USE OF TEXTILE FIBRES IN THE REINFORCEMENT OF A GYPSUM-CORK BASED COMPOSITE MATERIAL

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ABSTRACT

The study presented herein focus on the analysis of a series of experimental tests aiming at characterizing the performance of distinct textile fibers acting as a reinforcement of a gypsum-cork composite material. Two groups of textile fibers were selected, namely synthetic fibers (glass and basalt) and natural fibers (banana and sisal). The reinforced composite material was submitted to distinct types of loading, namely compression tests, which it was possible to obtain the compressive strength and to calculate the elastic modulus, and flexural loading. Additionally, aiming at assessing the mode I fracture energy, indirect tests on notched beams were carried out.

INTRODUCTION

The shortage of environmental, economical and even social resources demands the increase on research of new alternatives in the civil construction relating to new materials and processes. On this basis, the building industry has been developing new construction processes, as well as the study and application of new materials. The building industry has been playing an important role on the reuse of by-products from other industries. The results obtained in a recent study pointed out that by Vasconcelos et al. (2013) show that it is possible to obtain a composite material resulting from the combination of FGD gypsum, regranulated cork and textile fibers resulting from recycling process of tyres that can be applied in blocks for partition walls. All these materials can be considered as by-products coming from distinct industries. It was seen that the textile fibers, composed mainly by polyamide, exhibit a great variation on the length and diameter. This dimension scattering possibly can prevent a better performance of the composite material particularly to flexural and tensile loads. Based on this, it was decided to reinforce the gypsum-cork composite material with textile fibers with a known diameter and length, being selected two synthetic fibers (glass and basalt) and two natural fibers (sisal and banana) with the same length. The natural fibers of sisal and banana have been used in distinct studies in order to evaluate its performance to work as a reinforcing material. Different matrixes have been used to apply natural fibers, namely cement matrix (Andrade Silva et al., 2009; Toledo Filho et al., 2010; Andrade Silva et al., 2010) and glue matrix (Show et al., 2007; Mohan Rao et al., 2010; Jun Tae and Netravali, 2010; Prasad and Rao, 2011). Glass fibers have been also used in the reinforcing of gypsum based composite materials (Hernandez Olivares, 1999).

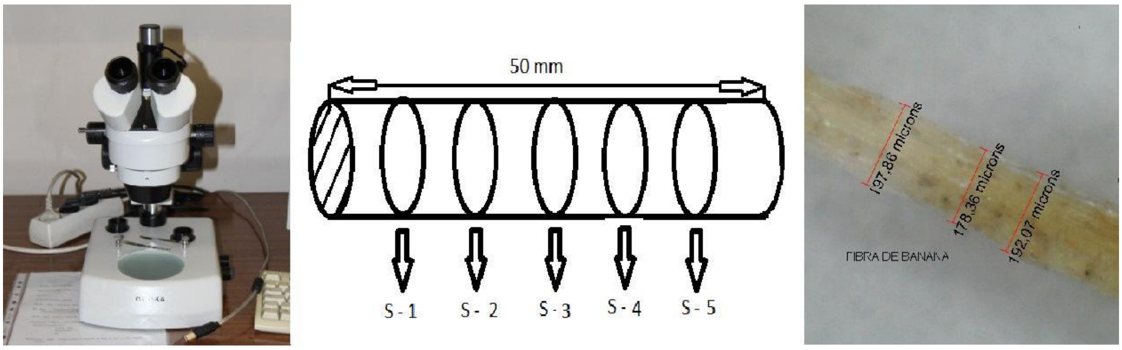
Thus, the major objective of this work is the assessment of the role of textile fibers in the mechanical performance of the gypsum-cork composite material. Different percentages of these textile fibers were considered being possible to evaluate the possibility of improvements in the compressive strength and especially in the tensile fracture energy. For this the reinforced composite material was submitted to distinct types of loading, namely compression tests, from which it was possible to obtain the compressive strength and to calculate the elastic modulus, flexural loading. Additionally, aiming at assessing the mode I fracture energy, indirect tests on notched beams were carried out. Besides the presentation of procedures and results an analysis and discussion on the results is provided.

