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Short sisal fiber reinforced recycled concrete block for one-way precast concrete slabs

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HIGHLIGHTS

- Short sisal fiber reinforced concrete (SSFRC) shown a deflection hardening behavior.
- Recycled aggregates had not influence on the cracking and maximum flexural stress.
- SSFRC blocks shown higher strength and ductility than commercial solutions.
- Slabs with SSFRC blocks presented higher stiffness than slabs with the other blocks.
- The numerical analysis shown good agreement with experimental results.

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ABSTRACT

This work is dedicated to the assessment of the structural performance of a new lightweight block for one-way precast concrete slabs made of short sisal fiber reinforced concrete (SSFRC) containing natural and recycled aggregate. The influence of the sisal fibers and recycled aggregate on the physical and mechanical properties was assessed experimentally, with clear benefits of fiber reinforcement on the post-cracking flexural capacity, while the higher water absorption of recycled aggregates had favorable impact on the compressive strength mainly in the FRC. Flexural tests were carried out on SSFRC blocks, as well as on ceramic and expanded polystyrene (EPS) blocks used commercially. The SSFRC blocks presented higher load and deflection capacity with much more ductile behavior, and with a geometry favorable for the passage of infrastructures. Slab panels including SSFRC, ceramic and EPS blocks were tested under four point bending configuration to assess the benefits of the new SSFRC block in quasi-real slab conditions. The results of these tests demonstrated the best structural performance of the SSFRC blocks over the other considered commercial solutions, not only in terms of initial stiffness, but also for the load at serviceability limit deflection conditions (average increase of 23%) and yield initiation (average increase of 38%); The observed continuous crack pattern crossing the SSFRC blocks and the main precast RC beams demonstrated the potentialities of these blocks to contribute for the structural performance of this type of slabs. Material nonlinear finite element simulations were carried out to derive, by inverse analysis, the values of the fracture mode I parameters of SSFRC. This multidirectional smeared crack model was also used to simulate the behavior of the composite materials and the SSFRC blocks, and the obtained level of accuracy has demonstrated the adequacy of the adopted inverse analysis strategy. A Finally, a parametric study was carried out to preview the potentialities of these new SSFRC blocks for this structural application, having been verified that a SSFRC block of 12 mm thickness and 250 mm height, of about 10 kg, is capable of accomplishing the standard recommendations, constituting a competitive and efficient solution for this market segment.

1. Introduction

In less developed and in overpopulated countries, the need to reduce the consumption of non-renewable natural resources and energy has encouraged the development of low cost, safe and sustainable constructive solutions, such is the case of affordable

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houses [1]. This strategy requires the use of local raw and renewable materials, and recycled constituents according to a methodology that mobilizes effectively their properties. This is being pursued by several researchers in diverse countries like Malaysia, India and China [2]. By using the prefabrication technology, these materials can be applied on the development of lightweight and durable constructive components according to suitable standards of quality control for the building of modular houses.

One way precast concrete slabs are used in United States since the 1950s, being composed by longitudinal prefabricated concrete slender beams reinforced with passive or prestressed steel wires, lightweight blocks (that can be made by diverse types of materials) supported in these beams, and concrete cover layer cast in place. This slab is the most popular flooring system for residential buildings in several countries [3,4]. The simple and fast method of executing, lightness and relatively low cost make them highly competitive, since the use of formworks is avoided, and the requirements for skilled manpower and time construction are reduced. Due the lightweight character of this type of slabs, currently designated by "beam-and-block floor system – B&B-FS" [5], the permanent loads transferred to their supports (beams and columns) and foundations are smaller than when massive RC slabs (heavier) are used [6], with consequent benefits in terms of the costs of these other constructive elements and better behavior of the building under seismic events.

The comparative life cycle analysis (LCA) performed by López-Mesa et al. [4], where the local construction practices adopted in Spain were considered, has indicated that the B&B-FS has lower environmental impact than in situ cast floors for residential buildings.

