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Sisal fiber reinforced hollow concrete blocks for structural applications: Testing and modeling

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HIGHLIGHTS

- Tests on blocks, prisms, and walls made of concrete reinforced with sisal fibers were carried out.
- The influence of the fibers was pointed out by comparison with tests on plain concrete specimens.
- Fibers decrease the stiffness of the specimens, but increase their ductility.
- Fibers decrease the strength of blocks and prisms, but increase the strength of the walls.
- Finite element models were developed to predict the mechanical behavior of the blocks.

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ABSTRACT

An experimental programme was carried out to investigate the mechanical behavior of masonry elements made of concrete and natural sisal fibers. Compression tests were carried out on individual hollow blocks, as well as on prisms and wallettes made of hollow blocks. For comparison, the mechanical response of companion plain concrete specimens was also assessed. The results of the tests are presented, and the influence of the sisal fibers on the mechanical properties of the elements is discussed. Numerical models were also developed to predict the nonlinear behavior of the blocks. The parameters and the boundary conditions that define the models are calibrated to match the experimental load-displacement curves. A qualitative description of the damage evolution in the elements using the smeared crack model implemented in the commercial FE program DIANA and the XFEM implemented in Abaqus is obtained. The experimental and numerical results are critically discussed, and possible future improvements of the proposed models are outlined.

1. Introduction

The use of unconventional building materials (green materials) is rapidly increasing for the construction of sustainable buildings. Special attention is given to concrete blocks reinforced by vegetable fibers, which stand out because of their low cost and large availability in many emerging countries. Vegetable fibers enhance the mechanical properties of concrete, control opening and propagation of cracks, usually increase tensile strength, toughness and ductility of the elements in which they are used, allowing relatively large deformations without any loss of integrity.

Many authors investigated how adding vegetable fibers to building materials affects their mechanical properties: exhaustive reviews on this subject have recently been carried out by Pacheco-Torgal and Jalali [1] and by Ardanuy et al. [2]. According to these surveys, cellulosic or vegetable fibers enhance the mechanical, thermal and physical performances of cement-based composites when added to the cementitious matrix, as they increase their flexural strength, toughness and impact resistance, reduce shrinkage on drying and thermal conductivity, and increase sound absorption.

Vegetable fibers of different nature can be added to cementitious materials for structural and non-structural applications. Gastaldini et al. [3] evaluated the influence of rice husk on the compressive strength and the shrinkage of concrete, showing that the cost per cubic meter of concrete with compressive strength ranging between 35 and 55 MPa can be reduced by replacing 5%

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of Portland cement by rice husk ash. Tong et al. [4] added chemically treated luffa fibers to cement mortar to increase the cracking resistance; no significant reduction in drying shrinkage was observed compared to untreated luffa fibers. Corrêa et al. [5] added bamboo fibers and synthetic termite saliva to adobe to enhance its mechanical and physical properties.

Among the vegetable fibers that are being used in the construction industry, sisal fibers have a prominent place for a number of reasons, e.g., easy cultivation, low cost, good thermal and acoustic insulation properties, excellent tensile strength (≈400 MPa), high toughness, abrasion resistance. Sisal fibers are obtained by processing leaves of *Agave sisalana*, a plant of the agave family. Sisal fibers have long been used for marine and agricultural applications (as they can be twined into ropes and wires), as well as in handicraft (as they can be woven into carpets, fishing nets, bags, and fabrics). More recently, these fibers have also been used as reinforcement in cementitious composites [6–8]: these composites are currently considered to be one of the most promising structural materials in sustainable engineering technologies. Suitable thermo-chemical treatments can positively affect the mechanical properties (namely, the tensile strength) and the interface bonding of sisal fibers in cement based composites [9]. Sisal fibers are also found to be effective as reinforcement in polymeric matrix composites [10].

Compared to plain concrete specimens, sisal fibers reduce the propagation of cracks by controlling their opening, and may delay rupture of concrete elements [11]. The resulting composite has higher tensile and impact strength, higher energy absorption capacity and good performance even during the post-cracked stage. The fiber shape also affects the mechanical performances of concrete: flat and corrugated cement-based laminates reinforced by long, unidirectional sisal fibers were found to exhibit strain–hardening in tension and bending, unlike sheets reinforced by short fibers, which exhibit strain-softening [12]. Compared to laminates in plain concrete, fiber-reinforced laminates have higher flexural strength and toughness.

