Plant fibre reinforced cement components for roofing

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Abstract

Composites of blast furnace slag (BFS) based cement mortar reinforced with vegetable fibres are presented. Roofing components are produced with these composites through a simple and low-energy consuming method, including ordinary vibration and curing in a wet chamber. Composites reinforced with eucalyptus pulp, coir fibres and with a mixture of sisal fibre and eucalyptus pulp gave a suitable performance, with compressive strength higher than 20 MPa and modulus of rupture (MOR) higher than 3 MPa. The performance of tiles made with these composites is in accordance with international requirements, with maximum load higher than 450 N, in wet conditions. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The consumption of building components made with fibre reinforced cement is increasing rapidly and nowadays in developed countries it is in the region of several million metric tonnes yearly. This occurs because it is possible to produce lightweight building components with this type of material, with good mechanical performance (mainly impact energy absorption), suitable thermal-acoustic insulation and is economically feasible.

Within the developing world, where the lack of housing and also of commercial, industrial and public service buildings is considerable, the introduction of these materials can help increase production of buildings with suitable performance. In these countries, vegetable fibres can be a good alternative due to low cost, as long as the low durability risks in an alkaline environment are eliminated. Besides, in some countries, asbestos–cement is still the sole composite in use, although health hazards are increasingly causing concern [1].

The main objective of this paper is to present the performance of roofing tiles made with blast furnace slag cement (BFS) mortar reinforced with vegetable fibres, following the research work already done for building partitions [2].

2. Fibre-cements overview

The use of high elasticity modulus fibres (e.g. steel and carbon) as reinforcement for cement-based matrices is well known for applications aimed at improving
strength. Low elasticity modulus reinforcements (such as plastic and cellulose fibres) improve the energy absorption of composites in the post-cracking stage as their main purpose. As a general view randomly distributed short fibres in brittle matrices perform good response to impact solicitation due to enormous ability for dynamic energy dissipation \[3,4\].

Wood fibre reinforced cement (WFRC) is considered suitable for thin wall and roofing components with good mechanical performance \[5\] (modulus of rupture in the range of 20 MPa and fracture toughness of 1.5 kJ/m²) and acceptable ageing behaviour \[6\].

The Hatschek based processes are the most frequently used for WFRC production provided some specific procedures such as preliminary fibre mechanical refinement, composite compaction under high pressure and autoclave curing are carried out. In the asbestos-free world the WFRC products provided a successful commercial alternative since the early 1980s \[7\].

In developing tropical countries the challenge for cost-quality compromise still demands research efforts supporting future industrial products. The utilisation of recycled non-wood and alternative cements combined with low-energy processes seems to have an endless potential for emerging building markets \[8\].

2.1. BFS-based cement

BFS is the residue of pig iron production and based on world steel annual manufacturing, approximately 150 million metric tonnes of slag are prepared every year.

Only in Brazil, 6 million metric tonnes of basic BFS are available every year and half of this amount is stocked without use, resulting in a serious problem for the steel industry as well as for the environment. Because it is a residue, the cost of BFS is as low as US$10.00 per metric tonne. For cement production, the slag must be ground to a similar fineness of ordinary cement, which adds a further cost of US$15.00 per metric tonne, and it must also be activated with chemical and/or thermal procedures. In this research work, the BFS was activated with lime and gypsum.

As BFS cement has low alkalinity, its mortars are suitable for vegetable fibre reinforcement \[2\] and also for other fibres which do not resist the alkalis within the Portland cements.

3. Plant fibres

As reported by Coutts \[9\], plant fibres contain cellulose, a natural polymer, as the main reinforcement material. The chains of cellulose form microfibrils, which are held together by amorphous hemicellulose and form fibrils. The fibrils are assembled in various layers to build up the structure of the fibre. Fibres or cells are cemented together in the plant by lignin, which can be dissolved by the alkalinity of the cement matrix. Then the usual denomination for fibres is in fact a reference to strands of fibres with some important consequences on durability studies, as discussed later in this item.

In Table 1, the most suitable Brazilian vegetable fibres are presented, based on their physical and mechanical properties, cost, durability in natural wet environments and production. As they are natural products, the fibres are heterogeneous so the coefficient of variation in some properties can be as high as 50%. Only as a comparison, the characteristics of polypropylene fibres are included in the table.

