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Cement & Concrete Composites 23 (2001) 389–397

Cement & Concrete Composites

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# Ground iron blast furnace slag as a matrix for cellulose-cement materials

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Received 19 May 2000; accepted 23 November 2000

**Abstract**

The use of ground iron blast furnace slag (BFS) as a low-cost alternative to ordinary Portland cement (OPC) binders in fibre-cement products was examined. Both high quality softwood fibres and residual sisal from agricultural waste were chemically pulped and used as reinforcement. Composites based on several different binder formulations consisting of slag chemically activated by mixtures of gypsum and hydrated lime displayed their optimum strength and fracture toughness properties at fibre contents between 8% and 12%, with values in the ranges of 14.7–24.5 MPa and 1.13–2.36 kJ/m$^2$, respectively. Corresponding flexural moduli lay in the range 4.3–7.8 GPa and, at 12% fibre content, the composites possessed water absorption values up to 34% by mass and densities in the region of 1.3 g/cm$^3$. A formulation of BFS activated by 10% gypsum and 2% lime presented a good compromise between strength and energy absorption combined with a reasonable price. 

*Keywords:* Blast furnace slag; Fibre composites; Sisal pulp; *Pinus radiata* pulp; Recycled materials; Mechanical performance; Low-cost construction

## 1. Introduction

The recycling of residual materials constitutes a present day challenge, especially for low-cost civil construction. In several industrialised countries this is true of blast furnace slag (BFS), a glassy granulated material originating as a by-product of pig-iron manufacture [1]. Despite consumption of basic BFS by its cement industry, in Brazil some 3 million tonnes, with an estimated value of US$ 10/t, are stockpiled every year. To be used as a hydraulic binder the BFS requires grinding to a fineness similar to that of commercial ordinary Portland cement (OPC), which adds a further cost of US$ 15/t, and some form of activation. BFS hydration takes place very slowly at ambient temperatures and chemical or thermal activation, either singly or in tandem, is required to promote acceptable dissolution rates [2,3].

The activation of BFS by OPC is based on the generation of both calcium hydroxide and gypsum. The calcium hydroxide, liberated in the main during the hydration of tri-calcium silicate, provides hydroxyl ions which attack slag grain surfaces while the gypsum reacts to form ettringite related phases [2,4].

The pH of pore water in hardened slag-based materials activated by gypsum and lime combinations is reported to be lower than that in OPC [5]. The lower alkalinity of BFS matrices makes them potentially better suited to vegetable fibre reinforcement since some components of natural fibres, notably lignin and hemicellulose, are known to be susceptible to degradation in the highly alkaline environment of Portland cement [6].

In the present work BFS – activated either by OPC or gypsum and lime combinations – was used as a binder for cellulose-cement composites prepared by a slurry vacuum de-watering method. Both *Pinus radiata* and sisal kraft pulps were studied as reinforcement, with a view to preparing panel products suitable for housing construction.

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0958-9465/01/$ - see front matter 
PII: S0958-9465(00)00083-4

## 2. Materials and methods

### 2.1. Materials and preparation

Alkaline granulated iron BFS (glass content ~99.5% by mass) obtained from Companhia Siderúrgica Tubarão (CST), Brazil, was used as the major matrix component. Table 1 shows the BFS chemical composition to be similar to that used in previous studies [1,7] and to meet the Australian standard requirements for use with Portland cement [8]. The BFS provided was ground using a ball charge laboratory mill to an average Blaine fineness of 500 $m^2$/kg and stored in sealed plastic bags.

Two types of chemical alkali-activation of the BFS were examined:

- OPC, as suggested by Richardson et al. [2] and Sato et al. [9], in proportions of 5% and 10% by mass of binder.
- Gypsum and lime, as proposed by John et al. [10] and Regourd [11]. Five combinations were examined to enable a comparison of the individual performances of gypsum (from 6% to 10% of binder mass) and lime (from 2% to 8% of binder mass). The selected range of activator proportions embraced those shown to produce acceptable results with similar slag cements in previous studies [5,10].

Commercial OPC – Adelaide Brighton brand, Type GP (Australian Standard AS3972 1991) – was employed as the matrix in composites prepared as controls for the purpose of mechanical performance comparison.