CHARACTERIZATION OF THE NATURAL FIBERS

The fibers used for the reinforcement of the gypsum-cork composite material are natural fibers from sisal and banana and synthetic fibers such basalt and glass. As can be seen from Fig. 1, the synthetic fibers are delivered in a spool, whereas the natural fibers are delivered in an hand-roll. The synthetic fibers are much continuous and the natural fibers are more discrete.

Fig 1. Example of fibers used in teh study: (a) basalt; (b) glass; (c) sisal; (d) banana

The physical characterization of the natural fibers was made through the use of an optical microscope (Fig.2a) in the textile department of University of Minho. 2c. For the characterization 20 specimens of each natural fiber were considered, being each specimen composed of only one filament. The measurement of the diameter was made by considering 5 cross sections used then to calculate the average diameter (Fig. 2b). With optical microscope it was possible to obtain amplified images of the filament with the corresponding measurements of the diameter, as shown in Fig. 2c, where the filament of banana fibers can be seen. The average values of the diameter of the natural fibers, sisal and banana is presented in Table 1. In the same table the average values of the synthetic fibers is also presented according to the information given in the deliver catalogues, as it was not possible to characterize in details the diameter of these fibers. The values of the coefficient of variation (C.O.V in %) obtained for It is seen that the diameter of the natural fibers is considerably higher than diameters of the synthetics fiber. This characteristic and the surface type of the fibers should have a central role influence of the gypsum-cork composite mortars.



(a) (b) (c)

Fig.1 Physical characterization of the natural fibers; (a) optical microscope; (b) scheme of the cross section considered to the measurement of the diameter; (c) view of the measurement of the diameter in case of banana natural fiber

Table 1 Average diameter of the textile fibers

Fiber	Average diameter (microns)	C.O.V(%)
Sisal	168.76	19.48
Banana	204.64	15.75
Glass	13	-
Basalt	10	-

The mechanical characterization of the natural fibers was made based on direct tensile tests carried out at the Department of Textile Engineering of University of Minho. For the this characterization, 20 specimens with only one filament were prepared for each natural fiber sisal and banana in order to have reasonable representativeness. The direct tensile tests were carried out by using a machine Hounsfield H100KS, with a load cell of 5kN. The tests were carried out at a displacement rate of 25mm/min. In this characterization, the length and the weight of the fibers was carried out. From this data it was possible to calculate the SI unity that characterizes physically density of the textile fibers, through the eq. 1:

$$Tex = \frac{m}{l} \times 1000 \qquad (1)$$

where *Tex* is the unit of measure for the linear mass density of fibers, *m* is the mass of the filament (g) and *l* the length of the fibers (m).

From the knowledge of the linear mass density and the maximum tensile load obtained in the direct tensile tests it is possible to calculate the tenacity, which is a measure of the strength of a fiber or yarn. It is defined usually as the ultimate tensile breaking force of the fiber/yarns (in gram-force units) divided the linear mass density, through eq. 2:

$$Tenacidade = \frac{f_{max}}{Tex} = N/Tex \qquad (2)$$

In Table 2, the average vales of the linear mass density (tex) and the tenacity for the distinct types of fibers are shown. The values of the natural fibers were calculated according to the procedure defined previously. The tenacity of the synthetic fibers was taken from the deliver catalogues. The comparison of the tenacity among the fibers allow to conclude that the tenacity banana is approximately the double of the sisal but they are considerably lower than the tenacity corresponding to synthetic fibers.