Table 1
Physical and mechanical properties of vegetable and polypropylene fibres

<table>
<thead>
<tr>
<th>Properties</th>
<th>Density (kg/m³)</th>
<th>Water absorption (%)</th>
<th>Elongation at break (%)</th>
<th>Tensile strength (MPa)</th>
<th>Young's modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coir (Cocos nucifera)</td>
<td>1177</td>
<td>93.8</td>
<td>23.9–51.4 [14]</td>
<td>95–118 [14]</td>
<td>2.8 [17]</td>
</tr>
<tr>
<td>Malva (Urena lobata)</td>
<td>1409</td>
<td>182.2</td>
<td>5.2 [18]</td>
<td>160 [18]</td>
<td>17.4 [17]</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>913</td>
<td>–</td>
<td>22.3–26.0</td>
<td>250</td>
<td>2.0</td>
</tr>
</tbody>
</table>

a na, information not available.
3.1. Fibre–matrix transition zone

A transition zone can be defined as a region of the paste close to the fibre, with thickness from 10 to 100 μm, and different characteristics from the bulk matrix.

In cement composites, low porosity and portlandite (calcium hydroxide crystals) concentration on transition zone must improve the fibre–matrix bonding. With the fibre–matrix bonding increase, the elastic tensile strength also increases and sometimes the ductility reduces [10].

3.2. Durability

Vegetable strand fibres are affected by environment temperature and humidity, and also by the medium in which they are immersed, due to the hemicellulose and lignin decomposition. These components are present in the intercellular layers and their decomposition reduces the reinforcement capacity of the individual fibres (cells). Tensile strength of sisal and coir fibres decreases up to 50% if immersed in saturated solution of calcium hydroxide (approx. pH 12) for 28 days.

To avoid ageing effects in the composites, some approaches are available: (a) protection of the strand fibres by coating or sealing the dry composite to avoid the effects of alkaline water; (b) high casting compaction and high-pressure steam curing for providing matrix carbonation, if necessary adding silica fume; (c) low alkaline binders based on industrial and agricultural by-products such as blast furnace slag BFS and fly ash [11–13].

After 10 years of use, external wall panels based on BFS reinforced with coir fibres used in a prototype located in São Paulo, Brazil, still present good performance. These results give additional support to the use of BFS in the present study.

4. Experimental procedures

4.1. Available fibrous residues

Technical visits were carried out to inspect the field production, extraction and processing of vegetable fibres commercialised in Brazil, with the correspondent generation of residues.

Based on the information collected on these technical visits, the residues were classified, following the selection criteria below:

- General identification of agricultural production which generates residues.
- Residues identification: correlation with main products and production processes.
- Available amount of residues: other possible uses with actual demands.
- Local availability: selection between transportation or local processing.
- Market value of the residue.
- Physical and mechanical properties of composites and components produced.

4.2. Evaluation of BFS composites

Based on previous results [2,14], BFS mortars reinforced or not reinforced with vegetable fibres were prepared with the following characteristics:

- Cement:sand ratio—1:1.5.
- Water/cement ratio—0.40 and 0.48.
- Volume fraction of fibres—2%. For one of the series produced, two different types of fibres were used together (volume fraction of 1% each), looking for a synergetic effect between fibres of different lengths.
- Selection of fibres: in accordance with selection criteria previously presented in this item. All the strand fibres were cut in lengths varying from 20 to 40 mm.
- Cement: alkaline granulated BFS from Companhia Siderurgica Tubarao (CST)—Brazil, milled up to Blaine fineness of 500 m²/kg. Oxide composition of the BFS wt.%: 32.27% SiO₂, 12.74% Al₂O₃, 0.424% Fe₂O₃, 0.204% MnO, 7.731% MgO, 42.17% CaO, 0.204% Na₂O, 0.403% K₂O, 0.516% TiO₂, 0.006% P₂O₅. Activators: gypsum (calcium sulfate di-hydrated) and lime (calcium hydroxide), in the proportions 0.88:0.10:0.02 and 0.86:0.10:0.04 (BFS:gypsum:lime).
- Mixture, compaction and manual moulding of the composite. Cure by water immersion, for the 7 initial days, followed by air curing until the date of the test.
- Fresh state tests: bulk density and flow table (consistency index), for workability evaluation.
- Hard state tests: axial compression (cylindrical specimen: 50 mm in diameter and 100 mm in height), 4 points bending (prismatic specimen: 300 × 150 × 15 mm) [15] and water absorption by immersion.