Two cellulose pulps were used for reinforcement:

- *P. radiata* kraft (chemical) pulp obtained from Kinleith, New Zealand. The supplied lap was disintegrated in cold water and refined in a laboratory Valley beater (20 min free circulation followed by 20 min with a 5.5 kg weight applied). This fibre was chosen to enable comparison with well-documented data regarding its performance in wood fibre-reinforced cement (WFRC) products for civil construction [12,13].
- Sisal (*Agave sisalana*) kraft pulp prepared in the laboratory under the conditions listed in Table 2, following procedures previously adopted by Coutts and Warden [14]. The strand fibre from which the pulp was produced is a by-product of the Brazilian cordage industry (~169,000 tonnes annual production [15]) and accounts for 75% by dry mass of the sisal crop. Strands were mechanically cleaned and cut into shorter lengths to facilitate handling prior to pulping. Pulping was carried out batchwise in pressure vessels. After cooking, the pulp was washed, mechanically disintegrated and screened in accordance with standard laboratory procedure [16].

Both pulps were vacuum and pressure de-watered, crumbed and stored in sealed plastic bags under refrigeration until used. Pulp and fibre properties are summarised in Table 3.

Table 1
Chemical composition of granulated BFS (% by mass) [5]

| | | | |
|---|---|---|---|
| Loss on ignition | 1.67 | $SO_3$ | 0.15 |
| $SiO_2$ | 33.78 | $Na_2O$ | 0.16 |
| $Al_2O_3$ | 13.11 | $K_2O$ | 0.32 |
| $Fe_2O_3$ | 0.51 | $S^{2-}$ | 1.14 |
| CaO | 42.47 | Free CaO | 0.1 |
| MgO | 7.46 | Insoluble residue | 0.53 |

Table 2
Sisal kraft pulping conditions

| Parameter | Value |
|---|---|
| Active alkali (as $Na_2O$) | 9% |
| Sulphidity (as $Na_2O$) | 25% |
| Liquor/sisal ratio | 5:1 |
| Temperature | 170°C |
| Time at temperature[a] | 120 min |
| Total yield | 55.4% |
| Screened yield[b] | 45.5% |

[a] The time to temperature was 75 min using an electrically heated air-bath.
[b] Passing a 0.23 mm Packer screen.

### 2.2. Composite preparation

Fibre-reinforced cement composites with fibre fractions ranging from 4% to 12% by mass were prepared in the laboratory by a slurry vacuum de-watering technique. Neat BFS and OPC matrices were produced as controls using the same procedure. The 26 combinations of binder formulation and fibre loading that were examined are listed in Table 4. Included in Table 4 are cost estimates for each binder formulation in the Brazilian

Table 3
Pulp and fibre properties

| Parameter | Sisal | *P. radiata* |
|---|---|---|
| Kappa number[a] | 31.7 | 17.0 |
| Canadian Standard Freeness (ml)[b] | 650 | 610–650 |
| Fibre length (mm)[c] | 1.65 | 1.72 |
| Fibre width (μm)[d] | 13.5 | 32.4 |
| Aspect ratio | 122 | 53 |
| Specific gravity (g/$cm^3$)[e] | 1.5 | 1.5 |
| Tensile strength (MPa)[e] | 300 | 500 |

[a] Appita P201 m-86.
[b] AS 1301.206s-88.
[c] Length-weighted average, Kajaani FS-200.
[d] Average of 20 determinations by scanning electron microscopy (SEM).
[e] Coutts [12].

market. BFS and activators were dry-mixed prior to water addition.

In the case of formulations incorporating 8% and 12% of fibre, matrix materials were added to the appropriate amount of moist fibres, pre-dispersed in water, to form a slurry of approximately 20% (by mass) solids. For 0% and 4% fibre content, slurries of about 65% and 30% solids, respectively, were employed to minimise material segregation during de-watering. After stirring for 5 min (or 2 min for plain matrices) using a high-speed laboratory mixer, the slurry was rapidly transferred to an evacuable $125 \times 125$ mm$^2$ casting box. An initial vacuum of between 60 and 80 kPa (gauge) was applied until the bulk of the excess water was removed and a solid surface formed. The moist pad was tamped flat and vacuum re-applied for 2 min. The consolidated pad was then removed from the casting box, transferred to an oiled steel plate and a fine wire mesh placed on top.

Three pads per composite formulation were prepared in this manner, stacked on top of each other and pressed simultaneously at 3.2 MPa for 5 min. In the case of BFS 6G2L-based materials, six pads were prepared to provide sufficient specimens for the determination of flexural properties at two different ages. On completion of press consolidation, the plates and meshes were removed and the pads sealed in a plastic bag to cure in saturated air at room temperature.

