the remaining samples commenced at both sites in July 1999.

At a total age of 13 months, test specimens were cut as described in the section on test methods and stored in laboratory conditions for 7 days to achieve equilibrium moisture content prior to mechanical testing. Table 2 lists the main long term climate averages for the Australian and Brazilian exposure site.

6. Results and discussion

Table 3 summarises the main mechanical and physical properties of BFS and OPC matrices with different fibre types and contents when tested at age 28 days. Figs. 1–4 compare the range of properties measured at each fibre content with those of corresponding composites after aging. Table 4 details the properties of composites after storage in a controlled environment or exposure to weathering in temperate and tropical conditions for 1 year.

6.1. Composites based on clinker free binders

The processing behaviour of BFS-based matrices in slurry de-watered composite production was akin to that of OPC. The addition of 4% and 8% fibre provided significant improvements in flexural strengths which were more than doubled at the higher loading (Fig. 1). The MOR and FT reached by OPC reinforced with 8% of waste fibres were inside the range of corresponding BFS-based composites (Figs. 1 and 2), confirming the acceptable performance of the alternative binder in fibre-cement products.

At fibre loadings of 4% and 8% by mass, composites based on BFS 6G2L exhibited relatively low strengths, in the region of 13.1–16.8 MPa. The poor performance of composites based on this formulation was probably a result of the lower total activator content failing to promote sufficient matrix strength development to allow effective stress transfer to the reinforcement.

As previously observed in the case of wood fibre reinforced OPC [9,15], FT was the property most improved by the inclusion of reinforcement as highlighted in Fig. 2. Warden et al. [16] previously reported

Table 2
Climate averages

Exposure site	Temperature (°C)		Relative humidity (%)		Average rainfall (mm/year)
	Ave max/month	Ave min/month	Ave max/month	Ave min/month	
Melbourne, Vic, AU[a]	25.8/Jan	5.9/July	82/ June	60/Jan–Dec	654
Pirassununga, SP, BR[b]	30.1/Jan–Feb	9.5/July	77/Jan–Feb	63/Aug	1363

[a] *Source:* Bureau of Meteorology, Australia.
[b] *Source:* Air Force Academy, Defence Ministry, Brazil.

Table 3
Mechanical and physical properties of composites at 28 days[a]

Fibre type	Content (% by mass)	Binder	MOR (MPa)	FT (kJ/m^2)	MOE (GPa)	WA (% by mass)
Nil	–	BFS 6G2L	8.1 ± 2.2	0.03 ± 0.01	11.6 ± 1.7	17.6 ± 0.9
Waste *E. grandis* kraft	4	BFS 10G2L	14.3 ± 0.9	0.25 ± 0.02	8.9 ± 1.1	23.9 ± 1.2
	8		18.0 ± 1.4	0.75 ± 0.11	6.6 ± 0.6	28.0 ± 1.4
	12		18.2 ± 2.8	1.25 ± 0.20	5.0 ± 0.6	32.3 ± 1.7
	8	OPC	21.4 ± 0.9	0.82 ± 0.11	11.4 ± 0.9	20.7 ± 0.7
By-product sisal kraft	4	BFS 6G2L	13.1 ± 0.4	0.53 ± 0.12	7.7 ± 0.7	26.6 ± 0.5
	8		16.8 ± 1.7	1.41 ± 0.22	6.1 ± 0.5	29.0 ± 1.0
	12		14.7 ± 2.0	1.68 ± 0.22	4.3 ± 0.4	33.1 ± 1.3
By-product sisal CTMP	4	BFS 10G2L	15.3 ± 0.9	0.30 ± 0.03	8.4 ± 0.5	26.0 ± 0.4
	8		18.6 ± 0.6	0.82 ± 0.21	6.5 ± 0.5	30.0 ± 0.7
	12		10.6 ± 1.4	1.60 ± 0.28	3.0 ± 0.3	36.8 ± 0.7
	8	OPC	20.8 ± 0.4	0.89 ± 0.19	10.6 ± 0.6	21.1 ± 1.2
Banana beaten kraft	4	BFS 10G2L	15.5 ± 1.4	0.24 ± 0.03	7.7 ± 0.9	25.2 ± 0.3
	8		21.8 ± 1.2	0.59 ± 0.06	6.7 ± 0.6	27.2 ± 0.6
	12		22.8 ± 1.6	1.74 ± 0.31	4.3 ± 0.3	29.3 ± 0.5
Banana screened CTMP	4	BFS 10G2L	17.7 ± 0.4	0.32 ± 0.05	8.5 ± 0.6	26.6 ± 0.5
	8		21.0 ± 1.1	0.76 ± 0.12	6.7 ± 0.5	30.4 ± 1.2
	12		Incomplete setting of binder			
	8	OPC	21.5 ± 1.8	0.60 ± 0.09	10.0 ± 0.6	23.0 ± 1.3

[a] ± single standard deviations of the means indicated.

