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Evaluation of the performance of recycled textile fibres in the mechanical behaviour of a gypsum and cork composite material

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ABSTRACT

Given the need for using more sustainable constructive solutions, an innovative composite material based on a combination of distinct industrial by-products is proposed aiming to reduce waste and energy consumption in the production of construction materials. The raw materials are thermal activated flue-gas desulphurization (FGD) gypsum, which acts as a binder, granulated cork as the aggregate and recycled textile fibres from used tyres intended to reinforce the material.

This paper presents the results of the design of the composite mortar mixes, the characterization of the key physical properties (density, porosity and ultrasonic pulse velocity) and the mechanical validation based on uniaxial compressive tests and fracture energy tests. In the experimental campaign, the influence of the percentage of the raw materials in terms of gypsum mass, on the mechanical properties of the composite material was assessed.

It was observed that the percentage of granulated cork decreases the compressive strength of the composite material but contributes to the increase in the compressive fracture energy. Besides, the recycled textile fibres play an important role in the mode I fracture process and in the fracture energy of the composite material, resulting in a considerable increase in the mode I fracture energy.

1. Introduction

The construction market is responsible for 50% of the total waste accumulated in landfill, for the production of 30% of the total CO_2 emissions and for 40% of total energy consumption. Such an impact on waste and energy consumption and the increasing problems with environmental changes are the origin of much of the effort of the scientific community to find alternative construction solutions that are more sustainable.

More sustainable construction can be achieved mainly from the reduction in energy consumption during the operation of the buildings and in the production of building materials by reducing the embodied energy during production and by choosing alternative raw materials, such as industrial by-products. Several studies are available in the literature reporting the use of recycled materials from industrial by-products in mortar and concrete, which act as aggregates or as alternative materials to cement binders, reducing the amount of cement and the corresponding impact on CO_2 emissions [1–3]. In this respect, flue-gas desulphurization gypsum (FGD) and granulated cork are two examples of raw materials considered as by-products which can be used in the design of construction materials, especially for non-structural purposes.

Cork comes from the outer layer of bark of the Quercus Suber L., a type of oak tree that is native to the western Mediterranean (Portugal, Spain and Algeria). Cork is composed mainly of suberin, which accounts for about 40% of its dry weight, lignin (±20%), polysaccharides (±20%) and extractables (±15%) [4]. Due to this chemical composition, together with its particular cellular structure, cork exhibits low density, low thermal conductivity, good sound absorption and water resistance. The low density and high gas content of cork's cellular structure contribute to the low thermal conductivity.

The work carried out by Hernandez-Olivares et al. [5] revealed good compatibility between gypsum and granulated cork. However, the mechanical properties can be improved by the addition of glass fibres. This composite material has been used in pre-fabricated elements for partition walls [6]. Granulated cork has been used in mortars, aiming to obtain a more durable material with higher ductility than conventional mortars [7], as well as in aggregates in lightweight concrete or mortar for non-structural applications [8,9]. Recently, work was carried out on the workability, mechanical, transport, microstructural and thermal properties of mortar and concrete to evaluate the impact of using cork as a

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sand replacement or coarse aggregate replacement [10,11]. The mix design variables include the percentage of cork, cork size and cork size distribution. The results demonstrated 46% greater thermal resistance for concrete–cork composites containing 20% cork in comparison to concrete without cork. Besides, it was seen that the percentage of cork used as the sand or coarse aggregate replacement has a more significant effect on the mechanical, microstructural and thermal resistance properties of concrete–cork composites than cork size or cork gradation.

Given its low price and the general recognition that it is an environmentally friendly material, natural gypsum is used in construction as plaster or a binder, even if other applications can be found, such as lightweight gypsum blocks for partition walls [6]. In general, gypsum is used for indoor construction elements as it does not exhibit adequate behaviour when subjected to high levels of humidity, even if its use can vary if it is water resistant [12]. In this respect, several studies have been carried out aiming to improve the water resistance of gypsum based mortars [13–15].

Vimmrova et al. [16] recently carried out work on the development of lightweight gypsum based materials with multi-functionally aiming to combine good thermal and mechanical properties. Such lightweight materials can be used as thermal insulation boards, renovation and fireproof plasters or in the form of load bearing lightweight precast blocks with a thermal insulation function.

Besides natural gypsum, it is possible to use gypsum resulting from other sources, such as red gypsum [13] and FGD gypsum [17–20], aiming to replace the traditional natural gypsum and contributing to more sustainable construction solutions by taking advantage of gypsum by-products. FGD gypsum has also been used in blended mortars and concrete by combining it with cement [21].