After seven days the pads were removed from the bags and three $125 \times 40$ mm$^2$ flexural test specimens were wet diamond sawn from each pad. Test specimen depth was the thickness of the pad, which was in the region of 6 mm. The samples were then allowed to air cure in an environment of $23 \pm 2$°C and $50 \pm 5$% relative humidity until the execution of mechanical tests which were conducted in the same environment.

### 2.3. Test methods

The flexural properties of the materials were measured 28 days after manufacture. In the case of BFS 6G2L-based materials, the mechanical properties were also measured at a total age of 42 days. Nine flexural specimens were tested for each composite formulation and test condition.

A three-point bend configuration was employed in the determination of modulus of rupture (MOR), modulus of elasticity (MOE) and fracture energy. A span of 100 mm, corresponding to a span to depth ratio of approximately 16, and a deflection rate of 0.5 mm/min were used for all tests on an Instron model 1185 universal testing machine. Fracture energy was obtained 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 paper, 'fracture toughness' was measured as the fracture energy divided by specimen width and depth at the failure location. The mechanical test procedures employed are described in greater detail elsewhere [17]. Although the flexural properties of fibre-cements have been found to be size dependent [18,19], and therefore of limited use for design purposes, such data are valuable at the research level for comparison with studies of similar methodology and more so when the prime application under consideration is thin panel products.

Water absorption, bulk density and void volume values were obtained from tested flexural specimens following the procedures specified in ASTM C 948-81. Six specimens were used in the determination of each of these properties.

Property data were subjected to one-way analysis of variance using Tukey's multiple comparison method

Table 4
Binder and composite formulations

| Binder code | Binder formulation (%w/w) | | | | Binder cost[a] (US$/t) | Composite fibre contents (%w/w) |
|---|---|---|---|---|---|---|
| | BFS | OPC[b] | Gypsum[c] | Lime[d] | | |
| BFS 6G2L | 92 | – | 6 | 2 | 25.17 | 0–4–8–12 |
| BFS 10G2L | 88 | – | 10 | 2 | 24.76 | 4–8–12 |
| BFS 8G4L | 88 | – | 8 | 4 | 25.76 | 4–8–12 |
| BFS 10G4L | 86 | – | 10 | 4 | 25.55 | 0–4–8–12 |
| BFS 6G8L | 86 | – | 6 | 8 | 27.54 | 0–4–8–12 |
| BFS 5OPC | 95 | 5 | – | – | 28.12 | 0–4 |
| BFS 10OPC | 90 | 10 | – | – | 31.23 | 0–4 |
| OPC | – | 100 | – | – | 87.32 | 0–4–8–12 |

[a] Estimated cost in Brazil of formulation based on similar raw materials (March, 1999).
[b] Adelaide Brighton brand, Type GP (Australian Standard AS 3972 1991).
[c] Natural ground gypsum mineral ($CaSO_4 \cdot 2H_2O$). Garden King brand, agricultural grade (analysis: calcium as calcium sulphate, 18.5% w/w; sulphur as calcium sulphate, 14.5% w/w).
[d] Commercial hydrated lime for construction purposes. Adelaide Brighton brand (Australian Standard AS 1672).

to determine the significance of observed differences in sample means at the 95% confidence level ($\alpha = 0.05$).

## 3. Results and discussion

BFS-based binders were found to be suited to use with the slurry de-watering composite production method, exhibiting a processing behaviour similar to that of OPC-based binders. The mechanical and physical properties of the fabricated materials are shown in Tables 5 and 6 with single standard deviations of the sample means indicated. To facilitate comparison of the mechanical performance of selected composites, some results are highlighted in Figs. 1–3. For the sake of clarity, a number of data points in Figs. 2 and 3 are shown slightly offset from their true positions along the horizontal axis.

