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FGD Gypsum Based Composite for Non-Structural Applications in Construction

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ABSTRACT: There are many by-products created in industry that can be recovered or valued for the creation of new products allowing, in this way, the decrease of environmental damages caused by its disposal in landfills. This research work aims at the valuing of several industrial by-products, such as: flue gas desulfurization (FGD) gypsum from exhaust gases of thermoelectric power plants; granulate cork from insulation black cork boards; and textile fibres from the recycling of used tyres.

The composite materials that come from the mixture of these products may be produced according to two different procedures, moulding or pressing, and the result will be products with different features. Through moulding one gets a lighter composite and through pressing one gets a thicker composite with higher mechanical strengths and better surface's finishing. These composites may be used to fabricate masonry blocks for non-structural inner walls of buildings. Therefore, one has done several lab tests in order to obtain the mechanical behaviour of the referred composites so as to confirm the possibility of using it in construction.

1 INTRODUCTION

Knowing that, nowadays, just about 10 % (in weight) of everything what is extracted from the planet by industry will be transformed in an useful product and the remaining can be considered a residue, a sustainable management of the existent natural resources that take us to a sustainable consume too appears to be urgent.

So, the need of a sustainable world demands that more and more alternative products should be used in construction, such as materials that include in their composition industrial wastes. These materials conventionally have been referred to as "green materials".

Several are the by-products generated by the industry that can be recovered or improved to a new product generation, that this way, can minimize the environmental damage resulting from the laying on landfill.

The gypsum is a material largely used in building construction due to its diverse applications. The building sector consumes about 95% of the total gypsum produced. It is calculated that about 80 to 90% of finishing interior work and partition walls in buildings are made of gypsum products, such as plaster and card gypsum (wastebook, 2007).

According to those thermal and acoustical properties, these products contribute significantly to the comfort of millions of persons. Having an extraordinary resistance to fire, the gypsum products contribute to the buildings' security, particularly in the public ones.

FGD Gypsum is a synthetic product derived from flue gas desulfurization (FGD) systems at electric power plants. It is chemically identical to mined natural gypsum and provides more environmentally friendly applications. There are many uses for FGD gypsum, including gypsum panel products, highway construction, agriculture, mining applications, cement production, water treatment and glass making (fgdproducts 2009).

The world availability of FGD gypsum is considerable. Approximately 18 millions of FGD gypsum tons were produced in 2008 in the USA, 60 % of which were reused (acaa-usa 2009). In the European Union, according to 2007 data referring to the 15 European countries (ecoba 2009) 11 millions FGD gypsum tons were produced about, 89 % of which were reused.

Some surveys show that the actual annual world production of FGD gypsum reaches values near the 225 millions of tons and in 2020 will be around 500 millions of tons per year (Malhotra, 2008). The developing countries, namely China (the biggest world producer of FGD gypsum, exceeding the 100 millions of tons in 2004 and India (about 20 millions of tons per year), will decisively contribute to this increase. It is expected that in India the productive capacity of electrical energy coming from electric power plants will double until 2010, what will result in an increase of FGD gypsum production that will reach the 40 millions of tons by then.

The FGD gypsum is also very cheap and rather affordable material, turning it especially attractive in economic terms.

Cork (bark of the plant Quercus Suber L), a substance largely produced in Portugal, is a material whose characteristics are of considerable interest for the construction industry. It is regarded as a strategic material with enormous potential due to its reduced density, elasticity, compressibility, waterproofing, vibration absorption, thermal and acoustic insulation efficiency (Gil 2005 & Hernández-Olivares, 1999).

The cork is a natural and ecological product, odourless and it is considered imputrescible and unalterable, maintaining its efficiency for quite a long time.

The cork industry consumes worldwide about 280 000 tons of cork per year. However, about 20% to 30% of the raw cork used at the processing unit is discarded, mainly cork dust and granules which have low granulometry with no industrial interest (Carvalho 1996).

Thus, it has economical and environmental interest to find alternative uses for this industrial by-product from cork transformation, mainly in Portugal, since it is the world's leader producer.

In this research work it was used granulated cork with the aim of lightening the mass of gypsum based composite and, at the same time, providing an improvement of the thermal and acoustic efficiency.