Despite the numerous advantages of the B&B-FS, some problems have been identified in its execution, mainly due to the susceptibility of the blocks to premature failure during the assembly process of the system, when the concrete cover is being cast, or during the installation of the housing infrastructures [3]. Numerous types of blocks are commercially available for B&B-FS, being clay, concrete and expanded polystyrene (EPS) the most used materials. In Brazil, the most often used lightweight blocks are made in clay and in EPS, with a share market of 55% and 85%, respectively [8]. However, despite the existence of quality control standards for the mechanical strength requisites of these blocks, a program for the assessment of their properties have registered values below the minimum limit imposed by these standards [7]. To avoid the deficiencies, and to increase the sustainability of B&B-FS, some initiatives are being done, such is the case of using recycled components [9,10,13] or lightweight materials [11,12] for the blocks

A review on the use of fiber-reinforced concrete (FRC) in precast concrete applications was executed by Banthia et al. [14]. FRC, where steel and glass fibers were adopted, was successfully used in formworks for beams and lightweight panels. Permanent formworks made by strain hardening cementitious composites reinforced with Polyvinyl alcohol (PVA) fibers were produced as an alternative approach for the construction of more durable RC slabs and beams [15]. The reinforcement contribution of this type of fibers has provided an increase in the load capacity of these elements. The potentialities of using sisal fiber as the reinforcement system of permanent formwork for slabs were evaluated by Schafer and Brunssen [16]. Arch and trapezoidal shape elements with a thickness of 10–20 mm were produced by using cement-based matrices reinforced with long sisal fiber layers. The load-deflection test of arch type formwork was characterized by a flexural hardening behavior with a maximum load twice higher than the first cracking load, and a failure load of about 7 kN was obtained. This performance indicators guarantees a high safety factor for all loading cases that may arise during the casting and construction process of this type of slab. According to these authors the manufacturing procedure of this type of formwork is, however, very labor-intensive and inappropriate for large scale production. In fact, despite the excellent reinforcement performance of long sisal fiber for cement based composites under bending [17,18], the lamination process requires more sophisticated production techniques than when concrete reinforced with short fibers is used.

The use of short sisal fibers for the reinforcement of cement-based materials can increase significantly its application since the traditional method of concrete production can be used in the execution of these composites. In past, many roofing tiles were produced with short vegetable fibers using conventional concrete technology, but their poor performance with rupture after 6 months has finished its use [19]. Recent studies, however, have shown that the use of short randomly distributed sisal fibers can result in composites having flexural hardening if appropriate measures are used in the production of the matrix and fiber treatment.

According [20] the hornification of sisal fiber by executing wetting and drying cycles provides a better fiber-matrix bonding behavior and an increase of 40% on the bond strength. In fact, composites reinforced with 4% and 6% of treated fibers of 50 mm length (l_f) developed a diffuse crack pattern with deflection hardening. The binder of this composite was composed of Portland cement and high content of both metakaolin and fly ash to guarantee the durability of the sisal fiber and also to ensure an adequate workability to the matrix for a proper fiber dispersion. Lima et al. [21] used similar binder, but part of natural aggregate was replaced by recycled concrete aggregate. The produced self-compacting matrix allowed a more homogeneous material reinforced with 40 mm fiber length, having been registered a flexural hardening behavior with multiple cracking and small crack spacing. Due to these characteristics, the application of this material for roof constructive element was numerically evaluated, having been demonstrated high potentialities for this type of application [22].

The objective of the present research is to evaluate the potential of using cementitious materials reinforced with short vegetable fibers (herein designated by the acronym SSFRC) in the production of lightweight blocks for precast concrete slabs. For this, a new block was designed, manufactured and tested experimentally. The self-compacting matrix was produced with recycled aggregate and substituting part of cement by silica fume and fly ash. The mechanical performance of the developed block was evaluated according to the Brazilian standard for this type of constructive elements, and compared with the one of blocks made by traditional materials, such as ceramic and EPS. Slab panels including SSFRC, ceramic and EPS blocks were tested under four point bending configuration to assess the benefits of the new SSFRC block in quasi-real slab conditions. Material nonlinear finite element analysis with a software capable of simulating the crack initiation and propagation was carried out to explore the potentialities of SSFRC for this type of blocks, and parametric studies were executed after the good predictive performance of the constitutive model has been assessed by simulating the experimental tests carried out.

2. Experimental program

2.1. Materials

2.1.1. Processing and characterization of sisal fiber

The sisal plant (Fig. 1a) is a member of the plant family of *agavaceae* that is indigenous of the arid zones of America. The plant is characterized by leaves that can exceed one meter length composed by long and very strong fibers. Harvesting is carried out by hand. After harvesting, the leaves are transported to a machine localized, in general, at plantation (Fig. 1b), and are decorticated to extract the cortex of ribbon fibers that develop along the length of the leaves (Fig. 1c).

The sisal fibers used in this research were collected in the city of Valente, state of Bahia, Brazil. Initially, the fibers were washed in hot water (50 °C) to remove surface soluble extractives [23]. The fiber treatment was conducted according the