### 3.1. Modulus of rupture

Shrinkage stresses generated during the drying process led to micro-crack formation in unreinforced matrices and to relatively high standard deviations being associated with their measured mechanical properties. A comparison of the relative strengths of BFS-based matrix formulations on the basis of the corresponding 4% *P. radiata* fibre composite MOR values indicates that combinations of gypsum and lime acted as better activators than OPC. The composite data are reproduced in Fig. 1, with like letters at the head of two or more columns denoting insignificant differences in the sample means. The lesser performance of OPC as an activator is

Table 5
Mechanical and physical properties[a] of binders and *P. radiata*-reinforced composites

| Binder code | Fibre content (% w/w) | Flexural modulus (GPa) | Flexural strength (MPa) | Fracture toughness (kJ/m$^2$) | Water absorption (% w/w) | Density (g/cm$^3$) | Permeable void volume (% v/v) |
|---|---|---|---|---|---|---|---|
| BFS 6G2L | 0 | 11.6±1.65 | 8.09±2.15 | 0.03±0.01 | 17.6±0.9 | 1.84±0.03 | 32.4±1.1 |
| | 4 | 7.16±0.48 | 14.4±1.20 | 0.70±0.18 | 25.7±0.5 | 1.51±0.02 | 38.9±0.4 |
| | 8 | 5.67±0.37 | 17.2±1.80 | 1.96±0.49 | 28.3±1.0 | 1.42±0.04 | 40.0±0.6 |
| | 12 | 4.28±0.26 | 15.7±1.20 | 2.36±0.42 | 31.2±0.5 | 1.32±0.02 | 41.3±0.2 |
| BFS 6G2L (42 days) | 0 | 11.7±1.05 | 8.49±1.97 | 0.04±0.01 | | | |
| | 4 | 6.63±0.80 | 13.4±1.30 | 0.77±0.16 | | | |
| | 8 | 5.57±0.56 | 17.1±1.30 | 1.86±0.25 | | | |
| | 12 | 4.48±0.27 | 15.8±1.00 | 2.54±0.28 | | | |
| BFS 6G8L | 0 | 17.1±1.80 | 9.80±1.21 | 0.04±0.01 | 14.0±0.4 | 1.91±0.02 | 26.7±0.5 |
| | 4 | 9.41±1.16 | 17.1±1.70 | 0.60±0.10 | 23.0±0.7 | 1.57±0.03 | 36.2±0.5 |
| | 8 | 6.82±0.75 | 21.5±2.10 | 1.57±0.25 | 27.4±0.6 | 1.43±0.03 | 39.1±0.4 |
| | 12 | 6.23±0.31 | 23.5±1.70 | 2.03±0.26 | 29.1±0.9 | 1.34±0.01 | 39.1±1.0 |
| BFS 8G4L | 4 | 8.24±0.77 | 16.4±1.50 | 0.60±0.12 | 25.1±0.6 | 1.53±0.02 | 38.2±0.5 |
| | 8 | 6.66±0.63 | 21.5±1.60 | 1.69±0.23 | 28.3±1.1 | 1.42±0.03 | 40.3±0.8 |
| | 12 | 5.72±0.34 | 22.4±2.10 | 1.77±0.32 | 32.9±1.0 | 1.30±0.02 | 42.6±0.8 |
| BFS 10G2L | 4 | 7.79±0.72 | 15.3±1.60 | 0.56±0.09 | 25.5±0.5 | 1.52±0.02 | 38.7±0.3 |
| | 8 | 6.79±0.47 | 22.1±2.30 | 1.53±0.29 | 27.4±0.7 | 1.46±0.02 | 39.9±0.4 |
| | 12 | 5.25±0.59 | 19.5±1.30 | 1.72±0.12 | 32.0±2.1 | 1.33±0.05 | 42.6±1.2 |
| BFS 10G4L | 0 | 11.6±0.80 | 8.96±1.44 | 0.04±0.01 | 18.9±0.7 | 1.80±0.03 | 34.0±0.8 |
| | 4 | 7.70±0.64 | 15.0±1.20 | 0.64±0.10 | 26.1±0.5 | 1.50±0.02 | 39.1±0.4 |
| | 8 | 7.84±0.40 | 24.5±2.70 | 1.13±0.22 | 29.6±0.6 | 1.41±0.02 | 41.6±0.41 |
| | 12 | 5.92±0.36 | 24.0±2.4 | 2.09±0.37 | 33.9±1.0 | 1.29±0.02 | 43.6±0.6 |
| BFS 5OPC | 0 | 13.0±1.20 | 5.20±0.44 | 0.02±0.01 | 9.6±0.8 | 2.13±0.03 | 20.5±1.5 |
| | 4 | 5.97±0.44 | 9.49±0.74 | 0.61±0.18 | 22.0±0.5 | 1.60±0.02 | 35.1±0.4 |
| BFS 10OPC | 0 | 16.0±1.90 | 6.94±2.30 | 0.02±0.01 | 10.1±0.8 | 2.11±0.04 | 21.3±1.3 |
| | 4 | 8.16±0.82 | 12.2±1.50 | 0.50±0.12 | 20.3±0.4 | 1.63±0.01 | 33.0±0.4 |
| OPC | 0 | 23.5±4.6 | 11.8±3.66 | 0.04±0.01 | 10.7±0.5 | 2.18±0.03 | 23.4±0.8 |
| | 4 | 13.8±1.4 | 19.2±1.90 | 0.64±0.09 | 18.5±0.5 | 1.69±0.02 | 31.1±0.5 |
| | 8 | 10.3±0.78 | 23.5±0.80 | 1.32±0.11 | 22.3±0.5 | 1.54±0.02 | 34.3±0.5 |
| | 12 | 8.21±0.69 | 25.0±2.10 | 1.93±0.42 | 24.4±0.6 | 1.46±0.03 | 35.6±0.3 |