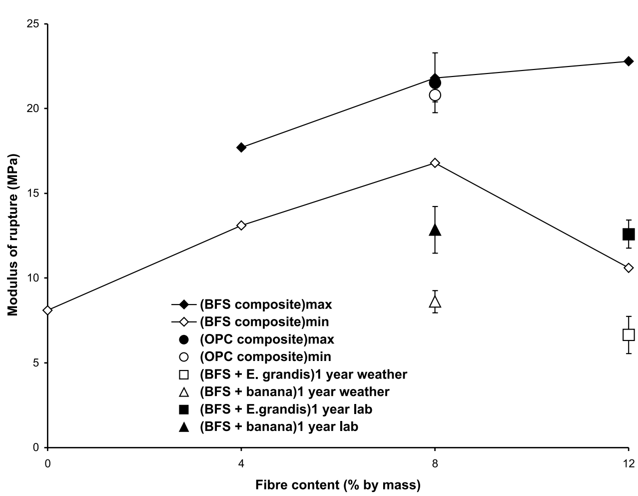

Fig. 1. Variation in MOR with matrix type and fibre content in the short term, and with condition of exposure (laboratory and tropical weathering) in the long term.

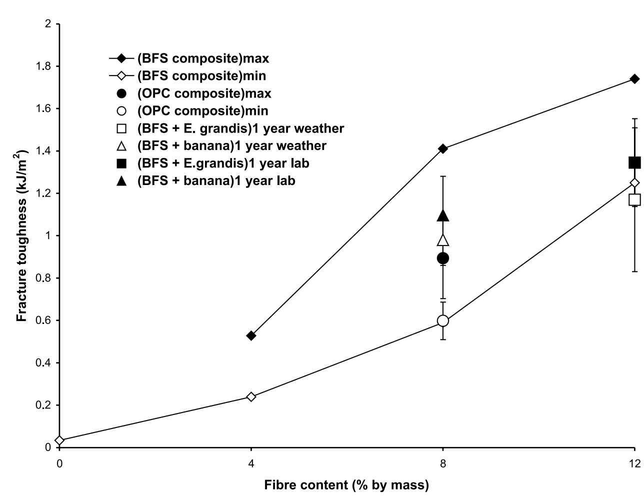

Fig. 2. Variation in FT with matrix type and fibre content in the short term, and with condition of exposure (laboratory and tropical weathering) in the long term.

toughness values in excess of 1.7 kJ/m^2 at a *Pinus radiata* fibre content of 12%, representing at least a 40-fold improvement over neat matrix values. Table 3 shows that BFS 6G2L-based composites developed considerable toughness, in the range of 1.41–1.68 kJ/m^2 at 8% and 12% fibre contents. It is thought that lower matrix strength relative to that of the fibre–matrix bond may have led to an increased contribution to energy dissipation through microcracking processes in the vicinity of fibre surfaces.

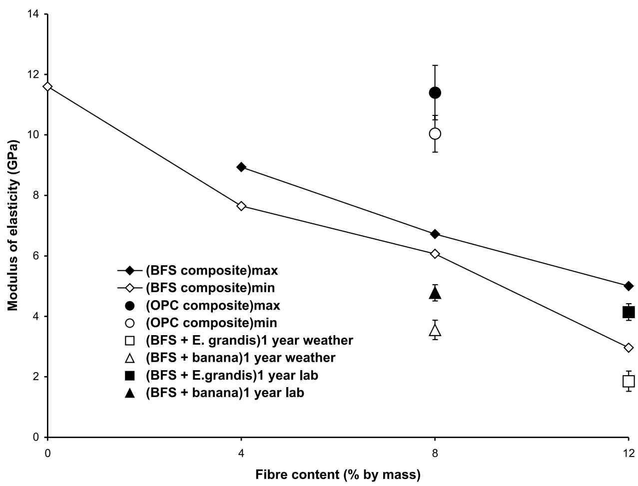

Fig. 3. Variation in MOE with matrix type and fibre content in the short term, and with condition of exposure (laboratory and tropical weathering) in the long term.