As far as non-structural applications are concerned, Roma et al. [13] analyzed the effect of adding sisal and eucalyptus fibers to cement matrix tiles, showing that vegetable fibers are an effective alternative to asbestos fibers.

Note that most of the authors quoted so far are Brazilian, according to the tremendous growth in the construction sector in their country, the climatic conditions of Brazil, and the availability of large amounts of cheap vegetable fibers.

To assess the possible advantages of employing sisal fibers in concrete structural masonry units, an experimental program was carried out at the Department of Structural Engineering of the University of São Paulo at São Carlos (SP), Brazil, in which individual concrete blocks, prisms, and small-size walls were tested to failure under displacement-controlled vertical compression. Indirect tension tests on blocks were also carried out. For comparison, tests on unreinforced concrete elements were also performed. Details on the properties of the materials used in the tests are given in Section 2, whereas the results obtained in the experimental campaign are presented in Section 3.

Indeed, experimental tests on large-size specimens are cumbersome and expensive. Accordingly, it would be important to have reliable numerical models available, capable of effectively describing the mechanical behavior of masonry structural elements made of hollow concrete blocks. Also, whereas proposals exist in the literature to relate the strength of the blocks and the binding material to the strength of the masonry element (see e.g. [14]), no similar expressions are currently available for concrete blocks with added fibers. This gap could either be filled by suitable testing programs, such as that described in Section 3, or by numerical analyses. A first step toward this goal was made in the present work, where two numerical models were developed to predict the mechanical behavior of the individual blocks before and after cracking. The first one exploits TNO DIANA finite element commercial program, in which a damage (or 'smeared crack') model is implemented. The second one is developed for Abaqus, which has the possibility of tracking the real crack evolution in any structural element using the eXtended Finite Element Method (XFEM). The numerical results obtained with the two models are presented in Section 4. The effects of the boundary conditions on the numerical predictions are discussed. Upon calibration of the material parameters, the first of the two models is shown to be able to effectively replace experimental tests.

Finally, in Section 5 the main results of the research are recalled and possible future developments are outlined.

2. Materials and methods

2.1. Materials and concrete mixes

In the preparation of the concrete mix, cement, sand, coarse aggregates, sisal fibers and water were used. Details on the individual materials and the mix design are given hereafter.

2.1.1. Cement

Table 1 lists the main physical, chemical, and mechanical properties of the cement used in the concrete mix (CP V-ARI RS), which is a high early strength sulfate resisting Portland cement. The characterization tests were performed in the laboratory according to the NBR 5733:1991 Brazilian standards [15].

2.1.2. Fine aggregates

Sand meets the requirements of NBR 7211:2009 [16] standards, and can be classified as fine sand in zone 2 (Fig. 1). Stone powder meets the specifications recommended by the same standards [16] for the granulometric range of zone 4, and can be considered as coarse sand accordingly (Fig. 2).

2.1.3. Coarse aggregates

Coarse aggregates have a very small (12 mm) mesh, a size that is widely used in the production of prefabricated elements. Table 2 shows the characterization of gravel or crushed stone, which can be classified as type 0 according to NBR 7211:2009 standards [16].

2.1.4. Sisal fiber

In the preparation of the concrete mix, 20 mm-long sisal fibers were used at 1% ratio with respect to concrete volume. The reinforcement was added in the form of individual fibers. Vegetable

Table 1
Physical and mechanical properties of CP V-ARI RS cement.

Trials	Results
Fineness-Sieve Res. # 200 (%)	0.15
Specific mass (g/cm^3)	3.12
Specific area (cm^2/g)	4743
Initial set (h:min)	1:50
Final set (h:min)	2:43
3 days Resistance (MPa)	44.4
7 days Resistance (MPa)	47.9
28 days Resistance (MPa)	52.2
Loss on ignition (%)	4.06
SiO_2 (%)	19.20
Al_2O_3 (%)	5.97
CaO (%)	63.47
MgO (%)	0.59
Alkali equivalent (%)	0.71
Free lime in CaO (%)	2.19