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Developments on vegetable fibre–cement based materials in São Paulo, Brazil: an overview

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Abstract

Vegetable fibres, which are widely available in most developing countries, can be used as convenient materials for brittle matrix reinforcement, even though they present relatively poor durability performance. Taking into account the fibres mechanical properties, with an adequate mix design, it is possible to develop a material with suitable properties for building purposes. In order to improve the durability of vegetable fibres, this paper presents the approach adopted in the research which is directed towards the development of alternative binders, with controlled free lime, using ground granulated blast furnace slag. Coir fibres demonstrate to be more suitable vegetable fibres for the reinforcement of large components as can be proved by in-use durability performance evaluation of an 11-year old prototype house. More recently, pulp from eucalyptus waste and residual sisal and coir fibres have been studied as a replacement for asbestos in roofing components.

Keywords: Vegetable fibres; Durability; Blast furnace slag; Coir fibres; Sisal fibres; Cellulose pulp; Roofing tile

1. Introduction

The purpose of fibre reinforcement is to improve the properties of a building material, basically the mechanical ones, which would be otherwise unsuitable for practical applications. The major advantage of fibre reinforcement of a brittle material such as cement paste, mortar or concrete, is the behaviour of the composite after cracking has started. The post cracking toughness that the fibres produce in the material may allow more intensive use of such composites in building.

Vegetable fibres are widely available in most developing countries, which make them convenient materials for brittle matrix reinforcement, even though they present relatively poor durability performance. With an adequate mix design and taking into account the fibres mechanical properties and their high coefficients of variation, it is possible to develop a material with suitable properties for building purposes [1,2].

There are two approaches for the development of new composites in fibre–cement [3]. The first one is based on the production of thin sheets and other components free of asbestos. Such components are very similar to those with asbestos–cement and they are produced by well-known processes in industrial scale as is the case of Hatschek and Magnani methods. The second one, adopted by this research group, consists of the production of composites for different types of building components, such as load bearing hollowed wall, roofing tiles and ceiling plates, which are not similar to the components commercially produced with asbestos–cement.

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The main drawback to the use of vegetable fibres is the durability of these fibres in a cementitious matrix and also the compatibility between both phases. The alkaline media weaken most natural fibres, especially the vegetable ones which are actually strands of individual filaments liable to be separated from each other. The mineralisation phenomenon proposed elsewhere [4,5] can be associated with loss of composite tenacity in the long term. The severe degradation of exposed composites can also be attributed to interfacial damages due to continuous volume changes of the porous vegetable fibres inside the cement matrix [6].

There are two approaches to improve the durability of vegetable fibres. One is based on the protection of the fibres by coating them or sealing the dry composite to avoid the effect of water, mainly alkalinity. The other approach, adopted by this research group, is directed towards the reduction of free alkalis in the matrix, by developing low alkaline binders based on industrial and agricultural by-products [7]. The same effect of reduced alkalinity can be reached by fast carbonation process as studied by Savastano et al. [8].

The activation of ground blast furnace slag (GBFS) by commercial ordinary Portland cement (OPC) is based on the availability of both calcium hydroxide and gypsum and enables the partial substitution of OPC in commercial blends [9,10]. The use of GBFS calcium-sulphate activated as a substitute for OPC offers some advantages in the production of natural fibre reinforced composites:

- Lower alkalinity [11].
- Cost reduction. In the Southeast region of Brazil GBFS from five large steel plants is readily available at prices about 60% of commercial Portland cements (transport and commercialisation fees included).
- Energy saving and low CO_2 release, characterizing an environmentally friendly product.

The clinker free binder is highly dependent on the efficiency of the applied activators in the hydration process [9,12]. The carbonation mechanism can also play a role in the loss of mechanical strength under natural ageing due to the decomposition of ettringite and calcium silicate hydrate (C-S-H), as suggested by Taylor [13] and Wang et al. [14].

The consumption of building components made of fibre reinforced cement is increasing rapidly specially in developed countries which is estimated to be around several million of tonnes per year [15]. This is because with this type of material it is possible to produce lightweight building components, with good mechanical performance (mainly impact energy absorption) and suitable thermal-acoustic insulation and it is also economically feasible.