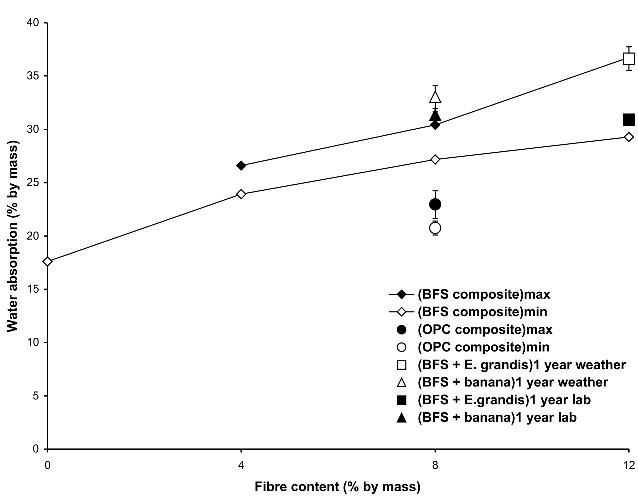

Fig. 4. Variation in WA with matrix type and fibre content in the short term, and with condition of exposure (laboratory and tropical weathering) in the long term.

Elastic moduli fell with increasing fibre content, in a similar fashion to that previously observed in the case of OPC-based materials [9,15], and were in the region of 6.5 GPa at a content of 8% (Fig. 3). They were consistently lower than those of the corresponding OPC composites—a drawback to the use of clinker free matrices in practical applications.

The BFS-based materials possessed significantly higher WA values than the OPC-based reference materials at an 8% fibre loading (Fig. 4). This behaviour is connected to higher permeable void volumes and hence lower density values of these alternative binders. At fibre contents of 12% the WA values of BFS-based materials reached 37% by mass, which is the limit acceptable by Brazilian Standards (NBR-7581/93) for corrugated sheets of asbestos cement.

Mixtures of gypsum and lime were chosen as the means of activating the BFS in view of their reported effectiveness and low pore water alkalinity [8]. A number of previous studies employing different activators have reportedly found BFS-based mortars and concretes to have lower permeable void volumes than OPC-based equivalents [17,18]. Alternate means of activation, and the effects of variations in production parameters such as compaction pressure [19] and curing environment [7], warrant investigation in an effort to reduce the WA values and permeable void volumes of BFS-based fibre cements. This would increase the usefulness of BFS composites as building materials.

6.2. The use of waste-derived pulps

Kraft pulps of softwoods such as *P. radiata* are a preferred reinforcement in commercial fibre cements produced using the Hatschek process. The long, low lignin content fibres are readily refined to increase their compliance, which aids compaction, and generate fibrillation to assist in web formation. This also was the case with beaten banana kraft pulp, which provided the

Table 4
Mechanical and physical properties of BFS 10G2L-based composites at 13 months[a]

Fibre		Exposure condition	MOR (MPa)	FT (kJ/m^2)	MOE (GPa)	WA (% by mass)
Type	Content (% by mass)					
Waste *E. grandis* kraft	12	Lab.	12.6 ± 0.8	1.35 ± 0.21	4.1 ± 0.3	30.9 ± 0.4
		Vic., AU	8.6 ± 0.7	1.14 ± 0.16	2.4 ± 0.3	33.0 ± 1.6
		SP, BR	6.6 ± 1.1	1.17 ± 0.34	1.9 ± 0.3	36.6 ± 1.1
By-product sisal CTMP	8	Lab.	13.1 ± 1.1	1.43 ± 0.25	4.7 ± 0.3	30.8 ± 0.6
		Vic., AU	10.1 ± 1.3	1.16 ± 0.19	3.8 ± 0.6	30.4 ± 1.3
		SP, BR	7.7 ± 1.7	1.01 ± 0.27	3.5 ± 0.8	33.4 ± 1.7
Banana CTMP	8	Lab.	12.8 ± 1.4	1.10 ± 0.18	4.8 ± 0.3	31.3 ± 0.3
		Vic., AU	8.8 ± 1.0	1.05 ± 0.17	3.2 ± 0.5	33.8 ± 1.4
		SP, BR	8.6 ± 0.7	0.98 ± 0.12	3.6 ± 0.3	33.0 ± 1.1

[a] ± single standard deviations of the means indicated.

best performance in terms of flexural strength in BFS matrices at pulp loadings of 8% and 12%. These materials possessed strengths of approximately 22 MPa (Table 3 and Fig. 1), similar to those of the corresponding OPC reference composites. Chemical pulps are, however, expensive and mill capital costs demand unacceptable investment levels. Mechanical pulps, in which most of the original lignin is retained, can provide adequate reinforcement in air-cured wood fibre-cement products [20]. These pulps are cheaper to produce and smaller mills can be operated viably at lower outputs, with less capital outlay and with reduced effluent problems.