[a] Single standard deviations of sample means indicated.

Table 6
Mechanical and physical properties[a] of sisal-reinforced composites

| Binder code | Fibre content (% w/w) | Flexural modulus (GPa) | Flexural strength (MPa) | Fracture toughness (kJ/m$^2$) | Water absorption (% w/w) | Density (g/cm$^3$) | Permeable void volume (% v/v) |
|---|---|---|---|---|---|---|---|
| BFS 6G2L | 4 | 7.65±0.68 | 13.1±0.40 | 0.53±0.12 | 26.6±0.5 | 1.50±0.01 | 39.7±0.6 |
| | 8 | 6.07±0.51 | 16.8±1.70 | 1.41±0.22 | 29.0±1.0 | 1.39±0.03 | 40.4±0.6 |
| | 12 | 4.27±0.35 | 14.7±2.00 | 1.68±0.22 | 33.1±1.3 | 1.29±0.02 | 42.7±1.4 |
| BFS 6G2L (42 days) | 4 | 6.82±0.50 | 11.8±0.80 | 0.50±0.09 | | | |
| | 8 | 5.75±0.54 | 15.8±1.40 | 1.42±0.21 | | | |
| | 12 | 4.12±0.25 | 14.5±1.10 | 1.74±0.26 | | | |

[a] Single standard deviations of sample means indicated

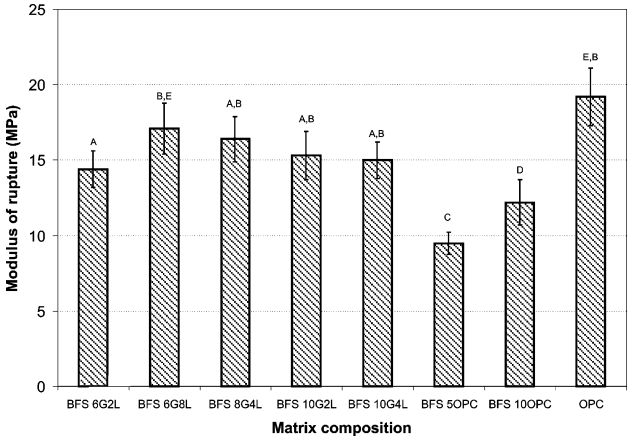


Fig. 1. Variation in MOR with binder formulation at 4% *P. radiata* content.

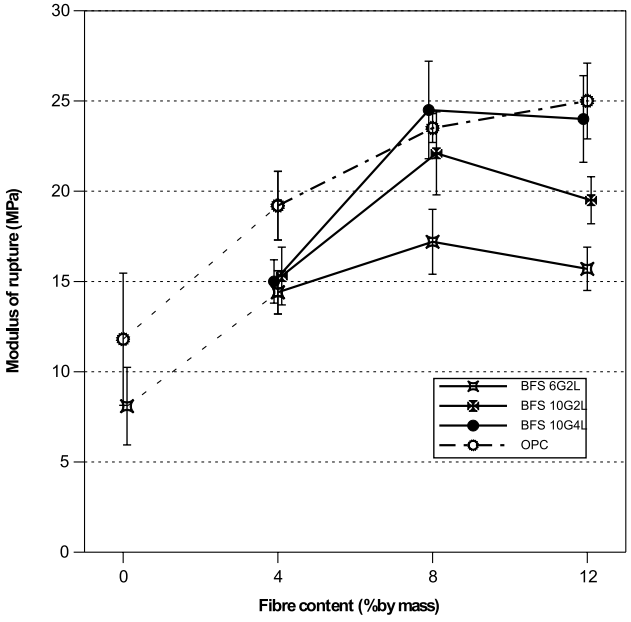


Fig. 2. Variation in MOR with selected binder formulations and *P. radiata* fibre content.

