EXPERIMENTAL INVESTIGATION OF THE FLEXURAL BEHAVIOR OF HYBRID SISAL FIBERS REINFORCED CEMENTITIOUS COMPOSITES

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ABSTRACT

This paper presents an experimental research of the performance of hybrid sisal fibers reinforced cementitious composites under bending test. The hybrid sisal fibers were composed by an association of long and short fibers. Such combinations were realized in order to improve the behavior of laminates reinforced with long sisal fibers. Usually, it is observed a lack of straightness on the long sisal fibers during the composites casting, which affects negatively the early response of the fibers once submitted to loading. Then, short sisal fibers of length and volumetric fraction varying between 20-30 mm, and 2%-4%, respectively, were introduced in order to act during the micro-cracking. The volumetric fraction of the long sisal fibers was fixed at 3%, and the matrix was made of cement, fly ash and metakaolin. Under bending, all the composites presented a strain hardening behavior, with multiple cracking. The highest strengths were registered on the composites reinforced with long fibers and short sisal fibers of 30 mm.

KEYWORDS:

Long sisal fibers; short sisal fibers; cementitious composites; strain hardening; multiple cracking.

INTRODUCTION

During the last decades, a great interest was observed in the field of vegetable fibers reinforcing cementitious concretes or mortars (Toledo Filho, 2000; Chakraborty, 2013; Wei, 2014; Silva, 2017, Zukowski, 2018, Stanislas, 2021). Such fibers are renewable, abundant, obtained through a low energy process, and present high tensile strength and tenacity. That strength is one the main reason of their introduction in cementitious matrixes, known as brittle material. Within the vegetable fibers, jute, curaua, flax, sisal, coir and cellulose are widely studied (Fidelis, 2019; Zukowski, 2018; Sawsen, 2014; Melo Filho, 2013; Texeira, 2022; Siqueira 2020). The sisal fibers are one of the most available in Brazil, and are inserted in composites as short or long fibers. When used as short fibers, they are introduced with length varying from 20 to 50 mm, volumetric fractions until 8%, and randomically distributed (Ferreira, 2012, Lima, 2014; Melo Filho, 2012) . In the case of long fibers, they are generally distributed between two and five layers interspersed with the matrix through a hand layup technique, in volume up to 10% (Silva, 2009; Melo Filho, 2013; Nagahama, 2015; Da Gloria, 2021). The fibers length is generally the same with the sample but limited to 1200 mm.

The reinforcement with long sisal fibers presents the advantages of the deflection and strain hardening response, when the composites are submitted to bending and direct tensile tests, respectively (Melo Filho, 2013; Da Gloria, 2021). However, one of the main difficulty observed is the alignment of the long fibers during the laying. As the fibers are flexible, they present lack of straightness that can negatively affect the early performance once the composites are submitted to tensile load. For this reason, Melo Filho (2013) proposed to stitch the fibers on the transversal direction while Da Gloria (2021) joined them with cement paste, in order to guarantee a facility of manipulation and alignment during the casting process. On a larger scale, the previous procedures may not be easily implemented and would bring additional cost to the process. Therefore, the solution proposed in this paper is to associate the long sisal fibers to composites containing short fibers in a hybrid reinforcement, in order to access how the bending behaviour can be promoted.

MATERIALS AND METHOD

Materials

The sisal fibers were obtained from the city of Valence, state of Bahia (Brazil), with lengths varying from 900 to 1200 mm. The bulk fibers present mean density, tensile strength and Young's modulus of 900 kg/m^3, 400 MPa and 19 GPa, respectively (Ferreira, 2012). Two types of sisal fibers were used in the current research: short fibers (SSiF) of lengths 20 and 30 mm, and long fibers (LSiF) of 400 mm. Before being used, the fibers were washed for one hour in hot water (80 ºC), dried, combed and cut according to their different lengths. Next, they were immersed during 1 hour in a calcium hydroxide solution, prepared by dilution of 1.85 g of $Ca(OH)_2$ per liter of water. Such treatment aimed at reducing the fibers dimensional variation, and promoting a better bond with the matrix (Ferreira, 2021). That process was followed by an air-drying of the fibers during two days. The fibers appearance is shown in Figure 1.

a) SSiF of 30 mm

b) LSiF

Figure 1 – Appearance of the sisal fibers.