In Europe tyres are produced at a rate of 250 million units per year (www.specialchem4polymers.com, 2004) and nowadays, there are recycling companies that proceed to shredding of used tyres, obtaining separated materials such as crumbed rubber particles, steel fibres and textile fibres from the tyre beads and reinforcement. The textile fibres can be reused, such as in insulation materials or as fibre reinforcing in concrete products (www.wastebook.org, 2007). In this research work the recycled used tyres textile fibres were used with the purpose of providing reinforcement for gypsum composites.

The main purpose of this research work was to develop new mixtures of FGD gypsum incorporating these by-products to value them and to turn the gypsum products more lightweight and sustainable, giving continuity to others studies that aimed at the development of eco-efficient products based on gypsum for construction applications (Eires et al. 2008, Eires et al. 2007a, Eires et al. 2007b, Eires et al. 2006).

Therefore, the characterization and improvement of the compositions was carried out. So, one has done several lab tests in order to obtain the mechanical behaviour of the referred composites so as to confirm the possibility of using them in construction.

2 MATERIALS, COMPOSITIONS, MANUFACTURE AND CONSERVATION

2.1 *Materials*

The FGD gypsum formed in the system of treatment gaseous effluents of a Portuguese electric power plant, is presented under the shape of calcium sulphate bi hydrated ($CaSO_4.2H_2O$) with 7% of humidity. In order to be reactive with water it should be changed to calcium sulphate hemi hydrated ($CaSO_4.0.5H_2O$). Based on the test of differential scanning calorimetry and thermo-gravimetrical analyses (DSC-TGA), it was selected the temperature of 105 ºC to the dehydration, changing the material as the equation 1:

$$CaSO_4.2H_2O \rightarrow CaSO_4.0.5H_2O + 1.5H_2O \tag{1}$$

In table 1 it can be seen the chemical similarity of FGD Gypsum with the conventional gypsum, available at the market and usually known as plaster gypsum.

Table 1 – Chemical composition of FGD and conventional gypsum

Gypsum	CaO	SO_3	F	Fe_2O_3	SiO_2	Al_2O_3	MgO	Na_2O	K_2O	TiO_2	P_2O_5	SrO	ZrO_2
FGD	40.1	54.4	1.61	0.28	1.58	1.11	0.418	0.261	x	0.0134	0.106	0.001	0.001
Conventional	41.3	56.0	x	0.22	1.11	0.395	0.696	x	0.0567	x	x	0.183	0.024

It was achieved the granulometric distribution of the FGD gypsum and a conventional gypsum and it was verified that the first had a bigger fineness, resulting in a small percentage of the retained material on the sieve 100µm (about 2%) opposite to the conventional gypsum (54 % of material retained in sieve 100 µm).

One has also determined the compressive strength resistances of FGD and conventional gypsum, according to EN 13279-2. The FGD gypsum presents a superior strength resistance, achieving 17.4 MPa, while the conventional gypsum reached a resistance of 9.2 MPa.

The used granulated cork was a regranulated of expanded cork, a by-product of a Portuguese industry of black agglomerate cork boards, being the material constituted by different particles sizes: 2/4mm, 2/9mm and 4/8mm. The density is respectively: 166, 182 and 198 kg/m^3 and the bulk density is 65, 73 and 72 kg/m^3.

The used tyre fibres are a material obtained by a Portuguese recycling company of used tyres shredding. These fibres are generally composed by wires and polymeric cords and some rubber residues, being the main element the polyamide 6.

Some dimensional analyses of the fibres were done that consisted of determining the length and the diameter, using an optic microscope with photographic record. It was verified a large dispersion of the fibres length, being the minimum value obtained of 108.2 µm and the maximum value of 12469.1 µm. The average value was 20.69µm with a standard deviation of 1993.2 µm. The fibres diameter is also variable, being the minimum value obtained the 7.2 µm and the maximum 34.1 µm with an average of 20.7 µm.

In the compositions it was also used a setting time retarder for gypsum: citric acid. The incorporation of this material was essential since it was verified that FGD gypsum reacts quickly with water, solidifying the mixture, hindering the maintenance of the working time at reasonable levels during the necessary time to handle the composite at wet state.