in apparent disagreement with the conclusions of Sato et al. [9]. Increasing the lime content from 2% to 8% in the presence of 6% gypsum provided a significant improvement in BFS binder strength. The apparent strengths of the remaining gypsum and lime-activated binder formulations, BFS 8G4L, 10G2L and 10G4L, ranged between those of the BFS 6G2L and 6G8L formulations and were not significantly different from either. The significant improvement in strength obtained by increasing OPC activator content from 5% to 10% suggests that further gains may be made at higher OPC concentrations, as already used in commercial BFS/OPC blends. However, increases in OPC content could involve unacceptable increases in binder cost, and the apparent strength of the OPC reference binder was not significantly greater than that of the BFS 6G8L formulation. Other possibly more cost effective approaches to improvement in OPC-activated formulation properties could include the use of elevated temperature cure, for example up to 60°C as suggested by Richardson et al. [2], or the combination of OPC with an additional alkaline activator such as sodium silicate, as proposed by Douglas and Brandstetr [20].

BFS-based matrices demonstrated a capacity similar to that of OPC to benefit from the inclusion of natural reinforcing fibre. The mechanical properties of the two matrix types were enhanced in a like manner, 4% and 8% *P. radiata* fibre loadings providing significant incremental improvements in flexural strength which was doubled at the higher loading at 28 days (Table 5). In the case of the BFS 6G2L binder formulation, the inclusion of 8% sisal fibre was seen to provide a similar improvement in strength (Table 6). The best performance of BFS-based composites in terms of flexural strength was achieved with the BFS 10G4L binder formulation and *P.radiata* fibre loadings of 8% and 12%. These materials exhibited MOR values of approximately

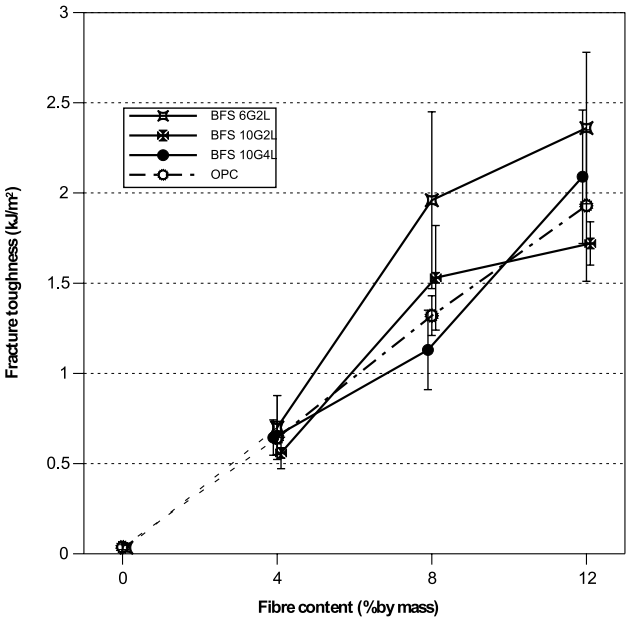


Fig. 3. Variation in fracture toughness with selected binder formulations and *P. radiata* fibre content.

24 MPa at 28 days, similar to those of the corresponding OPC reference composites. At the same fibre loadings BFS 6G2L-based composites performed relatively poorly while the remaining binder formulations provided intermediate MOR values which in most instances were not significantly lower than those of the BFS 10G4L or OPC-based composites (Table 5, Fig. 2).

Short-term strength development of BFS 6G2L-based composites was well progressed at 28 days, no significant increases in strength being observed when the cure time of *P.radiata*- or sisal fibre-reinforced formulations was extended to a total of 42 days (Tables 5 and 6). Despite being nominally weaker (Table 3) and not having been subjected to the beating process to provide external fibrillation and consequently stronger fibre-matrix and fibre–fibre bonds, sisal-reinforcing fibre produced composite strengths which were not significantly lower than those obtained with *P.radiata* fibre at the same loadings. The higher lignin content of the sisal pulp, as indicated by its higher Kappa number (Table 3), suggests the evaluation of cement composites at further ages in the next steps of the present research, although good durability of vegetable strand fibre-reinforced BFS has been reported by Agopyan and John [21].