Table 2 Physical properties of textile fibers

Fiber	Length (cm)	Mass (g)	Elongation (%)	Tex (g/m)	Tenacity (N/Tex)
Sisal	38.68 (25.84)	0.0104 (33.68)	2.67 (41.10)	33.28 (31.40)	0.17 (28.94)
Banana	62.82 (12.6)	0.0091 (42.11)	1.99 (36.08)	27.25 (27.34)	0.31 (30.26)
Glass	-	-	-	600	0.61
Basalt	-	-	-	600	0.66

EXPERIMENTAL CAMPAIGN

Composite material design

The raw materials used to produce the composite material are the FGD gypsum, working as the binder and the regranulated cork as the aggregate fixed in 5% of the gypsum mass. Additionally, due the properties of the FGD gypsum, it was needed to use a setting time material in order to obtain a workable material to be molded in a mold to produce blocks for partition walls (Vasconcelos et al., 2012). Based on previous work (Vasconcelos et al., 2013) it was decided to use 0.1% of the gypsum mass of citric acid and 80% of the gypsum mass of water to have a workable material corresponding to a flow table, obtained according to European standard EN 13279-2 (2004), of approximately 150 mmm. Therefore, the percentage of the different fibers was defined so that the flow table value was close to 150 mm taking into account the fixed percentage of water. This means that for all the mixtures the water/binder ratio (w/b) was kept constant. Notice that according to several authors, the w/b ratio takes a major role on the mechanical properties of cement based mortars (Haach et al. 2011). After preliminary tests, it was decided to consider for all the textile fibers a length of 10mm, as for higher values of the length the mixture was difficult and the workability was very poor. Notice that a great advantage of using the textile fibers over the recycled textile fibers is the possibility of controlling the variation of the length and diameter of the fibers. In fact, according to Aires et al. (2010), it was seen that the length and diameter of the recycled textile fibers was extremely variable, which can rule its performance as a reinforcing material of the composite gypsum based mortar. Difficulties in obtaining a workable material were observed when higher lengths of the textile fibers were used, see Fig. 2a. The aspect of the flow table test obtained for the composite material that complies with the requirements of having a workable and plastic material to be molded into a mold to produce the partition walls blocks is shown in Fig. 2b. Notice that it was intended to use also discrete carbon fibers but is was not possible to obtain a workable mortar mix.

In Table 3, a summary of the composite mortar mixes is made with the indication of the percentage of each type of fiber considered taking into account the constant values of regranulated cork (5% of the gypsum mass), w/b ratio (80% of the gypsum mass) and the same percentage of citric acid (0.1% of the gypsum mass). Notice that the percentage of textile fibers is different as the parameters that were kept constant was the raw materials, including the citric acid and the w/b ratio. As the fibers are very different, mainly the synthetic and the natural fibers, it was not possible to achieve similar workable properties for the same w/b ratio, being necessary to vary the percentage of fibers. Other approach would be variation of the w/b ratios and the maintenance of the percentage of fibers.

(a) (b)

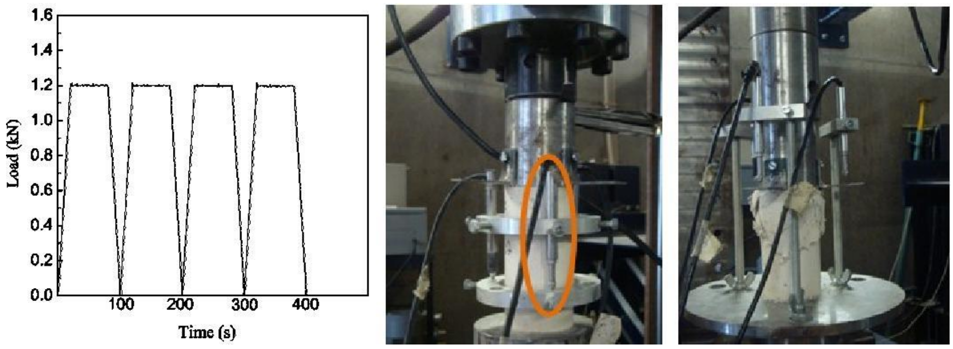
Fig.2 Results of the flow table tests to characterize the workability of the composite materials; (a) inadequate flow table tests; (b) adequate floe table test for textile fibers with 10mm length