The range of strength and FT values exhibited by BFS-based composites reinforced with CTMPs of sisal and banana are shown in Table 3. Mean strengths at a fibre content of 8% by mass were between 19 and 21 MPa. This figure compares favourably with the strengths obtained for air-cured OPC reinforced with *P. radiata* CTMP [20] or kraft pulped banana fibre [9,10]. The mechanical behaviour of BFS-based composites dropped drastically at the 12% content of the waste-derived banana and sisal CTMPs. The substantial amount of lignin and extractives remaining in the fibres may have led to disruption of matrix hydration and incomplete setting of composites at higher loadings of banana CTMP.

BFS incorporating 12% of waste *E. grandis* kraft fibre exhibited a FT value of 1.25 kJ/m^2, considerably lower than the values for composites with the same loading of sisal or banana pulp (Table 3). The short length of the hardwood pulps (Table 1) is recognised as the main reason for the low energy absorption during failure. Fibre pullout is limited at the post-cracking stage, and is confirmed by the image of the fracture surface in Fig. 5.

MOE and the physical properties of composites containing the five different types of waste pulps were similar at the several fibre loadings (Table 3). At 4% fibre content the *E. grandis* reinforced material was more dense and stiffer, probably due to the smaller fibre dimensions allowing better consolidation at this loading. Greater fibre compliance might also be expected as a result of lignin removal during chemical pulping.

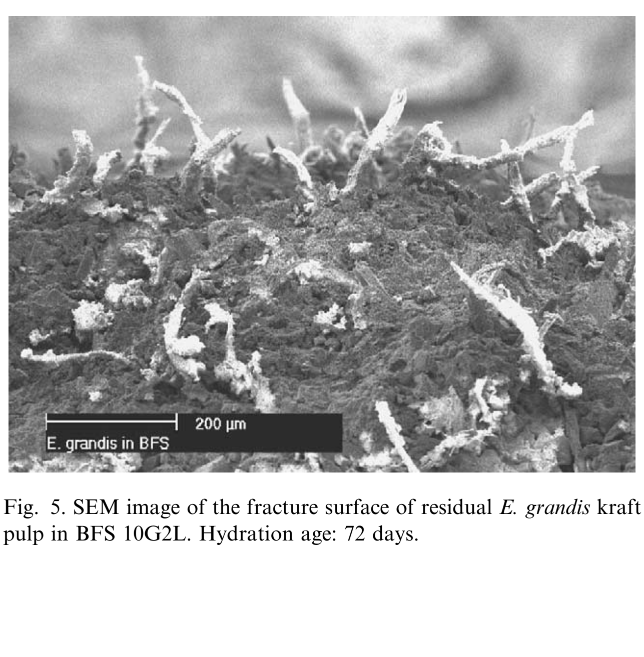

Fig. 5. SEM image of the fracture surface of residual *E. grandis* kraft pulp in BFS 10G2L. Hydration age: 72 days.

The results of this work represent a significant improvement over those previously reported by Savastano et al. [21]. In the earlier study, which used a dough mixing process for composite preparation, MOR values of less than 5 MPa were reported for BFS 10G2L-based mortars reinforced with waste *E. grandis* pulp.

6.3. The weathering effect

Fig. 1 shows one year of external exposure to tropical weather resulted in a considerable reduction in strength, which had fallen to 6.6 MPa in the case of the 12% *E. grandis* formulation exposed in Brazil. The loss in mechanical strength of composites subjected to either natural weathering or ageing in the controlled environment is mainly attributable to matrix carbonation. Such a mechanism [17] consumes calcium ions from ettringite and from the calcium hydroxide occasionally present in BFS cement, and simultaneously lowers the Ca/Si ratio of the calcium silicate hydrate as discussed by Taylor [22]. Qualitative evaluation using an indicator solution of 2% phenolphthalein in anhydrous ethanol revealed that the aged composites were completely carbonated.