The results of this work represent a significant improvement over those previously presented by Savastano Jr. et al. [22]. In the earlier study, which used a dough mixing process for composite preparation, MOR values of less than 5 MPa were reported for BFS-based mortars activated by 10% gypsum and 2% lime and reinforced with *Eucalyptus grandis* pulp.

### 3.2. Fracture toughness

As recorded in Table 5, the fracture toughness of BFS-based composites reinforced with 12% *P.radiata* ranged from 1.72 kJ/m$^2$ (BFS 10G2L) to 2.36 kJ/m$^2$ (BFS 6G2L). This represents an enormous improvement over the values obtained from the plain matrices (0.02–0.04 kJ/m$^2$), similar to that observed in the case of WFRC materials [12,13]. The comparatively high toughness of BFS 6G2L-based composites may be related to their lower flexural strengths (Figs. 1 and 2). A weakening of the matrix phase relative to the fibre–matrix bond may allow much more energy to be absorbed by microcracking processes close to fibre surfaces than would otherwise be absorbed by simple fibre fracture and pull-out mechanisms. The remaining BFS-based formulations exhibited similar values of fracture toughness to each other and the OPC reference composites in the fibre content interval between 0% and 12%, revealing the low influence of the tested matrices on the ductility of the resulting materials (Table 5, Fig. 3).

No significant changes in fracture toughness values of *P.radiata*- or sisal fibre-reinforced BFS 6G2L composites were observed when the cure time was extended to 42 days (Tables 5 and 6). The fracture toughness values of the 8% and 12% sisal-reinforced BFS 6G2L composites at both 28 and 42 days were lower than those of the corresponding *P.radiata*-reinforced composites. The lesser performance of the sisal fibres may have been a direct consequence of their lower strength and their not having been beaten to generate external fibrillation. These factors would act to reduce the extent of matrix microcracking which was suggested above as making a substantial contribution to the post-cracking energy absorption of BFS 6G2L-based composites reinforced with *P.radiata* fibre.

### 3.3. Modulus of elasticity

The elastic moduli of neat BFS matrices activated by combinations of gypsum and lime varied from 11.6 to 17.1 GPa and were negatively correlated ($r = -0.87$) with permeable void volume (Table 5). A strong correlation was also observed in the case of 4% *P. radiata* composites based on these binders and the BFS 8G4L and 10G2L formulations. The correlation was not significant for the OPC-activated BFS formulations which developed different and more dense microstructures.

Again in agreement with previous WFRC studies (e.g. Soroushian et al. [23]), elastic moduli fell continuously ($r = -0.79$) with fibre content increase and were in the range of 4.3–6.2 GPa for 12% *P. radiata*- or sisal-reinforced BFS composites. At each of the fibre contents examined, the OPC reference composites possessed greater stiffness and density than the BFS-based mate-

rials (Table 5). The relatively low stiffness of the BFS-based materials, particularly at the higher fibre contents where their optimum strength and toughness values were observed, could be a limiting factor in their adoption for practical applications.

As was the case with the other measured mechanical properties, no significant changes were observed in MOE on extending the cure time from 28 to 42 days.

### 3.4. Physical properties

While undergoing initial cure in sealed plastic bags the BFS-based composites developed a blue-green colouration as a consequence of iron (ferro) and manganese sulphide formation [7]. In contact with air these sulphides were oxidised and specimen surfaces became progressively much lighter coloured than those of OPC composites. The transition of colours may be useful as an indicator of other physical and mechanical properties of these materials since the rate of progression of the sulphide oxidation wave would be dependent on the amount of permeable porosity.

Matrices and composites based on gypsum and lime-activated BFS binder formulations were significantly less dense and had higher water absorption and permeable void volume values than corresponding OPC-based materials, irrespective of fibre content or type (Tables 5 and 6). The water absorption of *P. radiata*- and sisal-reinforced BFS 6G2L formulations, after an initial significant increase corresponding to the addition of 4% fibre, rose at a lesser and near constant rate with fibre loading, reaching an overall increase of 77–88% at 12% fibre content. The remaining BFS and OPC composites behaved similarly over the fibre load intervals at which they were prepared. The lower density values observed for the BFS composites are in keeping with their generally lower flexural strengths since porosity is known to have an effect on mechanical strength [24]. The higher water absorption of the BFS-based materials, coupled with their lower stiffness, represents a significant drawback to their practical use, particularly in the form of roofing elements. Since water absorption, void volume and density are interrelated variables, effort toward lessening the permeable void volume of the composites is warranted if they are to become a more realistic proposition as building materials.