In this work, the experimental study of a gypsum and cork composite material to be used in the production of blocks for partition walls is presented. In fact, it is believed that gypsum–cork composite blocks can be a good solution for partition walls, by combining their good mechanical and thermal behaviour [22], and an alternative to traditional solutions based on brick masonry units, mainly with horizontal perforation, or even to vertically perforated blocks [23]. The latter two types of partition wall are commonly associated with excessive waste of materials due to the need to apply infrastructures after the construction of the partition walls, contrary to the solution based on composite blocks [22].

In detail, this work presents and discusses the results of the design of the composite material to be used in the production of the blocks for the partition walls, namely its physical and mechanical behaviour. The idea was to combine three by-products coming from distinct industries, namely granulated cork, FGD gypsum and recycled textile fibres resulting from the recycling of used tyres. In spite of the blocks are not structural, it is important that the stability of the partition walls is ensured, meaning that the mechanical properties are important and are the basis for the design of the material. The influence of the percentage of granulated cork and recycled textile fibres on the mechanical behaviour under compression and on the mechanical properties, namely elastic modulus and compressive strength, is detailed and discussed. Additionally, bending tests were carried out to evaluate the fracture process of the composite material and its mode I fracture energy. These results are important as partition walls can be subjected to bending stresses due to eccentric compressive loads.

2. Raw materials and mortar mixes

2.1. FGD gypsum

As already mentioned, the composite material used in the production of the blocks results from the combination of three industrial by-products, namely FGD gypsum, granulated cork and textile fibres.

The FGD gypsum, formed in the treatment system of gaseous effluents in a Portuguese thermal power station, presents in the form of bihydrated calcium sulphate ($CaSO_4{\cdot}2H_2O$) with about 7% moisture content. The dehydration temperature of the FGD gypsum was studied based on differential scanning calorimetry and thermogravimetric analysis (DSC–TGA) in order to detect the gypsum reactions as a function of the drying temperature. It was seen that the tested gypsum presents two endothermic phases at 50.6 °C and 139.3 °C. Aiming to evaluate the effect of the dehydration temperature on the mechanical strength of the FGD gypsum, different pastes of gypsum and water (fixed at 60% of the gypsum weight) were considered in a complementary experimental study. For this preliminary study, dehydration temperatures for the FGD gypsum of 50 °C, 85 °C, 105 °C, 135 °C were tested. It was seen that for dehydration temperatures 50 °C and 85 °C the gypsum was not reactive. The compressive strength of the gypsum paste was determined and achieved 16.45 MPa and 16.22 MPa for dehydration temperatures of 105 °C and of 135 °C, respectively. For laboratory conditions, it was seen that the temperature of 105 °C was a reasonable solution. In comparison with other studies, similar dehydration temperatures of the FGD gypsum were found, being in the range between 110 °C and 150 °C [17] or in the range between 120 °C and 150 °C [20].

The chemical compositions of FGD gypsum and common gypsum plaster are presented in Table 1. It is seen that FGD gypsum presents a similar chemical composition to common gypsum plaster. Nevertheless, FGD gypsum presents chemical compounds that do not appear in the chemical composition of common gypsum plaster, such us fluoride (F), titanium (TiO_2) and phosphorus (P_2O_5), which result naturally from the process of obtaining this material. Similar waste compounds found in FGD gypsum were also found in recent studies [24].

Based on a sieve analysis of FGD gypsum and common gypsum plaster, carried out according to EN 13279-2 [25], it was seen that FGD gypsum presents a considerably higher value of fine particles. The percentage of particles that are retained in the 100 μm sieve is about 2% in the case of FGD gypsum and 54% in the case of common gypsum plaster.

2.2. Granulated cork

The granulated cork used in this work was obtained from the manufacture of expanded cork, and was a by-product of the Portuguese industry of black agglomerate cork board production as it results from the cork-oak tree branches. It can be classified as a lightweight aggregate with a density rather lower than traditional aggregates. Granulated cork has similar properties to expanded

Table 1
Chemical composition of FGD gypsum and common gypsum plaster.

Chemical compound	FGD gypsum	Gypsum plaster
CaO	40.1	41.3
SO_3	54.4	56.0
F	1.61	–
Fe_2O_3	0.28	0.22
SiO_2	1.58	1.11
Al_2O_3	1.11	0.35
MgO	0.418	0.696
Na_2O	0.261	–
K_2O	–	0.0567
TiO_2	0.0134	–
P_2O_5	0.106	–
SrO	0.001	0.183
ZrO_2	0.001	0.024