The greater severity of a tropical environment on composite properties can be attributed to a subsequent leaching under the action of rainwater (Table 2) and to the propagation of microcracks generated by the cyclic action of temperature and moisture. WA values support such a supposition (Tables 3 and 4). After 13 months of external weathering the WA of composites with 12% *E. grandis* kraft and 8% sisal or banana CTMP in BFS 10G2L reached 37% and 33% by mass respectively, exceeding their values at 28 days and after long term storage in a controlled environment.

MOE dropped to between 1.9 and 4.1 GPa after 13 months weathering. 12% *E. grandis* in BFS was again the worst performer (Fig. 3 and Table 4).

Fig. 2 and Table 4 show that, after a period of weathering or laboratory ageing, composites demonstrated FT values similar to or even higher than those at 28 days. 8% banana CTMP in BFS exposed in any of the environments possessed a toughness of about 1.0 kJ/m^2, which corresponds to an increase of more than 30% in comparison with the short term value. The improvements in ductility can be linked to the losses in MOR and MOE, confirming the expected compromise between strength and ductility in such composites.

FT values in the range of 1.0–1.2 kJ/m^2 after a year of weathering indicate that the integrity of the fibres within

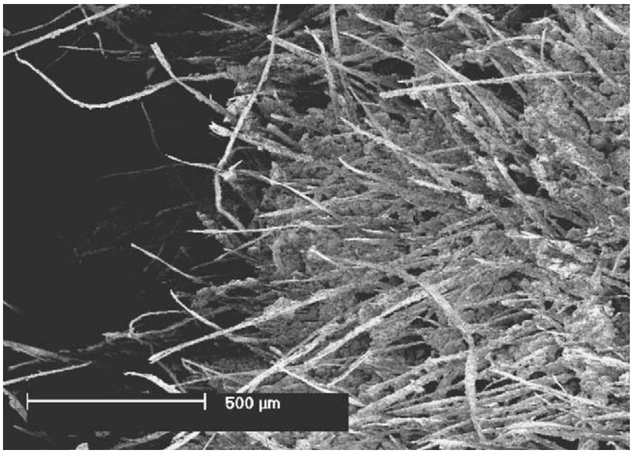

Fig. 6. SEM image of the fracture surface of banana CTMP in BFS after 12 months exposure to a temperate climate.

the lower alkalinity matrix has not been significantly reduced by decomposition or petrifaction.

In a previous study of sisal, malva and coconut strands in OPC, Savastano and Agopyan [23] reported reductions of at least 50% in ductility after only 6 months in a laboratory ambient. Tolêdo Filho et al. [24] and Bentur and Akers [25] noticed similar embrittlement in aged vegetable fibre-OPC composites and found that it could be directly attributed to the petrifaction of the reinforcement through the migration of hydration products to the fibre lumens and pores.

Examination of the fracture surfaces of weathered composites revealed still no evidence of fibre petrifaction and confirmed that the fibres remained in good condition. Fibre pullout rather than fracture was predominant in all of the composites, as would be expected in light of their toughness values. A fracture surface of 8% banana CTMP in BFS is shown in Fig. 6 with fibres largely intact. This suggests that the fibre–matrix interface or the matrix itself has weakened, in turn weakening the composite but improving its toughness by allowing greater dissipation of energy through the mechanism of fibre pullout.

7. Conclusions

Five alternative pulps based on by products from agriculture or the papermaking industry were suitable as reinforcement for fibre cements based on clinker-free binders and produced by a slurry vacuum de-watering method. When first prepared the flexural strengths and toughness of these BFS-based composites reached values up to 23 MPa and 1.7 kJ/m^2 respectively, very close to those achieved with corresponding OPC-based materials. However, the large amount of vegetable fibres employed (up to 12% by mass of the composite) produced low values of MOE, down to 3 GPa, and WA exceeding 36% by mass.

Composites based on the alternative cement suffered a severe lowering in flexural strength and MOE after exposure for one year to temperate or tropical environments. The reductions could be attributed to matrix carbonation followed by leaching and progressive microcracking. Further steps of this ongoing study may overcome this undesirable performance by refinement of the pore structure of the BFS matrix.

FT remained stable in the long term for the waste pulps in BFS, indicating fibres are retaining their integrity with satisfactory bonding to the cement matrix. This study represents an important improvement relative to previous studies on similar materials reinforced with OPC matrices and non-pulped fibres. The further optimisation of BFS activation and pulping procedures applied to waste fibres, in addition to formulation and processing adjustments for the composite, are imperative in providing fibre-cement production for low-cost housing in developing areas.

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