Several previous studies [7,25,26], in which a range of alkaline activators including OPC and sodium silicate, hydroxide and carbonate have been employed, have found BFS-based mortars and concretes to possess lower permeability than those based on OPC. The higher permeable void volumes recorded in Table 5 for the unreinforced BFS formulations activated by gypsum and lime may be a consequence of the different hydration and microstructural development mechanisms brought in to play through the use of this combination of activators [27]. Unreinforced OPC-activated BFS formulations displayed relatively low permeable void volumes, in agreement with previous findings. However, the void volumes of 4% *P. radiata* composites based on these binders significantly exceeded that of the corresponding OPC-based composite. Additional factors contributing to the higher levels of porosity observed in the BFS-based composites may include an increased susceptibility to air entrainment during fabrication by the laboratory slurry vacuum de-watering process, the use of uncontrolled water-binder ratios and greater shrinkage microcracking [28]. A reduction in permeable void volumes may be achieved through the use of compaction pressures greater than 3.2 MPa and/or extended press times, following the same principles studied by Coutts and Warden [29] for air-cured WFRC, although an undesirable increase in cost could be expected.

As stressed by Swamy [30], another feasible way of reducing the permeability of cementitious materials with high BFS contents, and consequently improving their mechanical properties and durability, is to extend the period of moist curing and/or to increase the fineness of the slag. In the study referred to it was demonstrated that the pore refinement expected in concrete with increased BFS content may not be realised if a sufficiently humid environment is not maintained to allow continued slag hydration.

## 4. Conclusions

Fibre-cements based on BFS binders and reinforced with either wood (*P. radiata*) or non-wood (sisal) fibres were suited to production by a laboratory scale slurry de-watering method simulating the Hatschek process.

The flexural strength and toughness of composites based on gypsum and lime-activated BFS were in most instances similar to those of OPC-based materials, with large improvements over neat matrix properties being observed in the 8–12% fibre content interval. Moduli of rupture generally exceeded 20 MPa and fracture toughness values 1 kJ/m$^2$ at a *P. radiata* fibre content of 8%. The moduli of elasticity of the BFS-based materials were, however, lower than those of OPC-based composites and varied from 5.6 to 7.8 GPa when reinforced with 8% *P. radiata*. At the proportions used, OPC appeared to be a less effective activator of BFS than mixtures of gypsum and lime.

The flexural strengths of 8% and 12% fibre composites based on BFS 6G2L were significantly lower than those of composites based on OPC or the other BFS formulations. The fracture toughness values of *P. radi-*

*ata* BFS 6G2L composites at these fibre contents were, however, significantly higher than those of the other materials, exceeding 2.3 kJ/m$^2$ at the higher loading. Low binder strength may have contributed to the toughness of these materials by facilitating more extensive microcracking in the vicinity of the fibres during post-crack deformation.

A BFS 10G2L binder formulation appears to offer an acceptable compromise between composite flexural strength and toughness. This formulation has the additional advantage of having a lower projected price in the Brazilian market than the other formulations studied.

Kraft-pulped sisal fibre-reinforced BFS 6G2L composites displayed strengths that were not significantly lower than those of the corresponding *P. radiata* fibre composites. Although fracture toughness values were lower than those obtained with the refined *P. radiata* fibre, these results indicate a potential for products possessing acceptable ''performance for cost'', since by-product sisal and BFS are available as low-cost residues in some developing countries and their recycling in the form of composite materials requires relatively little energy input.

Composites consisting of BFS formulations reinforced with 12% *P. radiata* or pulped sisal fibres generally possessed water absorption values exceeding 30% by mass. Corresponding densities lay in the region of 1.3 g/cm$^3$ and flexural moduli in the range 4.3–6.2 GPa. Efforts should be made in future studies to reduce the relatively high permeable porosity of BFS-based fibre-cements, with a view to further improving their general performance and potential for use in low-cost construction.

## Acknowledgements

The authors would like to thank the Fundação de Amparo à Pesquisa do Estado de São Paulo (Fapesp) for its financial support of this work (proc.n.98/02920) and Allyson Pereira and Göran Längfors of CSIRO Forestry and Forest Products for their generous assistance.

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