Table 3 Design of mortars mixes (values in percentage of the gypsum mass)

Mortar mix	Fibers	Regranulated cork	water	Citric acid	Fibers (5)
CMS	Sisal	5%	80%	0.1%	1.25%
CMB	Banana	5%	80%	0.1%	0.75%
CMG	Glass	5%	80%	0.1%	0.25%
CMBa	Basalt	5%	80%	0.1%	0.25%

Experimental procedures

The experimental program was composed of uniaxial compressive and bending tests, from which mechanical properties such us compressive strength, f_c, elastic modulus, E, and mode I fracture energy, G_f, were obtained. The uniaxial compressive tests were carried out on cylindrical specimens with 50mm diameter and 100mm height, leading to a height to diameter ratio of 2.0, considering a total of 5 specimens for each mixture. The specimens were kept in a oven at 40ºC during seven days, following the recommendations of EN 13279-2 (2004). The elastic modulus was obtained after two uniaxial compressive tests were carried out to estimate the compressive strength, based on the cyclic load procedure indicated in Fig. 1a, carried out in force control at 0.06kN/s EN 393 (1993). The steady load is estimated to be 30% of the average compressive strength obtained in the two previous uniaxial compressive tests. The mean displacement, from which the strain was calculated, was obtained by averaging the uniaxial displacement recorded by three LVDTs (linear field of ±2.5mm and a precision of 0.01%) placed in two steel rings distanced of 50mm and placed 120º apart around the specimen, see Fig. 3b. After the determination of the elastic modulus, the uniaxial compressive tests were carried out under displacement control at a rate of 0.005mm/s ensuring that the maximum load is attained in the range between 2 and 15mm after the onset of the test EN 13279-2 (2004) and the record of post-peak behavior was possible. The deformation was obtained by averaging the displacements recorded by three LVDTs placed 120º apart between the top and the base of the specimens, see Fig 3b. The mode I fracture energy of the distinct composite material mixtures was obtained based on bending tests adopting the three point load configuration, following the testing procedure provided in standard FMC1 (1993) for the obtainment of the mode I fracture energy of concrete and mortar, see Fig. 4. The dimensions of specimens (84mm length, 100mm depth and 100mm width, and effective span of 80mm) were defined according to the maximum dimension of the granulated cork, which was approximately 4.0mm. In total six specimens of each mixture were tested to obtain fracture energy.



(a) (b) (c)

Fig. 3 Details of mechanical characterization under compression; (a) test procedure for obtaining modulus of elasticity; (b) instrumentation for modulus of elasticity; (c) instrumentation

The fracture energy tests were carried out in a stiff steel frame equipped with a closed-loop servo control enabling to carry out stable tests. The fracture tests were carried out under displacement control at a rate of 0.002mm/s. The load was applied by means of an actuator of capacity of 25kN by using a steel roller, see Fig. 4. The deformation of the beam was measured through an LVDT aligned with the applied load. The calculation of the fracture energy was made based on the expression proposed by standard FMC1 (1993), see eq. 3:

$$G_f = \frac{(W_0 + mg\delta_0)}{A_{lig}} \quad (3)$$

where W_0 is the area under the force-displacement diagram, m is the weight of the specimen and of the load devices, δ_0 is the deformation of the beam at final failure and A_{lig} is the projection of the fracture zone on a plane perpendicular to the beam axis.