4.3. Roofing components evaluation

Roofing tiles were fabricated in conformation to the same procedures presented for composite production and using the Parry Associates (UK) equipment, for moulding and compaction by vibration. The dimensions
Table 2
Residues obtained from fibre processing

<table>
<thead>
<tr>
<th>Fibrous residues</th>
<th>Sisal field by-product</th>
<th>Waste of eucalyptus pulp</th>
<th>Residual short coir fibres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original humidity (%)</td>
<td>10</td>
<td>61</td>
<td>32</td>
</tr>
<tr>
<td>Market price (US$/ton)</td>
<td>Zero</td>
<td>15</td>
<td>90 (maximum)</td>
</tr>
<tr>
<td>Amount (ton/year)—source</td>
<td>30/000—1 cooperative</td>
<td>17000—1 large industry</td>
<td>7500—2 large industries</td>
</tr>
<tr>
<td>Main product</td>
<td>Commercial fibre before drying</td>
<td>Pulp for paper production</td>
<td>Fibres longer than 100 mm</td>
</tr>
<tr>
<td>Relation residue/ main product (%)</td>
<td>300</td>
<td>0.5</td>
<td>200—2880</td>
</tr>
</tbody>
</table>

of the tiles are $487 \times 263 \times 6$ mm (frame measures) with format very similar to ceramic Roman tiles.

5. Results

5.1. Selected fibrous residues

Based on the criteria presented, three different types of residues were selected, as in Table 2, all of them already available for immediate use in civil construction:

- Sisal field by-product. Large availability at the processing sites and low commercial interest. A good option as a complementary income for rural producers. This residue needs simple cleaning by passing into a manual cylindrical rotative sieve.

- Waste of eucalyptus pulp. Almost no commercial value and great availability. Disadvantage: very short fibres (average length = 0.66 mm) and high moisture content.

- Residual short coir fibres. Low commercial value, great potential for production but almost no use at present time. Powder separation (approx. 50% in weight) and drying are required.

![Fig. 1. Sisal field by-product. Strand fibres covered by mucilage.](image)

![Fig. 2. Waste of eucalyptus pulp. Fibrillated fibres after mechanical and chemical treatments.](image)

Samples of the selected residues were analysed by scanning electron microscopy (SEM) and some images are reproduced in Figs. 1–3. The sisal field by-product micrography (Fig. 1) shows a strand of fibres covered by mucilage (that can work like a set delayer of cements) and also with fibrillation and striation through the length direction. The waste of eucalyptus pulp (Fig. 2) presents particular morphology with fibrillated fibres quite altered by mechanical and chemical procedures during the pulp production. The coir fibres (Fig. 3) have a cylindrical shape with an external cellulosic cover, for strand protection against alkaline attack; superficial protuberances can also be seen, which help fibre anchorage in the reinforced matrix.

5.2. Composites properties

Physical (fresh state and 28 days) and mechanical (28 days) composites properties are presented in Table 3. The modulus of rupture (MOR) of coir fibre reinforced composite was 18% superior to the reference with the same water/cement ratio. The specific energy corresponds to the total absorbed energy divided by the transversal area of fracture; this property shows a sig-
significant difference between the fibrous composites and the plain matrix in the post-cracked stage.

5.3. Components’ properties

Tiles evaluation was made in compliance with the Brazilian standards for concrete tiles and the results are shown in Table 4.

The warping was always less than 3 mm, which constitutes a favourable point for the adopted fabrication process. This property is concerned with the capacity of one tile to adjust with others in the roofing.

All series presented no wet marks during the permeability test, after 24 h under 250 mm of water column pressure.

The water absorption was always less than 20% in weight after immersion for 24 h. These results are acceptable in compliance with Brazilian standards for fibro-cement sheets for roofing purposes.

During flexural tests the tiles reinforced with vegetable fibres presented absorbed energy and specific energy higher than that of plain tiles. All tested series (with six tiles) satisfied the minimum flexural load of 425 N (85% of 500 N, for saturated tiles) [16], in spite of better results with plain material.

Natural and accelerated ageing tests and also thermal insulation evaluation are in progress now, as a continuation of the present research program.

