Mechanical characterization of cement based composites containing construction and demolition waste (CDW) reinforced with sisal fibres

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1. Introduction

Since the beginning of cement-based materials, development in science and technology of materials has been constant. Progress is due to the creation of new technologies as well as the incorporation of new materials such as additives and fibres. Growing environmental concern makes it increasingly necessary to seek sustainable solutions which include the replacement of new materials by recycled ones.

The effectiveness of the addition of fibres is based on two criteria in comparison to the matrix whose behaviour is brittle: the first is to increase the strength and the second is to increase the tenacity of the composites (Bentur e Mindess, 2007). Some aspects regulating the efficiency of the fibres in improving mechanical properties of the cement matrix is the process of transferring the stress from the matrix to the fibres and the effect of "stress bridge" which occurs at a later stage of loading. The efficiency of this process requires control of the basic properties of the fibres, such as the geometry, the chemical composition, the surface characteristics, the strength and the stiffness. As for the failure mode, short fibre reinforced composites have not yet demonstrated behaviour of multiple cracking under direct tension.

The use of vegetable fibres appears to be quite beneficial in many ways, including: the wide availability of materials, the low energy consumption, the reduced costs to acquire it, in short, environmental preservation. Sisal fibre, in particular, presents high tensile strength but on the other hand, a reduced fibre-matrix adhesion (Guimarães, 1990). This leads to the need for a long length of fibre to reach the maximum tensile stress before being torn out of the matrix and thus contribute to the total transfer of stresses in the cracked matrix yielding a better overall behaviour of the composite. Due to this limitation, it is necessary to resort to chemical or physical treatments capable of increasing the capacity of fibre-matrix interaction.

A possible solution for the vulnerability of vegetable fibres in the alkaline environment of the cementitious matrix is the development of a matrix free of calcium hydroxide (Farias Filho, 1999; Lima, 2004 e Melo Filho, 2005). Therefore, replacements of Portland cement with metakaolin were tested in order to consume the calcium hydroxide ($Ca(OH)_2$) created during the hydration of cement. Additionally, one can resort to impregnation of fibres with blocking agents and/or water repellent and to sealing the matrix (decreasing the quantity and size of pores as well as their interconnectivity).

The adhesion of the fibres to the cementitious matrix is considerably reduced due to the high water absorption of the fibre, derived from its porous structure, leading to large volumetric expansion. One alternative that has been studied is the hornification of vegetable fibres, which is a term used to describe fibres submitted to irreversible changes to processes of wetting and drying. This treatment causes a loss of water retention capacity of the fibres, as well as changes in their structure (cell wall collapses closing the lumen walls and creating deformations on the walls of the fibre cell) and their mechanical behaviour (Brancato, 2008).

In addition to superficial treatment of the fibres, the introduction of recycled materials has also been studied. In this research, this solution was explored in the form of recycled sand.

2. Experimental campaign

With the aim of studying mortar cement matrix containing construction and demolition waste (CDW) reinforced with vegetable fibres, matrices were tested with introduction of 2% and 4% by volume of vegetable fibres and percentages of substitution of natural sand to recycled one of 25% and 50%.

The matrices used were composed of 33% of Portland cement CP II F-32, compound with limestone filler, 27% of metakaolin, 40% of fly ash, river quartz sand with maximum diameter of 0.84 mm (specific mass of 2.67 g/cm^3), superplasticizer *Glenium 51* (type PA) with solid content of 32.2% and 1.4 g of viscosity modifier *Rheomac UW 410* (manufactured by BASF) when in presence of fibres. Table 1 summarizes the variables of the experimental study and Table 2 the respective tests performed.

Table 1 – Variables tested

	Composite	Natural Sand	Recycled Sand	Natural Fibre	Treated Fibre
7)	**Matrix N**	100%			
8)	**Matrix AR1**	75%	25%		
9)	**Matrix AR2**	50%	50%		
10)	**Matrix N + 2% FN**	100%		2%	
11)	**Matrix AR1 + 2% FN**	75%	25%	2%	
12)	**Matrix AR2 + 2% FN**	50%	50%	2%	
13)	**Matrix N + 2% FT**	100%			2%
14)	**Matrix AR1 + 2% FT**	75%	25%		2%
15)	**Matrix AR2 + 2% FT**	50%	50%		2%
16)	**Matrix N + 4% FN**	100%		4%	
17)	**Matrix AR1 + 4% FN**	75%	25%	4%	
18)	**Matrix AR2 + 4% FN**	50%	50%	4%	
19)	**Matrix N + 4% FT**	100%			4%
20)	**Matrix AR1 + 4% FT**	75%	25%		4%
21)	**Matrix AR2 + 4% FT**	50%	50%		4%

Table 2 – Tests performed

Composite		Direct tensile	Pull-out	Compressive	Tensile	Bending
Natural fibres		25x				
Fibres with 5 cycles		25x				
Fibres with 10 cycles		25x				
7)	Matrix N			3x	5x	3x
8)	Matrix AR1			3x	5x	3x
9)	Matrix AR2			3x	5x	3x
10)	Matrix N + 2% FN		10x			
11)	Matrix AR1 + 2% FN		10x			3x
12)	Matrix AR2 + 2% FN		10x			3x
13)	Matrix N + 2% FT		10x			3x
14)	Matrix AR1 + 2% FT		10x			3x
15)	Matrix AR2 + 2% FT		10x			3x
16)	Matrix N + 4% FN				5x	
17)	Matrix AR1 + 4% FN					3x
18)	Matrix AR2 + 4% FN				5x	3x
19)	Matrix N + 4% FT				5x	3x
20)	Matrix AR1 + 4% FT					3x
21)	Matrix AR2 + 4% FT				5x	3x
Total		75	60	9	35	39

All mortars were produced with a fixed water/cement ratio of 0.4. The matrix used in this study, with the design presented in Table 3, showed an average flow table spread of 400 mm without fibres and 240 mm with reinforcement, according to the Brazilian standard NBR 13276 (ABNT, 1995).