2.2 *Compositions, manufacture and conservation*

Aiming at the final composition selection of the composite material to be used in the manufacture of blocks for interior building walls, it was realized an experimental campaign with the objective of characterizing, under a mechanical point of view, the produced compositions.

Thus, a pressed composition (P) and three moulded compositions (M) were studied. The P composition was constituted only by FGD gypsum, water and citric acid, and in the M compositions, with cork incorporation, the amount of granulated cork was varied from 5, 7 and 9 % (M5, M7 e M9) related with the gypsum weight used. The tested compositions are presented at Table 2.

Table 2 – Mixture compositions (at % of gypsum mass)

	Typology	water	Retard.	Cork	Fibres
M5	moulded	80.0	0.05	5.0	3.0
M7	moulded	87.5	0.05	7.0	3.0
M9	moulded	93.75	0.05	9.0	3.0
P	pressed	22.5	0.05	–	–

The water content of moulded compositions was determined experimentally so as to check an adequate working time, which consisted of assuring a flow spread comprised between 140 and 150 mm according to EN 13279-2.

The added water amount in the pressed mixture also resulted from an experimental procedure, done with the objective of manufacture the compositions with the minimal amount of necessary water for gypsum hydration. One has done several tests of pressing with different water percentages in the mixture until obtaining an optimal solution that assured a good superficial finishing, that was admitted as guarantee of a good compactness.

The used retarder dosage was fixed after experimenting several mixtures, containing different acid citric dosages. The tests revealed that the setting time increased with the retarder rise, the same occurred with the flow spread. However, it was verified that the mechanical resistances (compressive and flexural strength) diminished with the retarder dosage increase. So, according to the described, it was adopted a acid citric dosage of 0.05 % of gypsum mass, since that assured the obtaining of paste with enough setting and working time without affecting significantly the mechanical resistances.

The textile tyres fibres dosage was selected based on the product availability and on the fibres effect in the mechanical resistances. Considering the two aspects, it was adopted the dosage of 3 % of gypsum mass.

Regarding to the pressed composition, one has decided not to include the cork in the mixture neither the textile fibres, since this incorporation has revealed adverse, both the mechanical resistances point of view and the superficial finishing.

The mixture process and the samples manufacture were accomplished according to EN 13279-2.

To evaluate the behaviour and the mechanical properties (compressive and flexural strength and elasticity modulus) of the compositions M5, M7 and M9 6 cylindrical samples with 50 mm of diameter and 100 mm of height and 6 prismatic samples with 40x40x160 mm^3 were moulded.

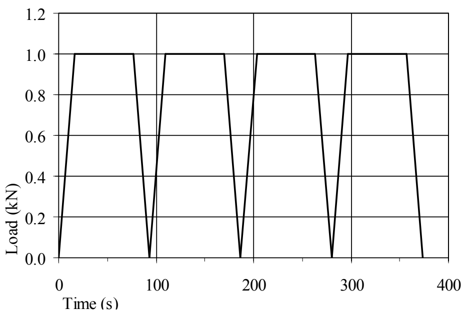
The samples of composition P, shaped by pressing, result of moulding of boards with 35x300x600 mm^3 that were submitted to a pressure of 5 MPa after, diminishing the thickness from about 13 to 14 mm. From these boards, through the cut by damp way, 6 samples with 13x14x27 mm^3 and 6 with 13x40x160 mm^3 were produced.

After manufacture, all the samples were kept in the laboratory at room temperature (about 22 ºC) during 7days. In relation to the samples resulting of pressed board, obtained through cut by damp way, immediately after the cut, they were placed in a drying oven at a temperature of 100 ºC during about 2 hours.