In developing countries, where the lack of housing as well as the lack of commercial, industrial and public service buildings is considerable, the introduction of these materials can help increasing the production of buildings with suitable performance. Provided that the low durability risks in alkaline environment are eliminated, the vegetable fibres can be a good alternative in these countries due to low cost. Besides, in some regions, asbestos–cement is still the sole composite in use, although health hazards are becoming an increasing concern [16].

The main objective of this paper is to discuss the most relevant results of 20 years of research activities in the field, developed by our research group in São Paulo, Brazil, and in comparison with related works available in the literature. The research started with a survey of vegetable fibre availability and costs, characterization of some selected fibres, investigation of an activated granulated blast furnace slag binder with low alkalinity, development of components, microstructure characterization and durability studies, including a long-term in-use study. Durability is further discussed in depth elsewhere [17]. Other studies have been also carried out, such as the investigation of the use of vegetable fibres to control drying shrinkage stresses [18], sisal reinforced gypsum panels [19], as well as the use of cellulose recovered by disintegration of newsprint paper [3].

2. Fibres

Tropical countries like Brazil are indeed the domain of natural fibres mainly directed to cordage, textile and papermaking production. The heterogeneity and perishing of such fibres and also the market of restricted uses lead to intense generation of residues with high potential for ambient pollution. For example for each tonne of commercially used sisal fibres, three tonnes of residual fibres have been dumped causing hazard to the environment [20].

As reported by Coutts [21], vegetable 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 lignin 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 [22]. Then the usual denomination for fibres is in fact a reference to strands of fibres with some important consequences on durability studies.

Coir fibres, extracted from the mesocarp of the coconut fruit, and banana fibres cut from the pseudo-stem of the plant, are examples of widely available fibres.

Eighteen types of potential fibres were selected, including cellulose pulp recovered from newspaper, malva, coir and sisal [3]. However, if cost projection and availability are taken into account the number of suitable types of fibres reduces drastically.

Coir and sisal chopped strand fibres and also eucalyptus residual pulp were previously identified as fibrous waste materials suitable for cement reinforcement [20]. The main physical properties of these fibres are presented in Table 1. Specific gravity, permeable void and water absorption were obtained by the method of immersion of the specimens in water. The calculation of these physical properties was based on the Brazilian Standard NBR-9778, which is focused in cement mortars and concretes.

- *Coir* (*Cocos nucifera*) *residual fibres*. The coir fibre production in Brazil is rudimentary. Out-dated equipment crushes the husk and separates the fibre from the mesocarp of the fruit. The shortest fibres and the residues available in the large urban centres are of low value.
- *Sisal* (*Agave sisalana*) *field by-product*. This material is readily available, but with no commercial value.
- *Waste Eucalyptus grandis pulp*. This resource accumulates from papermaking and is readily available.

The properties of vegetable fibres have high variability, and age and location of the fibre in one single plant can have important effects [23]. The design of composites reinforced with these fibres should consider a safety factor in accordance with the variability observed in the raw-material. This factor allied with different methods and condition of testing and natural biodegradation before and during process of production can explain the high discrepancy of values in the published literature. Tables 1–3 present some properties of sisal, eucalyptus pulp and coir fibres.

Vegetable fibres have both tensile strength and elongation on rupture much higher than the cement matrix, but its elastic modulus is significantly lower (Table 2). Increasing degree of porosity and lignin content reduces mechanical performance of the fibres [24].

As shown in Table 3, coir fibres have a higher content of lignin and hemicellulose than sisal. Lignin is an amorphous chemical species with high solubility in an alkaline medium and its removal is an essential part of the pulping process.

The resistance of the coir and sisal fibres to alkaline attack has been also evaluated by Agopyan [3]. This study analysed fibres originated in Brazil from other commercial uses. The fibres were drawn on a saturated solution of calcium hydroxide (pH ~12) at laboratory temperature. The results (Fig. 1) confirmed those obtained by Cook [25], which concluded that coir fibres

Table 1
Average physical properties of Brazilian waste eucalyptus pulp, coir and sisal strand fibres [3,40,43,44]

Fibre	Thickness (μm)[a,b]	Specific gravity (kg/m^3)[c]	Permeable void (% by volume)[c]	Water absorption saturation (% by mass)[c]
Sisal	227	1104–1370	60.9–77.3	110–240
Coir	210	1117–1165	56.6–73.1	93.8–161
Eucalyptus grandis pulp	10.9	1609	89.2	643

[a] Coefficients of variation frequently over 50%.
[b] Determinations by scanning electron microscopy.
[c] Brazilian Standard NBR-9778.