Table 3 - Material consumption per m^3 of matrix used

MATRIX (kg/m^3)							
Name	C	Sand	MC	CV	W	SP*	VMA
Natural Matrix (N)	398	597	318	478	459	27	1,0

*Solids of SP/MC

C: Portland cement; MC: metakaolin; CV: fly ash; W: water; SP: superplasticizer; VMA: viscosity modifier

The sisal fibres used in the present study were obtained from the sisal plant cultivated in farms located in the Bahia state, Brazil. The fibre extraction from the leaf was done by semi-automatic scrapers. From 10 kg of sisal leaves about 3.5 kg of extractable fibre is obtained. These fibres were characterized mechanically by Silva *et al.* (2008 and 2010).

Regarding the sisal fibre microstructure, it is formed by numerous individual fibres (fibre cells) which are about 6–30 µm in diameter. The individual fibre cells are linked together by means of the middle lamella, as it is shown in Figure 1. More information on the sisal fibres microstructure can be found in the authors' previous works (Silva *et al.*, 2009; Silva *et al.*, 2010 and Sreekumar *et al.*, 2009).

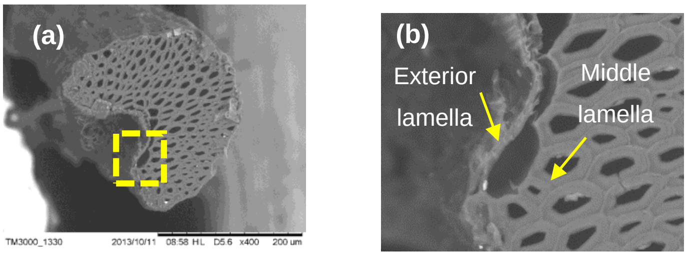

Figure 1 - Structure of sisal fibres: (a) fibre composed of hollow microfibres linked by the middle lamella; (b) detail of the middle lamella (composed of hemicellulose and lignin) and the exterior lamella

The surface treatment applied to the fibres aiming at their hornification consisted of 10 cycles of wetting and drying in a solution of calcium hydroxide (7.3 g of calcium hydroxide per litre of water). Hornification is the general result of these cycles, which increase the degree of crosslink within the fibre microstructure. The process used in the present work consisted of immersing the fibres in a solution of calcium hydroxide (T ~ 23°C) and its removal after 50 min for drying in a furnace at a temperature of 80 ºC for 16 hours with a heating rate of 1 ºC/min. After 16 hours of drying, the furnace was cooled down to the temperature of 22°C in order to avoid possible thermal shock to the fibres. During the procedure, the following variables were monitored after 1, 5 and 10 cycles: water absorption capacity and dimensional variation.

A special mold was developed to shape the pull-out specimens (Figure 2 a). After filling the mold with the matrix, the top cap was fixed and the fibre was stretched slightly for alignment. The mortar was placed in plastic bags before being placed in the mold as to facilitate the casting process (Figure 2 b). Embedment lengths of 25 mm were studied. After 24 hours, the specimens were demolded and placed in a fog room (HR% ≥ 95%) to cure in a moist environment for 7 days prior to the pull-out test (Figure 3).

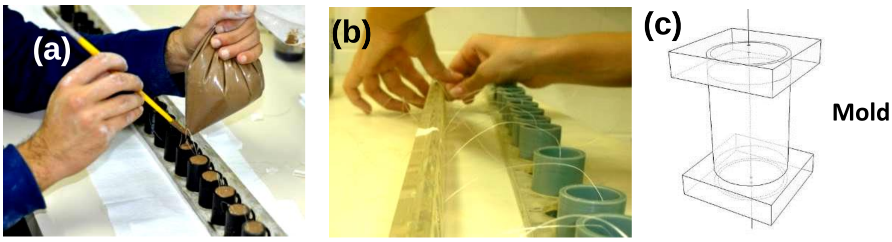

Figure 2 - Casting procedure of specimens for pull-out test: (a) filling the mold with the matrix and (b) positioning the fibre in the mold; (c) mold

Figure 3 - Pull-out test

The direct tensile tests on the fibres were performed in an electromechanical testing machine *Shimadzu AG-X* with a load cell of 1 kN. The fibres with a gauge length of 25 mm were glued to a paper template for better alignment in the machine and for a better grip with the upper and lower jaws in accordance with ASTM C1557 (Figure 4). To calculate the tensile strength of the fibres, their diameters were measured by image analysis from images obtained in a scanning electron microscope and with AutoCAD.