6. Discussion

The great availability of plant fibres ensures their use in industrial scale, especially in tropical countries. The alternative cements (e.g. BFS) constitute another cheap solution for non-structural purposes, mainly for mortar production. In each case, the regional available residues need to be previously observed, avoiding additional transport and handle costs.

The plant fibre composites based on brittle matrices are confirmed to be suitable as low-cost materials, with enough performance for the millions of homeless people in developing countries.

Nevertheless, as durability is a major concern, each type of component must be well evaluated before widespread commercial use.

Table 3

Properties of BSF cement mortar reinforced with vegetable fibres

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Slag/lime: gypsum: sand; w/c</th>
<th>Bulk density (kg/m³)</th>
<th>Flow table index (mm)</th>
<th>Water absorption (mass%)</th>
<th>MOR (MPa)</th>
<th>Specific energy (Nm/m²)</th>
<th>Compression strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference 1 (no fibres)</td>
<td>0.88:0.02: 0.48</td>
<td>2107</td>
<td>303</td>
<td>na</td>
<td>3.32</td>
<td>56</td>
<td>na</td>
</tr>
<tr>
<td>Reference 2 (no fibres)</td>
<td>0.86:0.04: 0.10:1.5; 0.40</td>
<td>2113</td>
<td>212</td>
<td>8.8</td>
<td>3.37</td>
<td>75</td>
<td>33.8</td>
</tr>
<tr>
<td>Eucalyptus pulp</td>
<td>0.86:0.04: 0.10:1.5; 0.48</td>
<td>2041</td>
<td>173</td>
<td>12.2</td>
<td>3.87</td>
<td>141</td>
<td>31.1</td>
</tr>
<tr>
<td>Sisal (1%) + eucalyptus pulp (1%)</td>
<td>0.86:0.04: 0.10:1.5; 0.48</td>
<td>2077</td>
<td>201</td>
<td>11.2</td>
<td>3.02</td>
<td>148</td>
<td>25.3</td>
</tr>
<tr>
<td>Coir</td>
<td>0.86:0.04: 0.10:1.5; 0.48</td>
<td>2142</td>
<td>273</td>
<td>11.2</td>
<td>3.92</td>
<td>105</td>
<td>21.0</td>
</tr>
</tbody>
</table>

*Test was stopped when load decreased 70% in relation to maximum load; na, information not available.

1na, information not available.
Acknowledgements

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References


Table 4

Physical and mechanical properties of the tiles

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Slag: lime: gypsum: sand; w/c</th>
<th>Warping (mm)</th>
<th>Water absorption (% in mass)</th>
<th>Dry mass at 100°C (g)</th>
<th>Thickness (mm)</th>
<th>Maximum load (N)</th>
<th>Absorbed energy (N.mm)^2</th>
<th>Specific energy (N.mm/mm^2)^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference (no fibres)</td>
<td>0.86: 0.04: 0.10: 1.5: 0.40</td>
<td>0.91</td>
<td>14.1</td>
<td>2101</td>
<td>9.37</td>
<td>672</td>
<td>1088</td>
<td>0.442</td>
</tr>
<tr>
<td>Eucalyptus pulp</td>
<td>0.86: 0.04: 0.10: 1.5: 0.48</td>
<td>2.01</td>
<td>17.6</td>
<td>1833</td>
<td>9.15</td>
<td>629</td>
<td>1269</td>
<td>0.527</td>
</tr>
<tr>
<td>Sisal (1%) + eucalyptus pulp</td>
<td>0.86: 0.04: 0.10: 1.5: 0.48</td>
<td>2.52</td>
<td>16.7</td>
<td>1867</td>
<td>8.59</td>
<td>556</td>
<td>1126</td>
<td>0.498</td>
</tr>
<tr>
<td>Coir</td>
<td>0.86: 0.04: 0.10: 1.5: 0.48</td>
<td>1.47</td>
<td>17.1</td>
<td>1993</td>
<td>10.9</td>
<td>454</td>
<td>2299</td>
<td>0.802</td>
</tr>
</tbody>
</table>

^a Test stopped when load decreased 70% in relation to maximum load.

7. Conclusion

Plant fibre reinforced brittle matrices presented technical and economical feasibility in comparison to similar commercial materials. The composites with reinforcement of eucalyptus pulp, coir or eucalyptus pulp combined with sisal fibres reached acceptable physical and mechanical performance, mainly concerning ductility increase.