The binder used was a ternary mixture composed by Brazilian Portland cement labelled CPV-ARI (CEM), metakaolin (MK) and fly ash (FA), in mass proportions of 30%, 30% and 40%, respectively. Such composition was chosen based on Da Gloria (2021) in order to have a free hydroxide calcium matrix. The densities of CEM, MK and FA were 3010 kg/m^3, 2640 kg/m^3 and 1890 kg/m^3, respectively. Out of the binder and the fibers, quartz river sand and the superplasticizer Glenium 51 (33% of solids) were used to produce the composites. The sand density was 2670 kg/m^3 with nominal diameter lower than 600 µm, and the mortar mix design in mass was 1: 0.4: 0.5: 0.015 (binder : water : sand : Glenium).

Short Sisal Fiber Cement Composite (SSiFCC)

The SSiFCC were produced with 2% and 4% of SSiF of length 20 and 30 mm. The volumetric fractions of fibers were chosen based on the mechanical results obtained by Ferreira (2012) with 25 mm of SSiF, and also in order to have composites with good spreading that facilitate the long fibers impregnation.

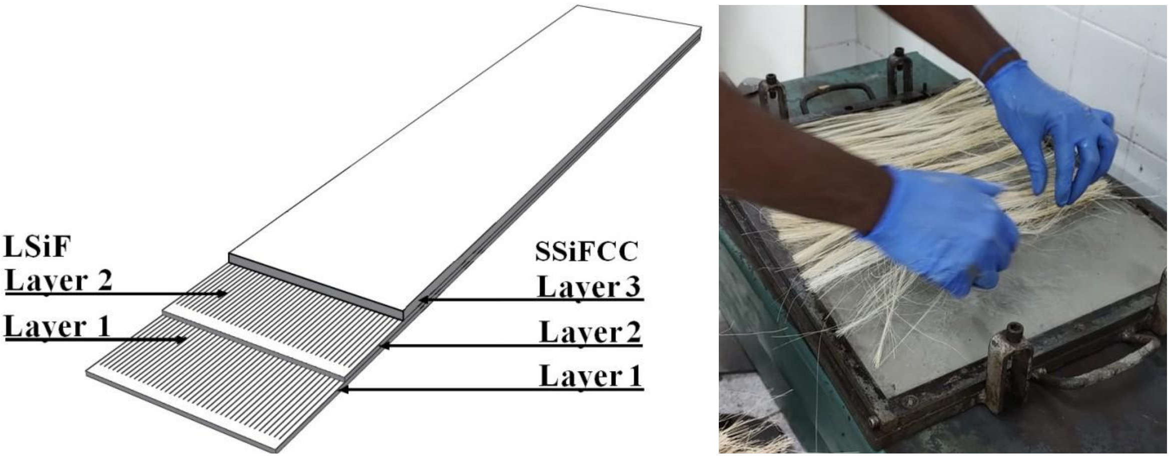
The composites were produced in a 20 L mixer. In accordance with Ferreira (2012) procedure, the casting sequence was: (a) mixture of CEM, MK and FA during 1 min, (b) Gradual addition of water + superplasticizer and mixing for 1 min, (c) Gradual addition of sand during 1 min, (d) Gradual dispersion of SSiF during 2 min, (e) mixture of the composite for 1 min. The consistency of the fresh SSiFCC-4%-20 is presented in Figure 2.

Figure 2 – Consistency of the SSiFCC-4%-20 under different angles.

Hybrid Sisal Fiber Cement Composite (HSiFCC)

Once the SSiFCC produced, they were associated to the 3% of LSiF through a hand layup technique to produce the HSiFCC. That volume of fibers was chosen based on the behavior observed by da Gloria (2021) after using 4% of LSiF distributed in 3 equidistant layers. In that case, one layer (volume of 1.33 %) remained in the compressive zone, and did not contribute to the tensile resistance. For that reason, only two LSiF layers of volume 2 x 1.5% were introduced into the composites of this study, specifically in the bottom region, according to the schematic representation of the Figure 3a .