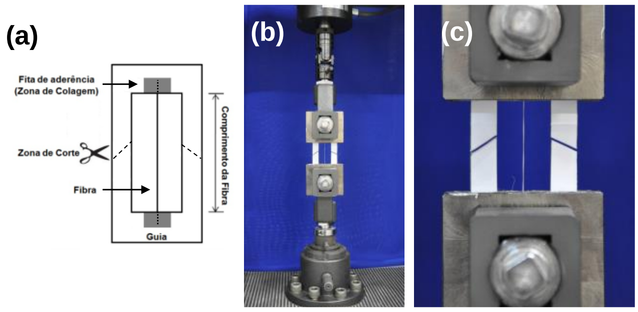

Figure 4 - (a) Paper template for direct tensile tests; (b) direct tensile test; (c) detail of the fibre subjected to direct tensile strength

In order to get the recycled sand required for the execution of this study, it was first necessary to carry out the demolition of a reinforced concrete beam of C30/37 class with a slump of approximately 50 mm. After the crushing and subsequent sieving (Nº 20 according to ABNT) with mesh opening of 0.84 mm the resulting material that should be used was obtained.

After the production of the composites, the mixtures were placed in aluminium molds with dimensions of 400 mm x 250 mm x 15 mm, with acrylic bottom to provide a better finish.

After demolding, the samples were placed in a humid chamber in order to guarantee curing in a controlled environment (T = 23 ºC e RH = 100%) until the day before the date of the mechanical tests, when the temperature was T = 23 ºC ± 1 ºC and RH = 43% ± 3%. For the bending tests, specimens were cut so as to have dimensions of 400 mm x 80 mm x 15 mm and for the tensile tests with dimensions of 400 mm x 40 mm x 15 mm.

The bending tests (Figure 5) were performed in an electromechanical testing machine *Shimadzu AG-X* with a load cell of 100 kN (0.3 mm/min), according to EN ISO 14125. The load and the deflection at mid-span were obtained by the system of acquisition of data *Trapézio* through the sensor of the testing machine and an LVDT.

The results were expressed in tensile bending stress (Equation 2.1) due to possible variations in the height of the test specimens.

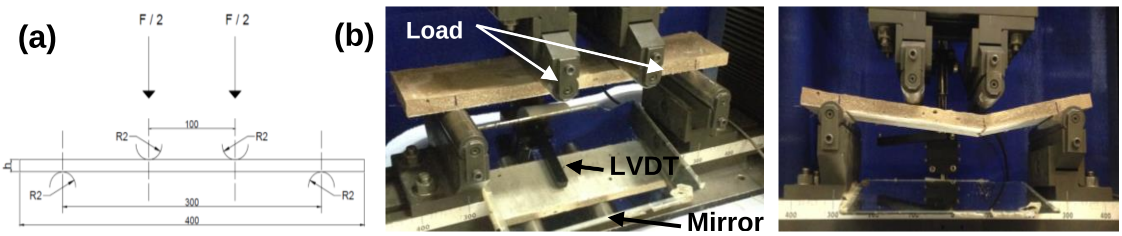

Figure 5 – (a) Sketch of test; (b) 4 point bending test

$$\sigma_{máx} = \frac{6M}{bh^2} \tag{2.1}$$

where "σ" is the tensile bending stress, "M" the bending moment "b" the width of the specimen and "h" the height thereof.

The index of tenacity was also calculated according to ASTM C1018 (1992), using equation 2.2 where the areas are shown in Figure 6, in which the letter “I” corresponds to 5.5 times the displacement of the first crack.

$$I_{10} = \frac{Area\ OACI}{Area\ OAG} \tag{2.2}$$

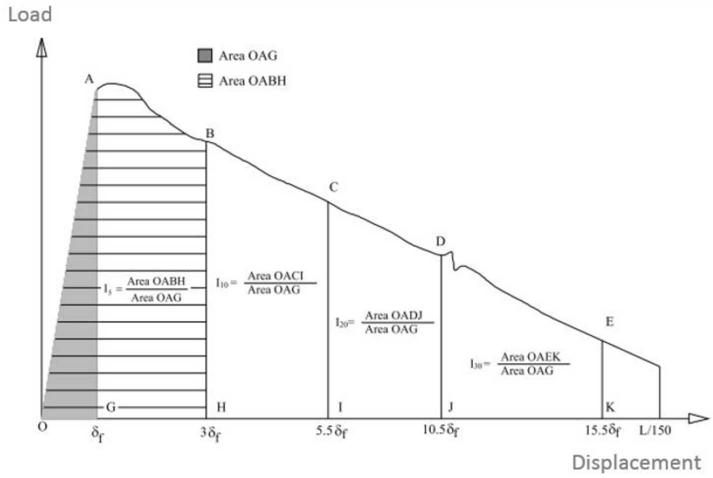

Figure 6 – Definition of points to calculate the index of tenacity according to ASTM C1018 (1992) (Lima, 2004)

The tensile tests (Figure 7) were conducted in the same machine at a cross-head speed of 0.1 mm/min. The axial displacements were obtained by the average readings of two LVDTs.

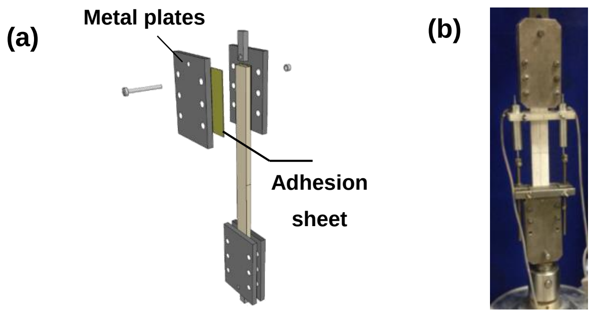

Figure 7 - (a) Configuration of the assembly of the tensile test specimens; (b) Direct tensile test

3. Results and discussion

The results of every experiment performed on all tested fibres and mortars are listed in Tables 4 to 10 with reference to each standard deviation and coefficient of variation. Due to the very high variability of most properties (characteristic of natural materials) identified, variations among compositions are not always statistically significant.