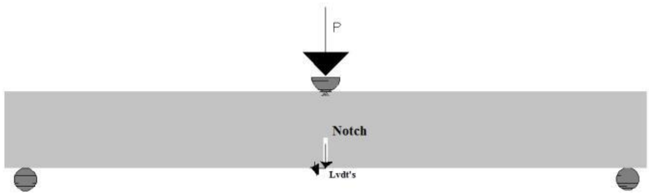


Fig. 4 Notched beam for bending tests to obtain mode I fracture energy

ANALYSES AND DISCUSSION OF RESULTS

Compressive behavior – global behavior and mechanical properties

The typical mechanical behavior of the composite material under uniaxial compression reinforced with the distinct textile fibers can be observed through stress-strain diagrams displayed in Fig. 5. For all composite mixtures, the pre-peak regime is characterized by two phases, namely an initial linear branch and a nonlinear branch with variable extension, which seems to depend on the ductility exhibited by the specimen. Indeed, the more ductile specimens (smoother post-peak regime) present a more remarkable pre-peak nonlinear range. Low to medium scatter characterizes the linear regime of the composite material. The post-peak behavior is characterized by a very smooth descending branch, whose smoothness is also variable, resulting in a higher scatter. For all mortar mixes it is seen that low degradation of strength was observed, even if the low strength degradation is accompanied by larger vertical displacements. This is the result of the higher ductility of this gypsum-cork composite material in compression, which appears to be improved by the addition of the synthetic and natural textile fibers.