Table 2
Average mechanical properties of some fibre samples from Brazil

Fibre	Tensile strength (MPa)	Elongation on rupture (%)	Elastic modulus (GPa)	Reference
Coir	107	37.7	2.8	[3,45]
Sisal	458	4.3	15.2	[3]
Malva	160	5.2	17.4	[46,47]

Table 3
Range of variability of the chemical composition (in % by mass) available on the published bibliography of sisal and coir fibres in comparison with other natural fibres

Fibre	Cellulose	Lignin	Hemicellulose	Reference
Coir	35–60	20–48	15–28	[17]
Sisal	43–88	3.8–9.9	10–21	[23,24]
Malva	76	10		[3,48]
Eucalyptus bleached kraft	89	0.5		[49]

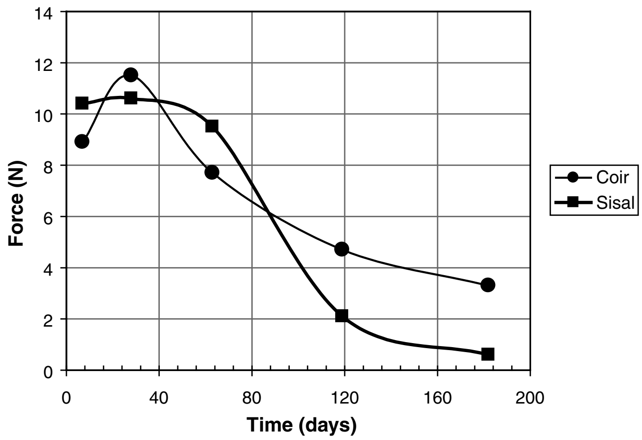

Fig. 1. Effect of calcium hydroxide water solution on coir and sisal fibres [3]. Test performed accordingly to ASTM D 3822/1982. Average of 30 measurements. Coefficient of variation above 40%.

were more resistant to calcium hydroxide alkaline attack. On the other hand, the low resistance of sisal fibre under alkali attack was discussed in details by Gram [22]. The increase in the tensile strength of coir fibres noted at 28 days of exposition (Fig. 1) is observed on mercerisation—a short-term controlled alkaline treatment of vegetable fibres [24]. Table 2 brings the average tensile strength of non-aged coir and sisal fibres. The loss of tensile strength was also accompanied by a similar decrease on elongation in rupture. Waste fibres had shown lower initial elongation at rupture and also a proportionally higher reduction of elongation during ageing.

The relatively higher resistance of the coir fibres to the alkaline environment has been explained [3] as being a result of its structure covered by an external layer with low permeability, partially expressed by its lower total water absorption (Table 1). Cook [25] stated that the chemical composition and morphological properties of coir fibre provide a better protection against decomposition than is the case for sisal fibre. That work presented data where coir fibre immersed for 6 months in lime solution (pH 12.6) lost only 35% of their initial strength. Guimarães [26] discussed that the impregnation of sisal fibre with a 0.375% polyvinylalcohol (PVA) aqueous solution heated during 60 min led to a tensile strength of the fibre 78% greater than unimpregnated sisal fibres after 140 days under lime solution exposure.

Agopyan [3] reported that subjecting the coir fibres to tap water followed by drying at laboratory environment or oven at 105 °C also did cause a significant reduction in the tensile strength and in elongation. This can be attributed to biodeterioration [22] but the leaching of extractives can also contribute.

Fibres have been analysed using scanning electron microscopy–secondary electron image (SEM–SE), and a massive surface degradation has been observed [27].

After these results, coir fibre has been selected besides sisal and eucalyptus fibre and its residues for further studies.

3. Matrix

In order to improve the durability of the composites the reduction of the alkalinity of the matrix was adopted. Therefore, the study of the cements with added by-products was pursued. Rice husk ash (RHA) and granulated blast furnace slag (GBFS) were tested for these purposes although the best mechanical results were obtained with the latter in that stage of the research; so all the results presented in this paper are from specimens made of GBFS based cement.