The surface treatment performed in sisal fibres proved to be effective as regards to the reduction of water absorption capacity (Table 4). Note that after 10 cycles the variation of the property in question is almost 80%. The same table shows that the treatment caused a reduction in the cross-sectional area of the fibres, although one expected such variation to be higher to ensure that all the voids had collapsed and that there would be no chance of the fibre to extend or retract in contact with water (dimensional stability is a very important factor for the fibre-matrix bond adhesion). The most adequate explanation for this phenomenon is the formation of irreversible hydrogen bridges between fibrils and micro fibrils, preventing water absorption (Figure 8) (Stone *et al.*, 1968).

Table 4 - Water absorption capacity and cross-sectional area of natural and hornified sisal fibres

Fibre	Absorption index (%)	Cross-sectional area (mm^2)
Natural fibre	-	0,030 ± 0,01
1 Cycle	240	-
5 Cycles	181	0,022 ± 0,01
10 Cycles	163	0,025 ± 0,01

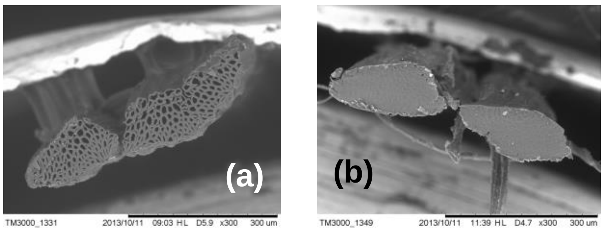

Figure 8 - Cross section of a (a) untreated fibre and (b) treated fibre

The fibre treatment did not decrease, as much as expected, the scatter of the test results of the direct tensile test (Table 5) of the fibres; however, a consistent increase of the average ultimate stress along the cycles occurred, reaching a maximum of 8% for fibres with 10 cycles of treatment. The deformability of the sisal fibres decreased almost 50%, however an increase of the stiffness of the fibres for 10 cycles of about 18% was observed.

As for the curves obtained (Figure 9), it is possible to identify a brittle behaviour at rupture, a greater linearity, an increased stiffness and a lower ultimate strain on the treated fibres in comparison to the natural fibres. For the reasons mentioned, the fibres with 10 superficial treatment cycles were used.

Table 5 - Direct tensile test of fibres - mechanical properties of natural fibres, with 5 and 10 cycles of treatment

Fibres	F_u (N)	σ_u (MPa)	ε_u	K (N/mm)
Natural	9,69 ± 3,7 (37,7)	416,17 ± 211,9 (50,9)	0,08 ± 0,04 (51,5)	10,67 ± 3,6 (33,8)
5 Cycles	9,07 ± 3,9 (43,6)	425,89 ± 106,2 (24,9)	0,04 ± 0,01 (26,3)	10,04 ± 4,5 (44,9)
10 Cycles	10,63 ± 3,8 (35,4)	448,69 ± 119,1 (26,5)	0,04 ± 0,01 (29,7)	12,54 ± 4,7 (37,1)

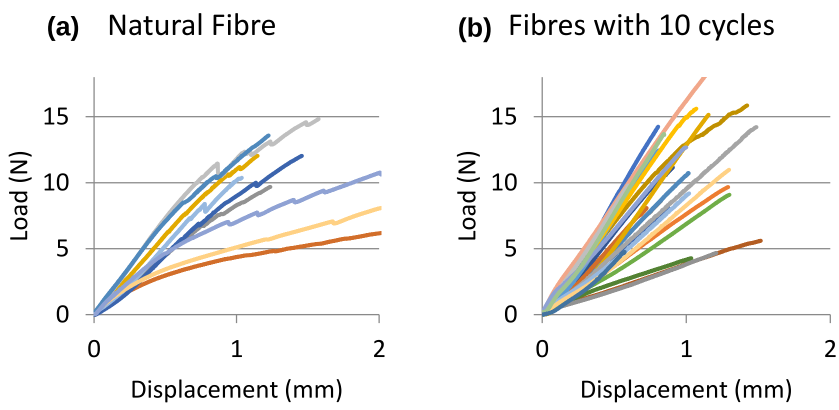

Figure 9 - Load - displacement curves for evaluating the effect of treatment: (a) natural fibres and (b) fibres of 10 treatment cycles

The adhesion of the fibres to the matrices was evaluated by pull-out tests, whose theoretical graphs are presented in Figure 10, in which two regions can be identified: a first one corresponding to the linear elastic range, in which the adhesion is idealized as being perfect, which occurs before the cracking of the matrix; and a second region, characterized by unstable crack propagation in the fibre-matrix interface represented by a slight decrease of the pull-out load. This second part culminates in an abrupt decrease of load, which symbolizes the complete breakage of the fibre-matrix bond, subsequently initiating the pull-out of the fibre, characterized by a frictional adhesion process, maintaining the load substantially constant.