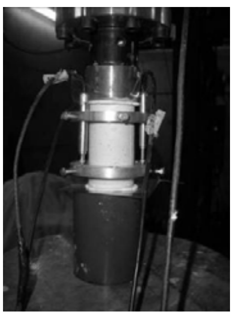
3 TEST PROCEDURES

3.1 *Compressive behaviour*

The elasticity modulus in compression of moulded and pressed material was obtained based on the LNEC specification E 397.



a)



b)

Figure 1 – Elasticity modulus tests: a) loading load; b) general setup for moulded samples

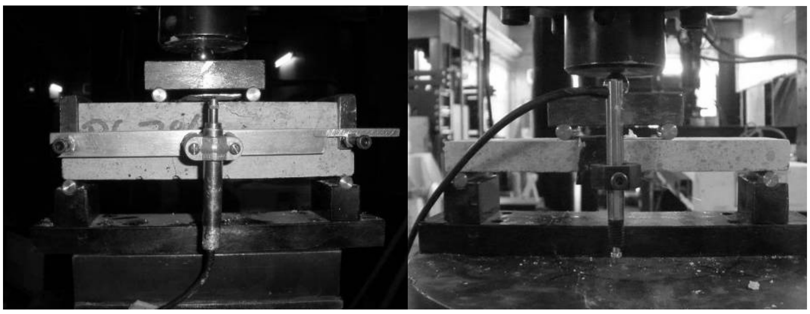
The samples were submitted to 4 load and unload cycles with constant velocity of 0.06 kN/s. The maximum and minimum values of applied load were determined through preliminary tests of uniaxial compression in order to assure that the applied stress was not superior to 30 % of compressive strength. It is generally accepted that the elastic material behaviour in compression is developed just for load less than 30 % of that corresponding to compressive strength (Choi e Shah, 1998; Vasconcelos, 2005). After the maximum load of 30 % of average compressive strength was reached, the samples were maintained under the load action during 60 second, period after which the unload was initiated. The loading law followed in the elasticity modulus tests can be founded at Figure 1a. The load application on the sample was carried out using a thick steel board so as to be sufficiently rigid to uniform the vertical load (Fig. 1b).

In order to minimize irregularities of side samples, these were previously rectified and after covered at the base and top side with a polyester resin of rapid cure. The covering material was always applied before beginning of the test, with the sample vertical aligned and slightly compressed so as to assure the perfect adjust between the load application elements and the sample. In the moulded samples, the vertical displacement was measure through of 3 LVDTs fixed at the sample and positioned according to three equidistant generatrix lines, distanced of 120 º. The used LVDTs have a measure field of ± 2.5 mm and a precision of 0.01 %. The measured distance by the LVDTs was approximately 45 mm. Due to the reduced height of pressed samples, the vertical displacements were pointed out turning to an external transducer, that measured the displacements between the metallic side boards in contact with the sample.

The behaviour under compression of the studied compositions was analyzed based on uniaxial compression tests realized through vertical displacement control. The used loading velocity was 5 μm/s, assuring the maximum load was achieved in a period of time comprised between 2 and 15 minutes. Simultaneously, the adopted velocity had as objective the registration of the complete stress-strain diagram and, allowing this way to characterize completely the behaviour of each material after reaching the maximum stress. The vertical displacements registration was made using the same LVDT configuration used for measuring elasticity modulus.

3.2 *Flexural behaviour*

For the moulded samples, the flexural behaviour was evaluated based on the EN 13279-2 and on the ASTM C1018. The application load scheme was the 4-point flexure test. The used samples for flexural test were prismatic with dimensions of 40x40x160 mm^3 and 13x40x160 mm^3, for, moulded and pressed samples respectively. The tests were carried out with displacement control, through a LVDT placed at sample middle-span. The load velocity for the moulded samples was determined according to the recommendations of ASTM C1018, which indicates that the rupture must occur after a period of 45 s (10 μm/s). The load velocity for the pressed samples, due to the lower thickness and the high rigidity, was fixed to the minimum velocity permitted by the test equipment in order to allow a period of time near to the anterior (1 μm/s). The vertical load was applied through a metallic rigid beam supported in two steel rollers that transmitted punctually the load to the sample. The flexural test setup is illustrated at Figure 2.



a) b)

Figure 2 – Flexural test: a) moulded sample; b) pressed sample

4 PRESENTATION AND DISCUSSION OF OBTAINED RESULTS

Table 3 shows the average values of the densities, γ_m, and the mechanical properties, coming from experimental results, namely the elasticity modulus, E_m, compressive strength, f_m, and flexural strength, $f_{tm,fl}$. The coefficients of variation are presented in brackets and are in percentage.

