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Assessment of thermal performance of gypsum-based composites with revalorized graphite filler

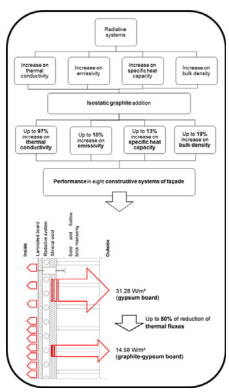
María del Mar Barbero-Barrera [a,*], Nelson Flores-Medina [b], Víctor Pérez-Villar [a]

[a] Department of Construction and Technology in Architecture, Escuela Técnica Superior de Arquitectura, Technical University of Madrid, Spain
[b] Escuela Técnica Superior de Arquitectura, Universidad Europea de Canarias, Spain

HIGHLIGHTS

- Graphite increases bulk density and λ up to 19% and 97%, respectively.
- Specific heat capacity is ranging from 1.01 and 1.22 kJ/kg.K.
- Emissivity increases between 6.1% and 10.3% with the graphite addition.
- Graphite-gypsum board reduces thermal fluxes between 6% and 54%.
- Graphite-gypsum boards shows a higher efficiency of the radiant system.

GRAPHICAL ABSTRACT



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ABSTRACT

European standards place great emphasis on the reintroduction of waste in the production chain. In this research, a combination of experimental tests has been carried out to analyse the use of revalorized isostatic graphite powder waste in gypsum-based boards. A series of gypsum pastes was prepared with a graphite content ranging from 0% to 25%, by weight substitution, and two w/b ratios. Its addition significantly increased the bulk density, thermal conductivity and emissivity of the samples until 19%, 97% and 10%, respectively. Additionally, a reduction of 54% in thermal fluxes towards the outside can be achieved when graphite-gypsum boards replaced gypsum ones at radiative constructive solutions.

1. Introduction

Buildings are responsible for about 40% of the total energy consumption in the European Union [1]. However, this percentage would increase, going on the trend in energy consumption, for a few more decades [2]. Concerning this, different pieces of

* Corresponding author at: Department of Construction and Technology in Architecture, Escuela Técnica Superior de Arquitectura, Technical University of Madrid, Avenida Juan de Herrera, 4, 28040 Madrid, Spain.

E-mail addresses: mar.barbero@upm.es (M.M. Barbero-Barrera), nelson@arquingenieros.com (N. Flores-Medina), heliocrono@gmail.com (V. Pérez-Villar).

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legislation have been introduced to reduce both the energy consumption of buildings and their environmental impact [3,4]. Embodied energy of materials is considered a key issue to attenuate CO_2 emissions. Indeed, the environmental impact and the optimization of resources are not isolated events, but rather a group of activities in which each material and system is involved. It means that from raw material extraction up to its production, distribution, operation, maintenance, demolition and recycling should be considered. Among them, production has a notable influence and can account for 40%–60% of the total energy consumption [5,6]. Hence, the revaluation of waste materials and useless products can be considered an alternative for a more efficient resource management [7]. Most research into by-products from industrial processes, in different binders, focused on the improvement of mechanical and water-proofing characteristics [8–14]. From thermal point of view, most researches focused on the reduction in thermal conductivity of cement mortars and pastes [15–22], lime [23] or ceramics [24].

Additionally, apart from the use of renewable energies, radiant heating systems could contribute to the reduction in energy consumption, yet maintaining the level of comfort and wellbeing [25]. The use of materials with a high thermal conductivity is essential in order to guarantee an efficient energy transfer to indoor spaces. Additionally, a high or medium heat-specific capacity is required to ensure the accumulation of energy and stability of the whole system. Isostatic graphite is a synthetic material whose popularity has grown in recent decades in the field of industry. It has been used in synthetic graphite blocks for Electrical Discharging Machinery (EDM) moulds. Its properties can be summarised by a low thermal expansion coefficient, 3.8×10^{-6}–4.0×10^{-6} °C^{-1}, and extensive heat conductivity, 100.0–104.4 W/m.K [26]. Moreover, it should be highlighted that it is not included in any Waste Catalogue or Hazardous Waste List [26]. As a result of the production process, the amount of EDM graphite disposal worldwide oscillates at around 14,600 tons/year. Until now, there was no commercial alternative to its recycling or reuse.

The use of natural graphite powder has been studied in mortars and concretes for different purposes, such as reducing their setting time [27], increasing their strength [28–29] and improving their waterproof properties [30,31]. As regards thermal behaviour, natural graphite powder has been added to reduce thermal stress at high temperatures [28,32], to increase energy dissipation [33] and to reduce the risk of cracking [34]. Its high specific heat capacity justifies its use for geothermal applications [35] and its incorporation into phase-change materials to enhance their thermal inertia [36,37]; while its low thermal emittance makes it suitable for thermal insulation materials [38,39]. However, information on the thermal performance of isostatic graphite powder as an addition in composites has been unavailable until now.