In a parallel work, Cincotto et al. [28] studied non-ground RHA and the results of compressive strength at 28 days ranged from 7 to 11 MPa for mixtures containing between 30% and 50% of RHA burned in a fluidised bed boiler as a substitute of OPC. All the tests were performed with binder to sand ratio of 1:2.5 and workability of the mortar of 250 mm (flow table test).

Only in Brazil, more than 6 million metric tonnes of basic GBFS are available every year and about 2 million tonnes of this amount is stocked without use, causing a problem for the steel industry as well as for the environment [29]. Consequently, the cost of GBFS is as low as US$10.00 per tonne. For cement production, the slag must be ground to at least a similar fineness of ordinary cement, which adds a further cost of US$15.00 per tonne, and it must be activated with chemical procedures.

The GBFS supplied by Companhia Siderúrgica Paulista (Cosipa), milled to 500 m^2/kg was used in the production of the pre-cast wall panels and durability studies carried out by Agopyan and John [7]. The chemical composition follows in Table 4. Since almost no Na^+ and Ka^+ elements were present and based on Gram's [22] emphasis on the deleterious effect of Ca^{2+} elements on fibre degradation, the content of free CaO

Table 4
Chemical composition of granulated blast furnace slag (% by mass) [11]

Compound/supplier	Cosipa	CST
SiO_2	34.48	33.78
CaO	42.72	42.47
Al_2O_3	11.49	13.11
MgO	6.79	7.46
SO_3	0.02	0.15
Fe_2O_3	0.85	0.51
K_2O	0.42	0.32
Na_2O	0.28	0.16
Insoluble residue	0.22	0.53
Glass content	97	99.5

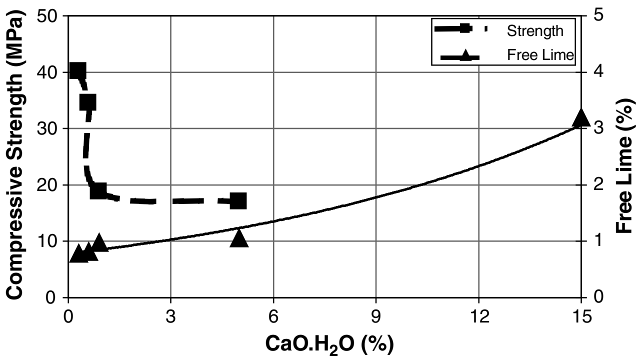

Fig. 2. Effect of calcium hydroxide content on free CaO and compressive strength (1:3:0.5—binder:sand:water, by mass) at 28 days. Natural gypsum content equal to 10%.

was taken as indicator of total alkalinity. As Fig. 2 shows for binder formulation containing 10% of natural gypsum, an increase of $CaO \cdot H_2O$ content results in an increase on free lime content. It was found that the $CaSO_4 \cdot 2H_2O$ content does not affect the free lime content. An increase on calcium hydroxide causes a very sharp reduction on 28 days compressive strength (Fig. 2), but increases the 24 h compressive strength. It has been demonstrated that a minimum 2% of calcium hydroxide was necessary to allow removing from moulds after 24 h of room temperature curing. Based on these results, the selected binder composition was 0.88:0.10:0.02 (GBFS:natural gypsum:calcium hydroxide) in relation to the total dry mass of the raw-materials.

For the production of the roofing tiles, GBFS was supplied by Companhia Siderúrgica de Tubarão (CST), Brazil, milled until Blaine fineness of 500 m^2/kg. The main oxide average composition follows in Table 4. Gypsum and later phosphogypsum (residue from fertilizer industry)−41.3% SO_3 and 18.7% combined water—and commercial hydrated lime—91.0% $Ca(OH)_2$—were used as activators in the proportion varying from 0.86:0.10:0.04 to 0.88:0.10:0.02 (GBFS:gypsum:lime) by mass. Silica sand (fineness modulus above 2.12 and maximum characteristic dimension of 2.4 mm) performed the aggregate for mortar formulation of 1:1.5 (binder:sand) by mass.

4. Microstructure

The hydrated cement phases have been studied by X-ray diffraction (XRD). Calcium silicate hydrate, ettringite (calcium sulphoaluminate hydrate), portlandite (calcium hydroxide), calcium monosulphoaluminate hydrate, calcium monocarboaluminate and AFm phases have been found to be present.