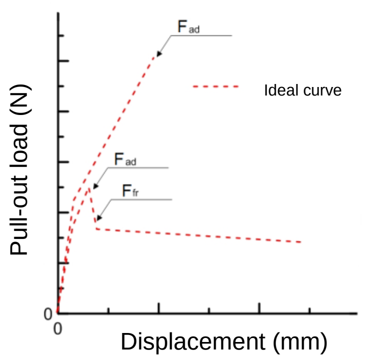

Figure 10 - Ideal load - displacement curve of a pull-out test where F_{ad} is the adhesional load and F_{fr} the frictional load

On average, the performance of AR2 with natural fibre was very similar to the same matrix with treated fibres; the same was also found for the AR1 matrix (Table 6, Table 7 and Figure 11). The results obtained for the natural matrix already denoted a higher difference between the uses of hornified or natural fibres, in particular for the maximum stress property.

Table 6 - Adhesional mechanical properties of the composites submitted to pull-out tests

Composite	K (N/mm)	F_{ad} (N)	σ_{ad} (MPa)	D_{ad} (mm)
1) N + Natural fibre	19,41 ± 9,75 (50,2)	4,70 ± 1,35 (28,7)	0,18 ± 0,04 (19,9)	0,53 ± 0,36 (68,8)
2) N + Treated fibre	17,68 ± 5,40 (30,5)	4,59 ± 1,38 (30,2)	0,15 ± 0,06 (39,2)	0,88 ± 0,67 (76,5)
3) AR1 (25%) + Natural fibre	17,28 ± 9,22 (53,3)	4,24 ± 2,78 (65,7)	0,14 ± 0,08 (55,0)	0,52 ± 0,25 (49,1)
4) AR1 (25%) + Treated fibre	10,90 ± 5,38 (49,4)	2,75 ± 1,15 (41,9)	0,11 ± 0,05 (48,7)	1,08 ± 0,44 (41,2)
5) AR2 (50%) + Natural fibre	9,93 ± 5,12 (51,6)	2,91 ± 0,85 (29,1)	0,11 ± 0,04 (32,5)	1,26 ± 0,84 (66,9)
6) AR2 (50%) + Treated fibre	11,44 ± 5,66 (49,5)	3,60 ± 2,68 (74,5)	0,11 ± 0,08 (67,0)	1,13 ± 0,82 (72,7)

Table 7 - Frictional mechanical properties of the composites submitted to pull-out tests

Composite	F_{fr} (N)	σ_{fr} (MPa)	D_{fr} (mm)
1) N + Natural fibre	3,21 ± 1,57 (49,0)	0,12 ± 0,04 (29,8)	1,21 ± 0,08 (6,5)
2) N + Treated fibre	2,75 ± 0,92 (33,3)	0,09 ± 0,04 (45,0)	1,45 ± 0,88 (60,6)
3) AR1 (25%) + Natural fibre	3,16 ± 2,20 (69,6)	0,10 ± 0,06 (56,0)	1,13 ± 0,06 (52,9)
4) AR1 (25%) + Treated fibre	1,61 ± 0,45 (28,1)	0,06 ± 0,02 (32,4)	1,59 ± 0,48 (30,5)
5) AR2 (50%) + Natural fibre	2,31 ± 0,60 (26,0)	0,09 ± 0,03 (37,2)	1,36 ± 0,63 (46,1)
6) AR2 (50%) + Treated fibre	2,90 ± 1,80 (61,9)	0,09 ± 0,05 (50,7)	1,44 ± 0,79 (54,8)

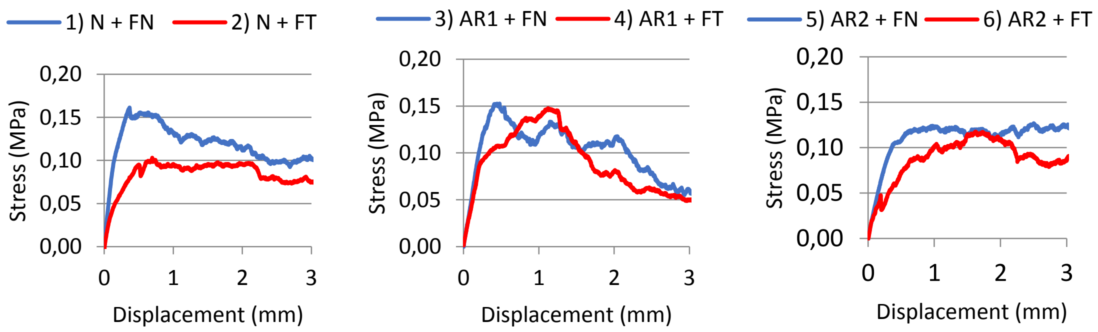

Figure 11 - Average response of the composites submitted to pull-out tests

For AR2 matrix mostly curves revealed an absence of a sudden load reduction as shown in the ideal curve above, which leads to the conclusion that there is less fibre-matrix bond adhesion in the presence of a higher percentage of recycled sand, leading the fibre quickly to the pull-out stage without taking advantage of the pull-out adhesional part (ideal fibre-matrix bond adhesion).

The results did not indicate a significant improvement in their ability to anchor the fibre to the matrix in presence of the treated fibres. In all cases examined, the average adhesional stress remained constant or decreased in comparison with the tests conducted with untreated fibres.

The results of this study showed that, for the embedment length of 25 mm, the rupture of the fibre for most of the specimen tested did not occur, so this length is not sufficient to fully mobilize the tensile strength of the fibre through the fibre-matrix bond adhesion, leading to its sliding within the matrix.

For the natural matrices and AR1, there was a decrease in the average value of the frictional and adhesional stress of approximately 20% with the replacement of fibres without treatment for hornified fibres. In the case of matrix AR2 (50%), this property remained constant during the analysis between treated and untreated fibres.