The HSiFCC were manufactured by overlapping 2 layers of LSiFCC interspersed with SSiFCC in a prismatic mould of 550 x 400 x 13 mm^3. The casting sequence was: (a) spreading of around 3.25 mm (1.25 kg) of SSiFCC in the mould, (b) positioning of the LSiF (Figure 3b), (c) repetition of the steps (a) and (b), (d) spreading of 6.50 mm (2.5 kg) of SSiFCC, (e) vibration during 30 s on the vibratory table. The fresh composites were kept in the mould and protected against moisture, and withdrawn from the moulds after 24 h. Next, the samples were cured into a humid chamber of 100% RH, at 20 ± 3 ºC until completing 28 days of old.



a) b)

Figure 3 – a) Schematic representation of the LSiF and SSiFF distribution in the samples, b) Laying of LSiF on the SSiFCC.

Four-point bending test

From the prismatic sample of 550 x 400 x 13 mm^3 produced for each HSiFCC, 6 laminates of 80 x 400 x 13 mm^3 were obtained after cutting and they were submitted to four-point bending test, in order to study the flexure behaviour of the composites. The tests were performed in a universal machine Shimadzu of capacity 100 kN, at different speeds. The test begun at the rate of 0.3 mm/min, and after each 5 mm of machine displacement, 0.05 mm/min was added to the previous one. Such increase was realized in order to reduce by half the total duration of the test (estimated at 3 hours) per sample. In fact, the test was stopped once the final load reached 40% of the value of the maximum load, and that final was registered around 55 mm. The span and the distance between the load points were 300 and 100 mm, respectively. The deflection at mid-span was monitored by a LVDT positioned below the laminate (Figure 4).

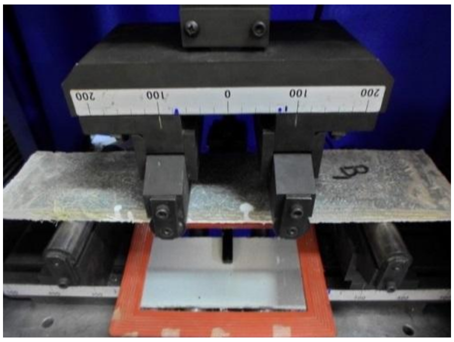


Figure 4 – Four-point bending test configuration.

RESULTS AND DISCUSSIONS

The typical flexural stress versus mid-span deflection curves of all the composites produced are illustrated in Figure 5. Globally, as expected when long sisal fibers are used, the composites presented a deflection hardening response with a multiple cracking formation. Such behavior was previously observed by Silva (2009), Melo Filho (2013), Da Gloria (2021) and can be divided in 4 regions. In the first one, the composites presented a linear behavior until the appearance of the first crack, followed by the beginning of the multiple cracking process. The third phase is characterized by a widening of the cracks that appeared in the precedent phase, few new cracks are also observed until reaching the maximum stress. Next, a deflection softening is registered because of the localization of one existing cracks. It is worth mentioning that in the softening phase, new crack could open and that fact is not usual for cementitious mortar reinforced by only long fibers.

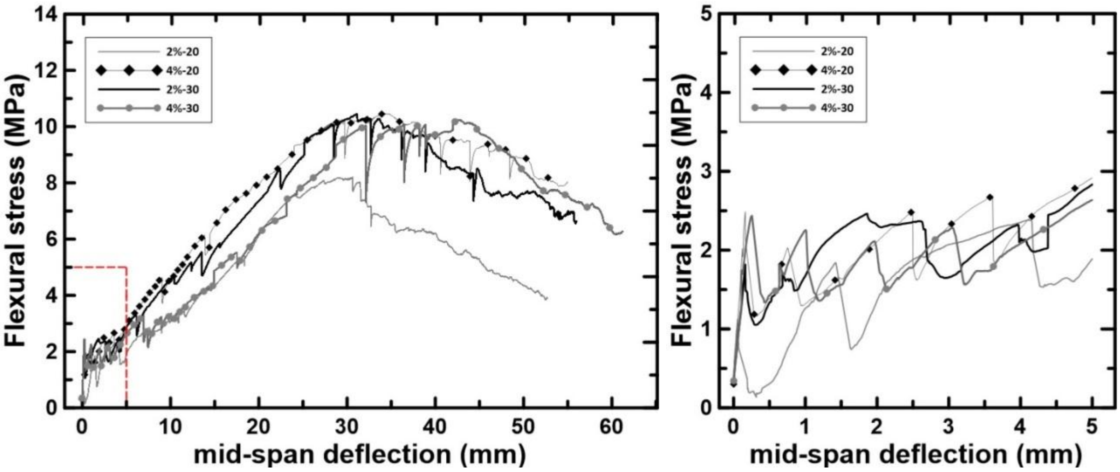


Figure 5 – Representative Flexural stress versus mid-span deflection curves until a) 60 mm b) 5 mm.