The transition zone of the OPC matrix is characterized by a high porosity, very frequently forming a gap (debonding) around the vegetable fibre (Fig. 3). The transition zone also revealed a higher concentration of portlandite. As in normal concrete, the transition zone thickness increases with the water–cement ratio and decreases with curing time. The high porosity has been explained by the very high initial water absorption of the fibres. The gap between the fibre and the matrix can be explained by the higher desiccation shrinkage of vegetable fibres [30].

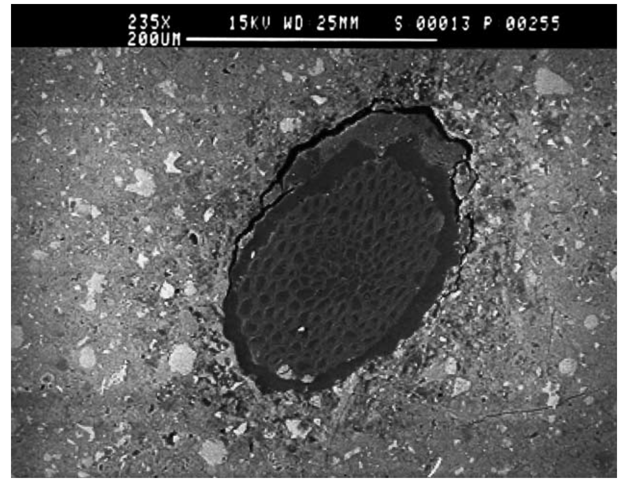

Fig. 3. SEM—backscattering electron image. Coir fibre–cement composite, *w/c* ratio = 0.38, age = 28 days.

GBFS activated by hydrated lime and natural gypsum presented the same configuration but almost no portlandite concentration in the transition zone. Although the advantage of less alkalinity, the mechanisms of degradation related to the fibre–matrix interaction seem to remain active at least for situations of aggressive environmental attack and with the consequent decay of mechanical behaviour in the long term (see Section 5.4).

5. Components and their durability

The studies were basically carried out on two types of components: wall panels and roofing tiles.

5.1. Wall panels

Hollowed load-bearing wall panels were developed with this composite where the GBFS was activated with 10% of gypsum and 2% of lime, and the water/binder ratio was 0.509. The fresh mixture reinforced with 2% of coir fibres (3 ± 1 cm long), by volume, presented the following properties: workability of 250 mm (flow table index—Brazilian Standards NBR-7215), 6.5% of air content and specific gravity of 2025 kg/m^3. The static mechanical strength and toughness obtained from compressive and bending tests were not significantly different from those for unreinforced matrix; however, the impact strength doubled that of the matrix itself. The degradation of this composite was also analysed and the results follow in the Section 5.2.

The panels were 2.4 m high and 0.395 m wide, with a thickness of 0.09 m. They presented good thermal performance. The thermal resistance (inversely proportional to the thermal conductibility) of the panel was equal to 0.14 m^2 K/W for 8% of humidity of the composite in indoor environment, which is similar to an ordinary concrete panel with same shape [2]. The wall made with them had an acceptable mechanical performance: compressive strength of 6.48 MPa; Young's modulus of 9.55 GPa; and Poisson's ratio of 0.167. The detailed production and properties of the panels are presented elsewhere [2,7].

A prototype of a low cost house with approximately 20 m^2 was assembled with these panels in a low-cost housing settlement located in the city of São Paulo. The panels have no surface protection except a single layer of PVA emulsion paint. The roofing employed commercial asbestos–cement corrugated sheets and wood structure. The prototype also used other thin panels for internal and external application based, respectively, on gypsum and OPC matrices reinforced with disintegrated cellulose pulp (recycled newsprint). Since 1989 this prototype has been in use by the local community as a nursery, house and community meeting centre. Agopyan [31] provided supplementary information on the characteristics and constructive details of the prototype.