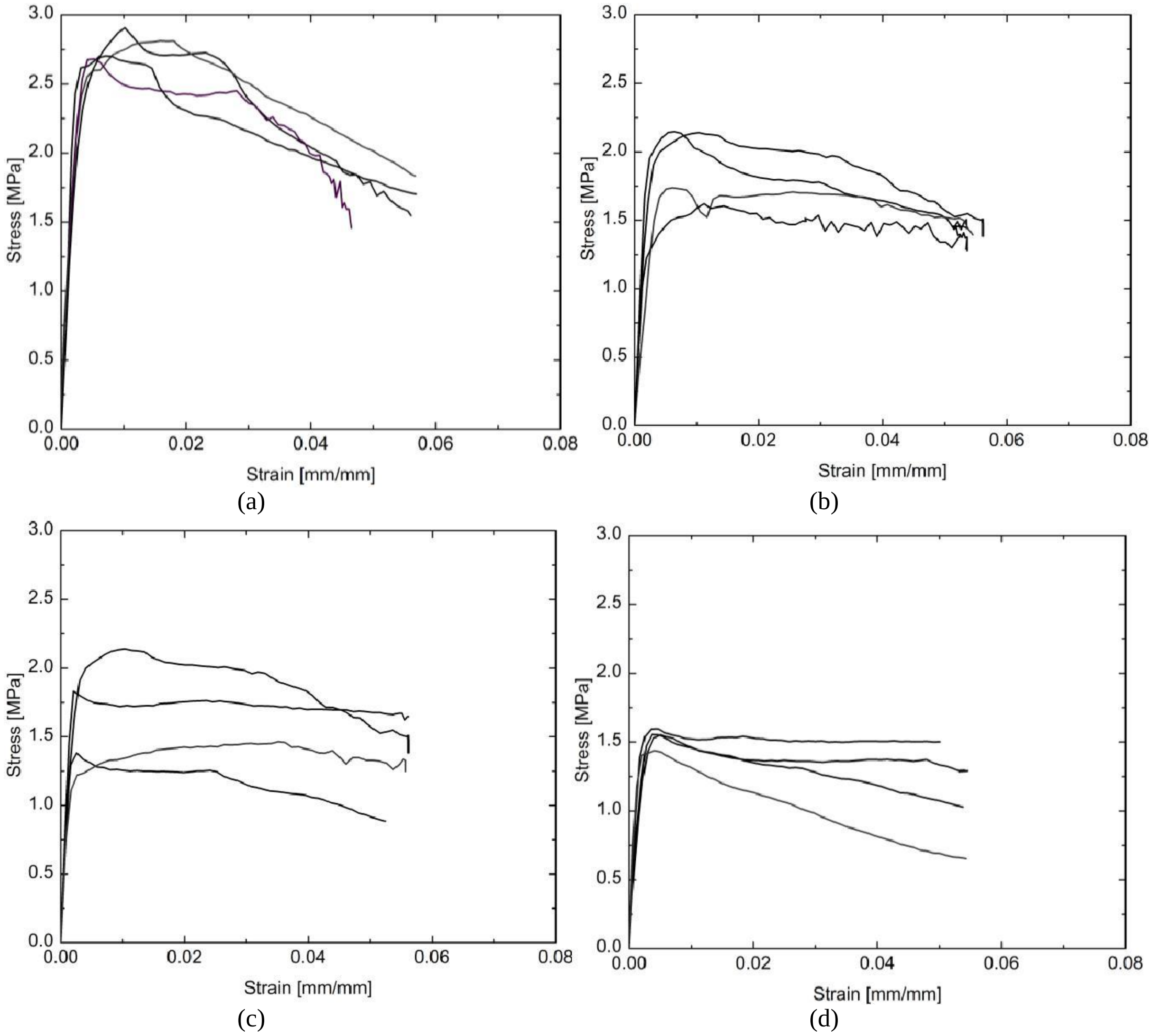


Fig. 5 Stress-strain diagrams obtained in compression: (a) mortar with glass fibers; (b) mortar with basalt fibers; (c) mortar with banana fibers; (d) mortar with sisal fibers

The high ductility of the gypsum-cork composite material in compression is associated to the nature of the aggregate (regranulated cork), which enables that higher deformations develop without collapse, see Fig. 6, where the crack patterns of some specimens are presented. It is seen that there is a trend for high lateral deformation are associated to the crushing of material, which corresponds essentially to the collapse of the resisting structure of the composite material attributed to the gypsum. The opening of thick cracks, inclined or sub vertical can be associated also to the relative sliding between both lips of the crack. The mechanical properties obtained in the compressive tests in cylinders and specimens obtained according to EN 1052-1 (1999), are summarized in Table 4. Besides the elastic modulus, *E*, obtained in the compressive tests carried out in cylinders, the average values of the compressive strength obtained in cylinder, $f_{c,c}$, and according to EN 1052-1 (1999), $f_{c.p}$, are also given. It is seen that there a considerable difference between the average values of the compressive strength obtained in cylinders and the one obtained according to the procedure indicated in EN 1052-1 (1999), being the latter reasonably higher. These results should be expected as in the case of cylinders the restriction effect of the boundaries is minimized, leading to lower values.

Fig. 6 Crack patterns under compression

The compressive strength is clearly higher in case of the composite material is reinforced with glass fibers. The reinforcement with basalt fibers leads to a compressive strength 12.5% lower. The reinforcement with natural fibers, namely with banana and sisal fibers results in a lowering of the compressive strength in relation to the composite material reinforced with glass fibers of about 21.5% and 30% respectively. Besides, it should be noticed that the percentage of banana and sisal fibers is of 3 and 5 times higher than in case of glass and basalt fibers respectively. This means than the synthetic fibers exhibit a better performance than the natural fibers. In spite of the percentage of the sisal fibers is higher than the banana fibers, it is seen that the compressive strength is higher in the mortar reinforced with banana fibers. Similar behavior is also observed in case of the elastic modulus and also in case of the flexural strength. Based on the results obtained, it is observed that the flexural strength is considerably higher than the values found in Aires et al. (2010) for the same mortar reinforced with recycled textile fibers.

Table 4 Mechanical properties of the reinforced composite material

Mix	E(MPa)	$f_{c,p}$ (MPa)	$f_{c,c}$ (MPa)	f_f (MPa)	G_f (N/m)
Vidro	2478.7 (4.7)	4.53 (13.7)	2.82 (3.2)	2.33 (10.7)	255.94 (11.8)
Basalto	2279.2 (9.7)	4.3 (8.9)	1.79 (7.1)	2.04 (13.6)	190.73 (12.5)
Banana	1975.6 (10.2)	3.31 (10.7)	1.58 (13.6)	1.83 (7.3)	120.09 (10.0)
Sisal	1816.4 (12.1)	2.72 (14.1)	1.56 (4.3)	1.63 (1.6)	125.88 (9.9)