Comparing the different matrices with natural fibres, one identified a decrease in the average value of the adhesional stress of 24% and 38% between N and AR1 (25%) and between N and AR2 (50 %), respectively, and the difference between AR1 and AR2 was 18%. The matrix identified as having less adhesion to natural fibres was the matrix with 50% replacement of natural sand (AR2).

As regards to the comparison of hornified fibres with different matrices, with the presented results, it can be concluded that with natural matrix the average adhesional stress is 23% above the average results achieved for the remaining composites (Figure 12).

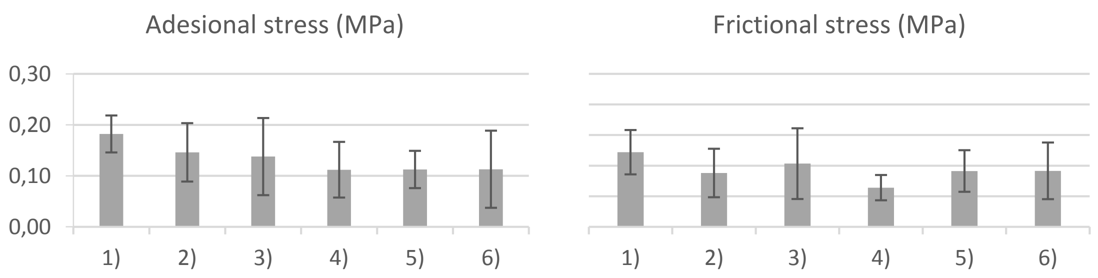

Figure 12 - Comparison of the average values of the adhesional (left) and frictional (right) stress of the matrices

The results of compression tests indicate an increasing trend of the maximum stress with the percentage replacement of natural sand for recycled sand, reaching a maximum of 32% (Table 8). This is most likely due to the fact that a constant water/cement ratio was used and to the aggregates containing waste pulp (these have a greater absorption), leading to a pulp with less free water, resulting, therefore, in a more compact and, consequently, higher mechanical strength.

Table 8 - Mechanical properties of matrices submitted to compression test

Composite	$\sigma_{máx}$ (MPa)	$\varepsilon_{máx}$ (‰)	E (GPa)	ITC (kJ/m^2)
Normal	33,56 ± 1,47 (4,39)	5,27 ± 0,07 (1,38)	13,27 ± 0,31 (2,34)	0,02 ± 0,00 (1,87)
AR1 (25%)	39,18*	0,22*	12,57*	0,04*
AR2 (50%)	44,25 ± 1,53 (3,45)	0,59 ± 0,03 (5,73)	12,32 ± 1,18 (9,59)	0,06 ± 0,01 (10,04)

* only one valid result

The rupture of all samples tested in direct tension test (Table 9) occurred in the jaws region, so the values obtained represent a lower bound of the actual capacity of the material.

The non-reinforced matrices had a brittle behaviour as opposed to the composites whose behaviour was ductile, absorbing energy beyond the 2 mm displacement. It may be noted that there is a tendency for an increase of the average maximum strength by almost the double when compared with the matrices of natural fibres and treated fibres.

Comparing the results in terms of natural fibres, there appears to be a better behaviour from the matrix AR2, a situation that is not observed in the case of the composites with the treated fibres, for which the resistance values have the same magnitude. Recycled matrix seems to have better adhesion to the fibres due to the roughness and irregularity of its particles, although the treated fibres in this test have led to a gain of resistance. This may be due to the fact that the larger area of contact of the fibre, caused by their hornification, has strengthened the fibre-matrix bond adhesion.

Table 9 - Mechanical properties of the matrices submitted to direct tensile tests

Composite		σ_{1f} (MPa)	ε_{1f}	E (GPa)
7)	**Normal Matrix**	1,69 *	0,26 *	11,59 *
8)	**Matrix AR1 (25%)**	1,45 ± 0,64 (44,1)	0,10 ± 0,09 (92,4)	13,62 ± 4,71 (34,6)
9)	**Matrix AR2 (50%)**	0,72 **	0,5 **	4,29 **
16)	**Matrix N + 4% FN**	0,70 ± 0,03 (4,9)	0,33 ± 0,14 (42,5)	4,09 ± 0,88 (21,5)
18)	**Matrix AR2 + 4% FN**	0,86 ± 0,32 (37,0)	0,17 ± 0,07 (42,9)	6,55 ± 1,15 (17,5)
19)	**Matrix N + 4% FT**	1,29 ± 0,33 (25,9)	0,15 ± 0,04 (24,4)	8,41 ± 0,56 (6,7)
21)	**Matrix AR2 + 4% FT**	1,34 ± 0,28 (21,2)	0,16 ± 0,03 (21,1)	9,22 ± 4,16 (45,1)

* Less than three valid results;
** Test didn't reach the rupture

Bending tests (Table 10) were performed up to a maximum displacement of 10 mm, however the specimens tested with the fibre reinforcement would be able to deform further, since a complete rupture of these specimens did not occur. It was found that the test specimens without addition of fibres had a linear elastic behaviour up to rupture, as a normal brittle material. As to reinforced matrices with 2% and 4% treated fibres, these fibres functioned after the appearance of the first crack, showing a more ductile behaviour.

It was observed that mortar with 4% of fibres has better performance compared to that with 2% of fibres, the former presenting an increase in the early strength after the appearance of the first crack, whereas in the latter that value remained almost constant (Figure 13).