Furthermore, gypsum has been widely used for indoor applications. Its fast hydration, widespread availability, easy application and low embodied energy, as well as hygroscopicity, are some of the main reasons for its popularity. The main component of industrial gypsum is hemihydrate ($CaSO_4{\cdot}1/2H_2O$), although the dihydrate ($CaSO_4{\cdot}2H_2O$) can also be present in the event of an incomplete dehydration process. Furthermore, some additives can be used to modify the performance of the plasters, such as calcium carbonate to improve its workability. Gypsum is easily available in Spain, with deposits located mainly in the east of the country, which can produce up to 60,000 kt [40]. Therefore, a considerable amount of research has been carried out in which additives have been used to enhance the mechanical and physical properties of gypsum [26,41]. Several materials have been studied in order to reduce the thermal conductivity of gypsum-based composites, but a reduction in the mechanical properties of the composites has also been observed as a consequence. The addition of lightweight aggregates, such as cork [42] and wood [43,44] or expanded vermiculite [45], among others [46], as well as phase change materials for energy storage elements, has also been previously studied. Nevertheless, no researches had been found focusing on the increase in thermal conductivity and specific heat capacity of gypsum-based composites. Additionally, in the last decade considerable research, in which different types of waste was reintroduced into the productive chain of gypsum products, was developed: polyamide powder waste for industrial applications [47,48], ground waste rubber from pipe foam insulation for lightweight products [49]; ethylene vinyl acetate (EVA) waste from the footwear industry and vermiculite [50]; aluminium sulfate and sodium bicarbonate [51], rice husk fiber [52] or waste tires [53]. They focused on the decrease of the thermal conductivity [52,53] while analyzed mechanical and porosity properties [47,49–51] or from the rheological point of view [48]. Because of the aforementioned, the aim of this paper is to analyse the energy performance of gypsum boards with synthetic isostatic graphite powder waste as an additive.

2. Materials and methods

2.1. Materials

Commercial building gypsum for precast systems was used. It followed the European Standard EN 13279-1:2006 [54] and was mainly made up of semi-hydrated sulphate calcium with a lesser content of calcium sulphate anhydrites, portlandite and calcite. Its bulk density was 760 kg/m^3.

Synthetic graphite powder waste was obtained from isostatic graphite, synthesised in blocks and milled for EDM mould production. It was pure carbon of synthetic origin as the XRD and TGA analysis confirmed [26]. Its bulk density was 440 kg/m^3 and its particle size smaller than 20 μm.

Because of the fineness of the graphite, an increase in water demand was expected. Moreover, an air entraining mortar plasticizer was used. Its bulk density was 1050 kg/m^3.

2.2. Sample preparation

Composites with several graphite content ratios were prepared to analyse its effect on their thermal properties. Graphite waste replaced the gypsum content in weight at different percentages, namely, 5%, 10%, 15%, 20% and 25%. The use of a higher percentage was discarded because of the high water demand of the mixture and the low workability of the blend (Table 1). The water content was kept constant in order to analyse the effect of the graphite on the properties of the composites, in both the fresh and hardened state.

Preliminary research was carried out to select the most suitable proportion ratios. They were set to 0.74 and 0.60, by weight ratio. In the latter, samples with higher graphite content had a reduced workability; therefore, plasticizer was added to analyse its influence on the properties. An aqueous solution of alkali products, supplied by Sika company, was used as plasticizer due to the improvement of the mechanical and physical performance were previously analyzed by the authors [26]. In this case, 5% of plasticizer was added. Hence, four groups of samples were prepared with different graphite content ratios, as Table 1 shows.

As regards the procedure, first graphite was added to the water and mixed until a homogeneous paste was obtained. Then, gypsum was slowly introduced while stirring. To avoid the graphite or gypsum particles from absorbing plasticizer and reducing its effect, it was added at the end of the kneading time.

The raw materials were mixed for two minutes before being cast in moulds of 160 × 80 mm and 40 mm thick. They were unmolded on the 7th day and preserved for up to 90 days of curing time under laboratory conditions, after which the tests were carried out. Before testing, they were dried at 40 °C for two weeks to guarantee the complete loss of free water in the samples.

2.3. Experimental methods

2.3.1. Bulk density

A test was carried out in order to measure the bulk density, following Archimedes principle in accordance with the European Standard EN 1936:2006 [55]. As previously mentioned, first the samples were dried at 40 ± 2 °C until a constant mass was obtained. Once at room temperature, they were weighed with a 0.01 g precision and immersed in water for 24 h. The bulk density was calculated as the relationship between dry, saturated and immersed weight as expressed by Eq. (1):

$$\rho_{sample} = \frac{w_{dry}}{(w_{sat} - w_{imm})/\rho_{water}} \quad (1)$$