Fracture behavior under tension

The typical force-displacement diagrams found in the fracture energy tests are presented in Fig. 7. The analysis of the diagrams allows to see that there are considerable differences in terms of post-peak behavior. The post-peak behavior of the mortar reinforced with basalt and glass fibers is remarkable smoother with mush higher ultimate displacements, which should lead to higher values of the fracture energy. Particularly in case of mortar with sisal fibers, there is a steep decrease on the load after the peak, which should be associated to a more difficulty load redistribution of the bearing forces from the mortars to the fibers. The same behavior was found in some specimens of mortar with banana fibers but this is not systematic.

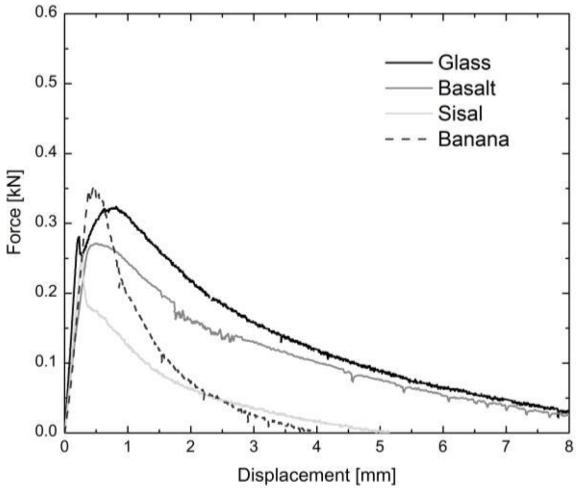


Fig 7 Representative force-displacement diagrams obtained for the composite material reinforced with the distinct types of textile fibers

The average values of the fracture energy calculated according to eq. 3, are given in Table 4. As expected from the force-displacement diagrams, it is observed that the fracture energy (G_f) of the material reinforced with glass fibers is considerably higher than the fracture energy of the mortars reinforced with basalt, being the reduction of 25%. However, the differences are much more significant when the values of the fracture energy found in the specimens with mortars reinforced with natural fibers. In fact, the fracture energy of the specimens with the glass fibers is practically the double of the fracture energy obtained in the specimens with mortars reinforced with banana and sisal fibers. In spite of the percentage of the sisal fibers added to the mortar was 66.7% higher than the percentage of banana fibers, the fracture energy is practically the same, which appears to confirm again the better performance of the mortar reinforced with banana fibers in relation to the sisal fibers. The differences found in the behavior of the synthetic and natural fibers should be associated to the nature of the fibers. The synthetic fibers exhibit a considerable higher tenacity than the natural fibers, which justify the better mechanical performance when added in the mortar mix. It should be mentioned that the lower tenacity of the sisal fibers also justify its worse performance. It should be also mentioned that in terms of fracture energy, the performance of natural fibers is a little bit better than the mortar mix reinforced with 1% of recycled textile fibers.

CONCLUSIONS

In this work a gypsum-cork composite material reinforced with distinct types of textile fibers was studied under uniaxial compressive and three point bending load tests, from which fracture energy was derived. Synthetic (glass and basalt) and natural (sisal and banana) textile fibers were selected in order to evaluate and compare its effectiveness in the mechanical behavior of the gypsum-cork composite material. From the experimental results it was possible to see that: (1) the compressive behavior of the gypsum-cork composite materials is similar in terms of the general configuration of the force-displacement diagrams; (2) the synthetic fibers result in better mechanical properties, namely, compressive strength and elastic modulus, even if much lower percentage was used when compared to natural fibers;

(3) the natural banana fibers performed better in terms of compressive and flexural mechanical properties; (4) the synthetic glass and basalt fibers lead to a more ductile behavior when compared to natural fibers, which is confirmed by the considerable higher values of the Mode I fracture energy; (5) the differences in the mechanical performance of the distinct

fibers should be associated to the distinct nature and mechanical properties as the synthetic fibers have much higher tenacity.

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