5.2. Durability of wall panels composite

A more detailed review of the accelerated ageing as well short-term studies are presented elsewhere [27,32]. A simple accelerated ageing test that is known as quick condensation test (Q-C-T) was performed in samples 200 × 50 × 10 mm. However the usual exposure time and cycling period were not suitable for the material degradation evaluation, and thus the exposure time was increased to 648 h with cycles of 8 h of water vapour (one side only) followed by 8 h drying at room temperature. The RILEM bending test [33] was adopted as degradation indicator. After this accelerated ageing the average MOR was 3.1 MPa, virtually the same 3.0 MPa of 28 days wet cured samples, but considerably lower than 4.3 MPa from samples with the same age (54 days) but conditioned in laboratory environment after the initial 28 days of wet curing. All the specimens for the bending test were previously dried at room environment.

The adopted GBFS based cement is very similar to a slag sulphate cement made with Portland cement, plaster (anhydrite) and GBFS. The slag sulphate cement has its strength reduced due to carbonation because ettringite is decomposed in weaker products. For this reason, the composite was submitted to an accelerated carbonation test (100% CO_2 environment, 35 °C and RH 75%) [27]. The carbonation, in fact, prevents the increase of the strength of the composite (Fig. 4).

Identical samples were exposed after 28 days of wet curing in a natural ageing station, located in the city of São Paulo (23°34 ′S, 46°44 ′W), Brazil. Fig. 5 summarises the results that were restricted to the evolution of bending strength during the period of only one year. With 95% of confidence, MOR of the composite was not affected in the period between 6 months and 1 year of ageing, what can be explained by further hydration of the cementitious matrix. Probably the measurement of the toughness could have been a better indicator of degradation of this material. Examination of the samples surface under optical microscopy had shown signs of decay and that part of the matrix has been leached, with holes up to 3 mm depth. Fibres did not show any visible degradation when examined under SEM–SE and optical stereoscope but their brown colour was faded [27].

One year of natural weathering resulted in lower MOR results, despite of progressive hydration. All aged samples presented MOR strength significantly lower than those with the same age but kept in the laboratory condition.

The in-use durability performance has been evaluated through the prototype. When the age of the material was 2.5 years the prototype has been inspected [7]. Fibres examined under SEM still appeared to be sound. The only problem found was a leaching on the bathroom wall, in an area exposed to heavy water spilling. A XRD analysis revealed the presence of gypsum, a product of cement carbonation.

The prototype is still in use and does not show any further degradation process. John et al. [17] present an in-depth discussion on durability of this prototype.

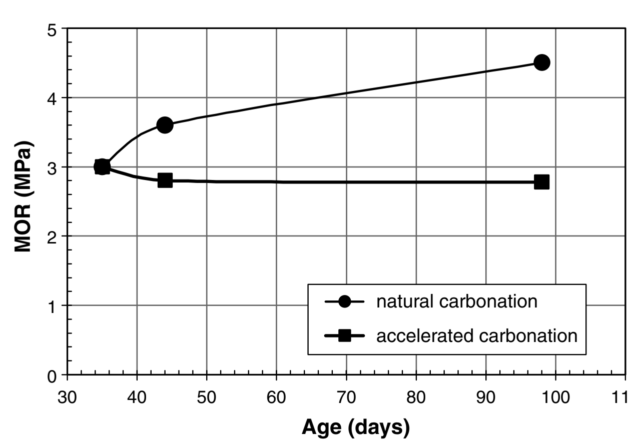

Fig. 4. Effect of carbonation on composite modulus of rupture. Accelerated carbonation started after 34 days [27].

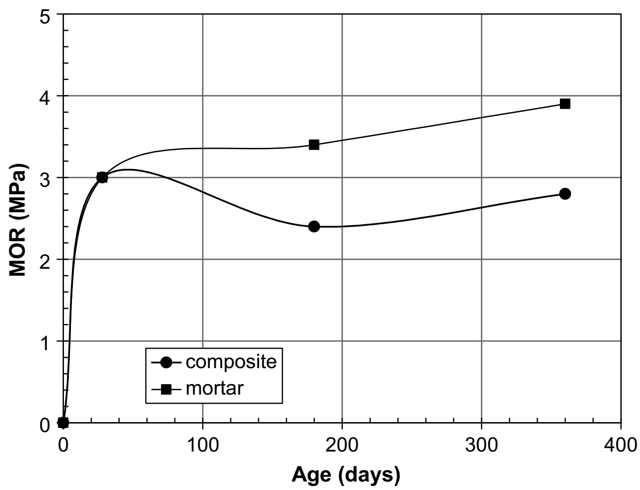

Fig. 5. MOR over time of GBFS lime–gypsum cement mortar reinforced with coir fibre exposed in a natural ageing station at São Paulo, Brazil.