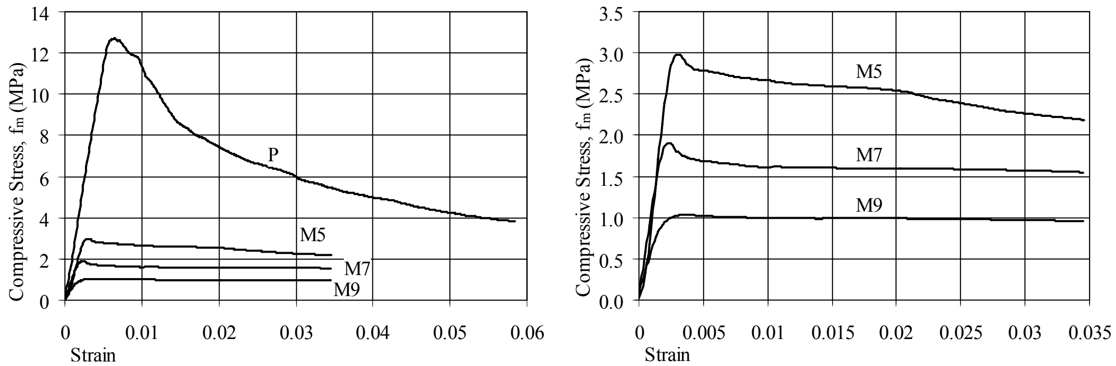
In Figure 3a it is possible to observe the behaviour in compression for the different compositions, expressed by the correspondent average stress-strain curve. Figure 3b shows the same average curves, but referring only to the moulded compositions.

Figure 4 shows the average diagrams stress vs. displacement at middle span obtained at flexural tests for the studied compositions. The flexural stress corresponds to the installed values in transversal section considering that the stress distribution along the section is elastic and linear. It is noted that the procedure for stress calculation is only approximated considering that in the pre-peak regime, and particularly in the post-peak regime, the behaviour is obviously non linear.

The global behaviour in compression and flexure of the pressed and moulded material is significantly different. The pressed material is considerably more resistant, but more brittle than the moulded one. The post-peak at the stress-strain diagrams of the pressed material expresses a stronger reduction of the stress to the same deformation than the verified at moulded material.

Table 3 – Experimental results

	M5	M7	M9	P
γ_m (kg/m^3)	825	760	675	1575
E_m (MPa)	1899.6 [4.7]	1311.8 [12.1]	823.3 [1.5]	2196.9 [17.1]
f_m (MPa)	3.1 [2.7]	2.0 [13.4]	1.1 [5.8]	13.3 [18.2]
$f_{tm,fl}$ (MPa)	0.58 [5.4]	0.68 [4.9]	0.55 [6.3]	1.47 [10.0]



a) b)

Figure 3 – Compressive behaviour (stress-strain curve): a) all compositions; b) moulded compositions

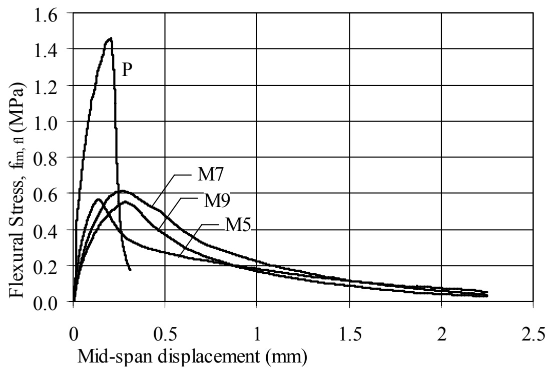
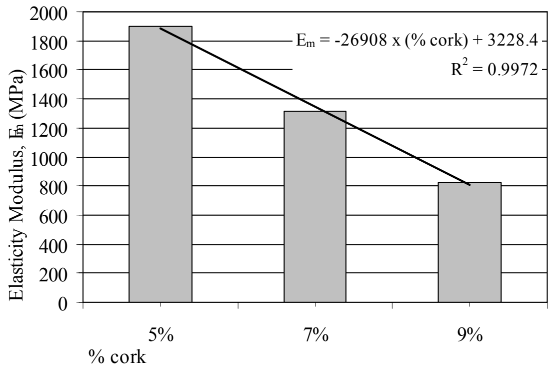