Table 10 - Mechanical properties of composites submitted to bending tests

Composite		σ_{1f} (MPa)	D_{1f} (mm)	σ_u (MPa)	D_u (mm)	E (GPa)	ITC - I_{10}
7)	**Normal Matrix**	5,93 ± 0,72 (12,2)	0,57 ± 0,01 (1,3)	-	-	13,74 ± 2,21 (16,1)	0,00
8)	**Matrix AR1 (25%)**	3,90 ± 1,15 (29,5)	0,29 ± 0,07 (24,9)	-	-	11,72 ± 3,57 (30,5)	0,00
9)	**Matrix AR2 (50%)**	4,99 ± 1,76 (35,2)	0,39 ± 0,11 (27,2)	-	-	10,44 ± 4,13 (39,6)	0,00
10)	**Matrix N + 2% FN ***	-	-	-	-	-	-
11)	**Matrix AR1 + 2% FN**	3,28 ± 0,13 (4,0)	0,33 ± 0,01 (3,0)	1,91 ± 0,14 (7,3)	4,24 ± 1,16 (27,3)	7,60 ± 1,10 (14,4)	4,81 ± 0,51 (10,5)
12)	**Matrix AR2 + 2% FN**	4,29 ± 0,29 (6,8)	0,35 ± 0,01 (4,0)	1,97 ± 0,66 (33,5)	2,71 ± 0,83 (30,8)	8,57 ± 4,96 (57,9)	4,48 ± 0,38 (8,4)
13)	**Matrix N + 2% FT**	3,77 ± 0,75 (20,0)	0,32 ± 0,04 (11,7)	1,48 ± 0,66 (44,6)	4,66 ± 2,69 (57,7)	8,40 ± 1,88 (22,3)	4,32 ± 0,41 (9,5)
14)	**Matrix AR1 + 2% FT**	4,45 ± 0,83 (18,7)	0,39 ± 0,02 (5,5)	1,97 ± 0,04 (1,8)	2,65 ± 1,12 (42,5)	7,65 ± 0,49 (6,5)	4,01 ± 0,12 (3,0)
15)	**Matrix AR2 + 2% FT**	4,14 ± 0,68 (16,4)	0,46 ± 0,04 (7,8)	1,52 ± 0,14 (9,3)	2,10 ± 0,74 (35,4)	8,18 ± 2,09 (25,5)	4,05 ± 0,09 (2,2)
16)	**Matrix N + 4% FN ***	-	-	-	-	-	-
17)	**Matrix AR1 + 4% FN**	1,48 ± 0,26 (17,7)	0,34 ± 0,08 (24,3)	2,08 ± 0,39 (18,8)	6,73 ± 1,71 (25,3)	3,26 ± 0,03 (0,8)	9,15 ± 0,95 (10,3)
18)	**Matrix AR2 + 4% FN**	2,60 ± 0,37 (14,1)	0,32 ± 0,06 (17,0)	2,72 ± 0,25 (9,1)	1,94 ± 1,15 (59,1)	3,40 ± 1,57 (46,3)	7,61 ± 0,15 (2,0)
19)	**Matrix N + 4% FT**	3,13 ± 0,34 (11,0)	0,42 ± 0,07 (17,2)	2,15 ± 0,32 (14,9)	2,68 ± 0,93 (34,6)	4,79 ± 0,19 (4,0)	6,39 ± 1,02 (16,0)
20)	**Matrix AR1 + 4% FT**	3,70 ± 0,57 (15,5)	0,33 ± 0,05 (15,1)	2,92 ± 0,54 (18,6)	2,12 ± 0,38 (17,8)	7,00 ± 1,40 (20,0)	6,41 ± 1,10 (17,1)
21)	**Matrix AR2 + 4% FT**	3,08 ± 0,84 (27,3)	0,29 ± 0,07 (23,2)	2,49 ± 0,37 (14,9)	1,83 ± 0,52 (28,5)	5,75 ± 2,91 (50,6)	7,18 ± 0,83 (11,6)

* Composites tested by Ferreira (2012)

The maximum resistance decreased with the introduction of vegetable fibres in the matrix, which is not true for matrices incorporating recycled sand. This decrease is due to the fact that the recycled material incorporates adhered paste and that the quality is lower comparatively to natural sand. Regarding the reduction of the maximum strength because of the introduction of fibres, this may be due to the fact that the fibres volumetrically replace a percentage of the mortar constituents (binder, sand) that makes it less resistant but more ductile.

With natural fibres the stress for the first crack is greater when using the matrix AR2; with treated fibres the values remain uniform in the three matrices. The average values of the post-cracking maximum stress showed that the reinforcement of 4% is most favourable (between 1.5 MPa and 2.0 MPa) than the 2% (from 2.0 MPa to 3.0 MPa). In general, the difference between natural and non-treated fibres was not visible, however, for the matrix AR1 hornified reinforcement showed a better behaviour than for natural reinforcement, possibly due to the more angular and irregular recycled sand particles thereby improving the adhesion of the fibres to the recycled matrices (AR1 and AR2).