5.3. Roofing tiles

Roofing tiles were fabricated using the Parry Associates (UK) equipment, for moulding and compaction by vibration. The matrix mixes are as detailed in Section 3 and with 2% total fibre volume fraction (V_f), equivalent to 3.7% of fibre by cement mass. The water/binder ratio varies as presented in Table 5. The dimensions of the tiles were 487 × 263 × 6 mm (frame measures) with consumption of 12.5 pieces/m^2 and format very similar to ceramic Roman tiles. After 48 h, the tiles were demoulded and submitted to saturated air condition during 7 days followed by air curing in laboratory ambient until tested. In the case of tiles for durability tests the period of air curing ranged from 60 to 70 days before submission to environmental exposition.

Three-point bend test specimen (major span = 350 mm, deflection rate = 5 mm/min) adapted from Gram and Gut [34] was employed for determination of maximum load and specific energy at 28 days of total age on tiles previously immersed in water for 24 h. Specific energy is proposed here as the total energy dissipated up to 70% of load reduction and divided by the cross-section area. Physical properties (warping, water tightness and absorption) were also determined in compliance with Brazilian standards for concrete roofing tiles (NBR-13852-2).

Series of tiles from the several matrix mixes were exposed in a rack facing North with 30° of inclination and submitted to natural ageing under environmental condition in a rural area at Pirassununga, State of São Paulo, Brazil (21° 59' S of latitude), for up to 60 months from July 1998 to August 2003. The main long-term climate conditions for the region were: average maximum temperature for January = 30.1 °C, average minimum temperature for July = 9.5 °C, average maximum relative humidity for January/February = 77%, average minimum relative humidity for August = 63% and average rainfall = 1363 mm/year. After the ageing period, the tiles series were submitted to the same mechanical and physical tests as described previously.

Table 5 presents physical and mechanical results, with coefficients of variation for mechanical results of about 30%.

For the series tested at 28 days (1 month in Table 5), the results for main properties attended prescriptions proposed by Gram and Gut [34] for similar products: (a) water tightness test did not generate more than damp marks on the underside of tiles after 24 h under 250 mm of water column pressure and (b) maximum load at bending test exceeded 425 N which is the value recommended for 8 mm tiles tested saturated. Besides, warping was less than 3 mm and water absorption did not exceed 16% by mass after immersion for 24 h. The main advantage of reinforced tiles was the at least 22% higher energy absorption than that of the reference which could help to avoid fragile rupture of tiles in the short-term under transportation or installation due to dynamic efforts involved.

The behaviour of tiles tested after 28 days was similar to those presented by Savastano et al. [20]. In another related study on alternative roofing reported at RAS

Table 5
Physical and mechanical properties of the tiles

Fibre (V_f)	Reference (no fibre)	Coir (2%)			Eucalyptus pulp (2%)			Eucalyptus (1%) + sisal fibre (1%)		
Water/binder ratio	0.40	0.45			0.48			0.50		
Condition	Air-cure	Air-cure	Ageing		Air-cure	Ageing		Air-cure	Ageing	
Age (months)	1	1	16	60	1	16	60	1	16	60
Warping (mm)	0.91	1.61	0.52	0.52	1.53	0.85	0.73	2.43	2.34	0.61
Water tightness	No signs	Damp marks			Damp marks			Damp marks		
Water absorption (% by mass)	14.4	12.6	12.2	12.7	14.5	14.5	15.4	16.0	15.1	15.7
Thickness (mm)	9.38	7.85	8.05	7.80	7.37	7.30	6.44	7.04	6.62	6.69
Maximum load (N)	697	482	235	248	587	262	139	447	237	159
Specific energy (J/m^2)	405	498	182	143	565	139	96	494	137	67

Technical Bulletin [35], ordinary Portland cement (OPC) mortars reinforced with 1% by volume of chopped sisal fibres showed 30% of reduction in flexural strength compared with plain mortar, at 14-day age, and up to 3-fold increase in impact strength.