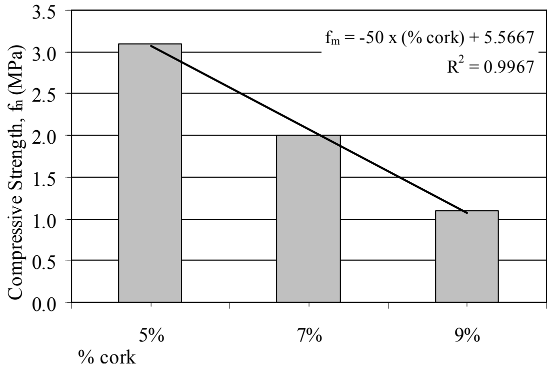
Figure 4 – Flexural behaviour: stress vs. at middle span displacement curve

In compression, the post-peak behaviour of moulded material is characterized by a slight resistance reduction for considerable displacement, expressing this way a much more ductile material. It is verified a resistance increase and a ductility reduction of the moulded material with diminish of cork percentage, in spite of not being registered a considerable difference in the flexural strength. On the other hand, it was verified that the pressed material reveals to be more brittle, with a very quickly resistance loss (without displacement increase) after achieving the maximum resistance. In terms of rupture it is verified that in moulded material the rupture developed through the base or the top, where a level of the sample is crushed and after developing gradually with the crushing of near successive levels. The appearance of the rupture in the base or top is related to the border effect on these areas. In the pressed material the rupture occurs with the development of vertical cracks that were propagated from a sample side to other. The diagrams stress-displacement analyses for the moulded mixtures makes it possible to conclude that important differences in the global flexural behaviour were not verified.

In Figures 5a and b it is possible to observe the cork dosage influence at the elasticity modulus of the composite and at the compressive strength, respectively.



a)



b)

Figure 5 – The cork dosage influence: a) at the elasticity modulus; b) at the compressive strength

In general terms, based on the obtained results, showed at Table 3 and Figures 3 to 5, it is possible to notice that:

- The mechanical characteristics of the pressed composition are, as predicted, quite superior to the moulded compositions;
- The compressive strength of pressed composition is about four times superior to the moulded composition;
- The flexural strength of pressed composition is, also, superior to the verified in the moulded compositions. However, the difference was not so strong, achieving about the double of the resistance of the moulded composition;
- The elasticity modulus of pressed composition is superior to the moulded compositions. However, the difference of the moulded composition with biggest elasticity modulus was only about 15 %;
- In the moulded compositions, the decrease of the elasticity modulus with the rise of the cork amount was nearly linear. To an increase of 1% of cork corresponded a decrease of the elasticity modulus superior to 30 %;
- In the moulded compositions, the decrease of the compressive strength with the rise of cork amount was, also, nearly linear. To an increase of 1% of cork corresponded a decrease of the compressive strength superior to 35 %;
- The results of flexural tests didn't reveal sensitive to the cork amount variation of the compositions;
- The capacity of energy absorption of moulded compositions, whether in compression or in flexion, was really superior to the pressed composition, showing a better ductility behavior.

5 CONCLUSIONS

According to the results obtained, one can conclude that the use of a mixture containing FGD gypsum, granulated cork and textile fibres is viable for several applications in construction, since it is regarded as constituent material of a product with non structural functions. At this context, the initial applicability premise of this kind of material in not resistant masonry blocks seems practicable and can be a very interest way of valorisation of these industrial by-products.

The obtained results of the realized tests allow to verify that there is a clear decrease of the compressive and flexural strength with the cork incorporation related to the pressed gypsum mixture.

Furthermore, it is verified that there is a linear relation between the elasticity modulus and the compressive strength with the cork percentage at the moulded mixtures, meaning that the bigger the cork percentage, the smaller the elasticity modulus and the compressive strength.

The mechanical performance of the material based on FGD gypsum can be considerably improved if one doesn't use the incorporation of cork and tyre fibres and if one uses shaping through pressing. However, this solution is significantly heavier, the manufacture process is also more expensive and the potentialities, in shape terms, are much more limited. Nevertheless, the combined use of these two solutions (moulded and pressed), can result in an interesting product once the pressed solution presents a smaller porosity and consequently an inferior permeability.

6 ACKNOWLEDGMENTS

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