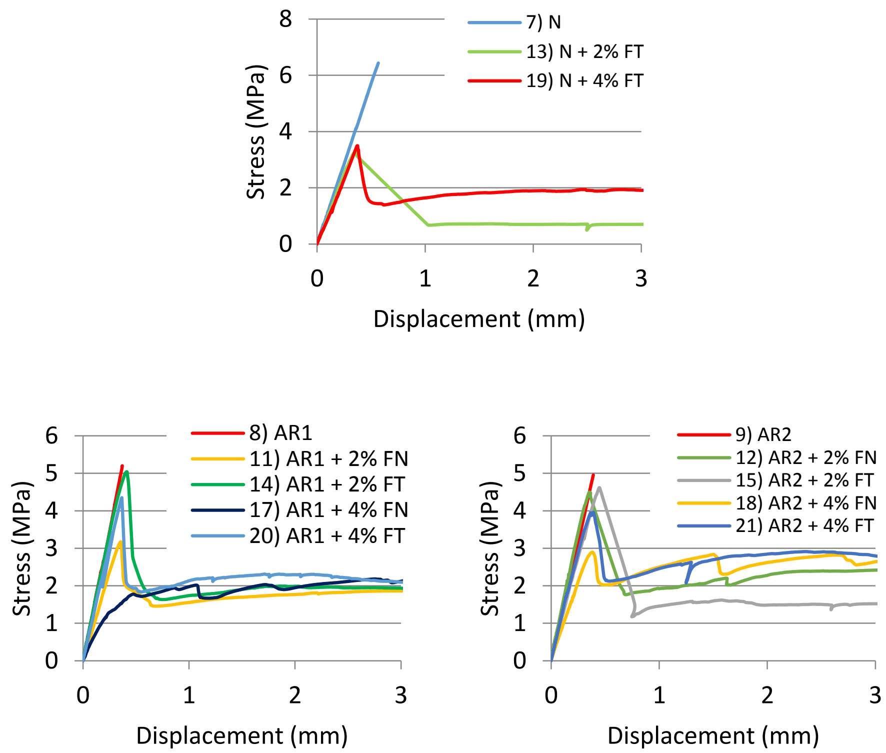

Figure 13 - Typical curves obtained from bending tests for natural matrices composites and matrices AR1 and AR2 with and without reinforcement

It is possible to verify (Figure 14) that the relationship between the stress for the first crack and the post-cracking maximum stress decreases considerably with increasing incorporation of hornified fibres of 2% to 4% (average decrease of 68%). This approach shows that the critical amount of reinforcement in bending is to be attained. The order of the average values of these stresses gets reversed with increasing reinforcement from 2% to 4% of natural fibres. This means that the post-cracking stress exceeds the first cracking stress, indicating that the critical volume of reinforcement has already been exceeded, both on the matrix AR1 and on the AR2. This result seems to show that there is no advantage in the treatment of the fibres when using recycled matrices, since with the hornification a higher percentage would be required to reach the critical value, definitely damaging the rheological behaviour of the composite.

The tenacity index (I_{10}) average values were 40% higher for the specimens reinforced with 4% of fibres compared with the ones with 2% reinforcement, once after the appearance of the first crack the number of fibres to endure the same amount of load is higher. For the same volume of reinforcement, this index was always lower for the treated fibres.

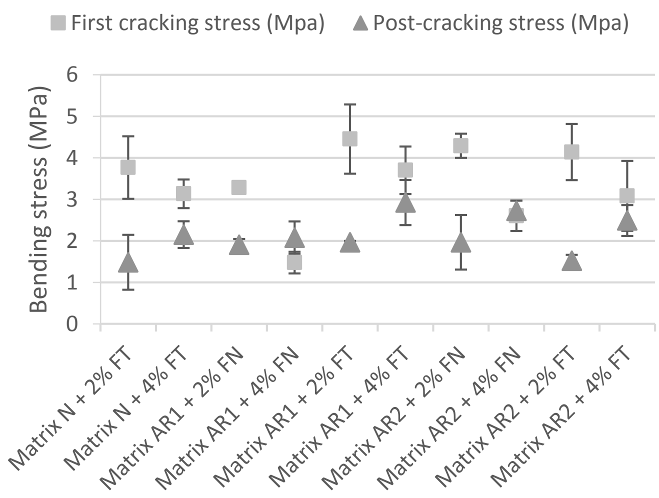

Figure 14 - Relationship between first crack stress and post-cracking maximum stress

As for the failure mode, for the composites without fibrous reinforcement and for those with 2% of vegetable fibres (treated or untreated) only one crack was observed, while for specimens with 4% of fibres more cracks were developed. This is similar to the effect of increasing steel reinforcement in concrete, *i.e.*, more cracks but smaller gaps (for the same load).

4. Conclusions

Based on the experimental study performed in this dissertation, where the efficiency of the hornification treatment on sisal fibres and the partial substitution of natural to recycled sand was evaluated in terms of adhesion of sisal fibres in cement mortars, globally, it was concluded that the superficial treatment used on fibres was not as effective as expected and that matrices with recycled sand present a better behaviour. Taking into account the results obtained, the following main conclusions can be drawn:

- 10 cycles of treatment produced more fragile fibres, with lower water absorption capacity and increased the direct tensile stress (8%) and the stiffness (18%).
- The fibre-matrix bond adhesion was not significantly improved with the surface treatment of the fibres, being the differentiating factor the recycled material characterized by more angular and irregular particles.
- In general, the use of recycled material favoured the adherence to natural fibrous reinforcement in the bending tests, a fact that was not observed for hornified fibres.
- As expected, the behaviour of the non-reinforced composites was brittle and the composites with introduction of fibres had a ductile behaviour.
- Composites with 4% of vegetable fibres presented a multiple cracking behaviour, in which more cracks appeared in the natural fibres than in the treated ones (for the same load).

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