Table 1 lists the average values of flexural stress at first cracking (σ_{1c}) and corresponding mid-span deflection (δ_{1c}), the maximum flexural stress (σ_{max}) and the corresponding deflection (δ_{max}), the number of cracks registered at the end of the test. From the results, it can be observed that the composites 2%-20 presented the lowest σ_{1c}, while 4%-30 showed the highest. The same trend was observed in terms of mid-span deflection at first crack. It is well known that until the first crack, the matrix and the fibers behave together. Nevertheless, it seems that in the composites 2%-20, the LSiF was not early solicited because in other composites of same SSiF length (4%-20) and same SSiF volume (2%-30), the first crack occurred after 0.20 mm. Immediately after that crack, a load decrease of 90% is observed, followed by a hardening that began near to 0.4 mm. That hardening occurred with multiple cracking until a deflection of 32 mm, where the maximum stress σ_{max} (10 times higher than σ_{1c}) was achieved.

The other composites presented after the first crack a load decrease around 40%, and reached a maximum stress 3 to 4 times higher than that of first crack. The highest values of σ_{1c} and σ_{max} were reached by the composites 4%-30 and 2%-30, respectively. However, the behavior of the composites 4%-20 and 2%30 was much closed. In terms of deflection at the maximum stress, the highest value showed by the composites 4%-30 revealed that the length and the fibers volume had a positive effect on the deflection capacity.

Table 1 – Summarized results of the bending test (variation coefficient in % in brackets).

HSiFCC	σ_{1c} (MPa)	δ_{1c} (mm)	σ_{max} (MPa)	δ_{max} (mm)	Number of Cracks
2% - 20	0.78 (8.31)	0.07 (22.8)	8.24 (2.45)	31.90 (7.33)	9 (8.75)
4% - 20	2.44 (7.46)	0.20 (16.71)	10.26 (14.24)	35.76 (9.63)	9 (11.9)
2% - 30	2.18 (15.17)	0.21 (24.69)	11.51 (7.66)	34.18 (9.77)	11 (5.09)
4% - 30	2.97 (14.03)	0.30 (18.25)	9.83 (4.74)	39.50 (10.89)	12 (9.90)

At the end of the bending test, an average of 9 cracks opened in the composites with SSiF of 20 mm, while 11 and 12 were registered on the composites 2%-30 and 4%-30, respectively. The use of short fibers of 30 mm was more effective in terms of crack opening. Figure 6 presents the failure mode of the samples 2%-20.

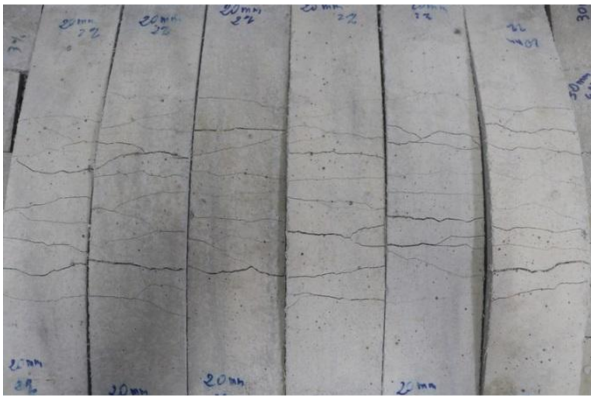


Figure 6 – Failure mode of the composites 2%-20.

CONCLUSION

Based on the results of this work, it can be concluded that it is possible to develop cementitious composites with deflection hardening response by combining both long and short sisal fibers. The composites with SSiF of 30 mm presented the best flexural behaviour, while no significative difference was observed between the composites 2%-30 and 4%-20. The use of 4% of 30 mm SSiF promoted the highest deflection at the maximum stress, and indicated encouraging results for developing composites with high tenacity. Further experimental and numerical studies will be done with higher fibers volume and length in order to optimize the composites mix design according to their application.

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