Related studies carried out by Pimentel [36] employed mortars based on OPC and reinforced with *Pinus caribaea* residues from pencil manufacture. The main result was the production of roofing tiles using the same Parry Associates device as previously presented. The mechanical behaviour of tiles at short term demonstrated to be comparable to that of the plain mortar used as reference. The flexural load was of at least 490 N and the toughness of tiles produced with the composite material was up to 124% superior to the control. Several other cement-based composites containing vegetable fibres or particles were extensively studied by the same research group [37,38] for rural construction applications.

Ghavami and Hombeeck [39] produced tiles using cement mortars reinforced with coir fibres and compacted under 2 MPa of pressure for about 5 min. The authors pointed out that the thermal insulating property of this product is 20% higher than that of asbestos–cement. This component was presented as a low-cost lightweight product for non-load bearing walls, ceilings and roofing.

Considerable better results for fibre–cement materials should be expected by using refined pulp and slurry dewatering process, followed by pressing [40]. The increase in energy consumption during these procedures seems to be justifiable by the improved performance of the composites. Such a production model is similar to Hatschek industrial method still employed for asbestos–cement based products in Brazil and can be a worthy approach for corrugated sheet fabrication in the near future when asbestos ban comes into effect.

5.4. Durability of roofing tiles

Series tested after 16 and 60 months of environmental ageing showed acceptable water tightness and absorption close to results from air-cured series previously tested at 28 days of age. Some tiles on the experimental rack suffered leaching and darkening on the upper surface after the weathering period of 60 months. Mechanical performance showed considerable decay with results dropping, respectively, in the range of 65% and 80% on maximum load and specific energy in comparison to initial results (Table 5). Tiles reinforced with coir fibre presented practically the same maximum load capacity in the tests after 16 and 60 months of weathering.

The loss of flexural strength in GBFS based materials was also reported elsewhere [14] and interpreted as a consequence of carbonation evolution. This mechanism can be of particular damage to composite performance if inadequate or insufficient water curing takes place at the initial hydration stages of GBFS cement [41]. In the present study, qualitative evaluation using a solution of 2% phenolphthalein in anhydrous ethanol solution revealed composites were fully carbonated at the end of ageing period.

It has been suggested that fibre petrifaction can also cause composite embrittlement [22,32]. In a similar study on air-cured fibre–cements, Bentur and Akers [4] observed that the fibre petrifaction can take place under ambient carbonating conditions, probably due to lower pH and greater solubility of the hydration products.

However, carbonation should be expected to reduce the incidence of $Ca(OH)_2$ and to avoid the alkali attack on the non-cellulose components of the fibre (lignin, e.g.) [42]. But this phenomenon did not appear to have a significant effect on the prevention of ductility dropping for the studied composites. The other mechanisms of degradation continue to act in the same form.

John et al. [6] also pointed out that generalised interfacial damage could be progressively generated by hygroscopic volume change of vegetable fibres inside the cement matrix hence contributing to the dropping of composite mechanical behaviour in the long run. Studies by Savastano and Agopyan [30] on vegetable fibre–cement microstructure demonstrated the poor bonding between both phases with significant incidence of high porosity and microcracking in the fibre–matrix transition zone (Fig. 3).

6. Comments

Air-cured roofing tiles produced with GBFS based mortar reinforced with waste crop fibres and/or residues from cellulose mills conformed to international compatible standards at initial ages for mechanical and physical main properties. The enhanced ductility in the post-cracking stage was the most favourable aspect of composite tiles in relation to unreinforced reference.

Sixty months of natural ageing under tropical climate conditions played a significant decay in the capacity of load support and embrittlement of fibre–cement roofing tiles, although major physical characteristics were preserved. The reduction on the mechanical properties could be attributed to a combination of different processes such as matrix carbonation, fibre petrifaction and transition zone degeneration.

Experimental efforts involving raw-materials preparation and fabrication procedures were already undertaken aiming at the improvement of composites mechanical performance as reported elsewhere.

Even high intensity accelerated tests (Q-C-T and carbonation test) were not sufficient to simulate the actual environment effects on similar size specimens of these composites. This may happen because these tests cannot reproduce the simultaneous actions of the degradation agents.

Since the coir fibres do not increase MOR of the composite, this property is an excellent tool only to measure degradation of the matrix.

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