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Use of multi-layered PCM gypsums to improve fire response. Physical, thermal and mechanical characterization

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ABSTRACT

The building sector is one of the highest energy consumers representing around 30% of total energy use. One of the recommendations of the IEA (International Energy Agency) to reduce energy consumption in buildings is to enhance the thermal performance of building envelopes. In the present study, PCM (Phase Change Material) gypsum materials have been manufactured using three different PCM inclusion methods and a thin layer of gypsum without PCM is added as external layer with the aim of improving the fire reaction behaviour. By performing a detailed physical, mechanical and thermal characterization, the suitability of the materials to be implemented in the building envelope as inner coating is demonstrated. Results show that also the thermal properties are improved in the three cases by the addition of PCM. Moreover, the negative effect of adding paraffin wax PCM into gypsum against flame can be easily reduced by the addition of a thin gypsum layer, which is a low tech and cheap solution without extra environmental impact.

1. Introduction

Building greenhouse gas emissions have doubled since 1970, representing 25% of total GHG (Greenhouse gases) emissions [1]. Furthermore, the building sector is also the responsible of 30% black carbon emissions (caused by the incomplete combustion of fossil fuels, biofuels and biomass) and, from 1/8 to 1/3 of Fluorinated gas emissions depending on the data source used.

The building sector is one of the highest energy consumers representing around 30% of total energy use. Focusing on the energy used in the building sector, space heating of residential and commercial subsectors represented 32–34%, respectively, in 2010 [1]. It means that a lot of energy is spent in space conditioning of buildings and, therefore, an enhancement of the thermal performance of buildings is required in order to reduce the energy demand. As Cabeza et al. [2] experimentally determined, the energy consumption can be reduced up to 64% in summer and 37% in winter in Mediterranean continental climate by the use of insulation. Therefore, it has been demonstrated that the implementation of insulation is crucial to decrease the energy demand in buildings.

In addition, Behzadi anf Farid [3] highlighted the necessity of insulation in buildings but also remarked the importance of the thermal mass of buildings, which can vary significantly depending on the materials used. PCM (Phase Change Material) can be used to increase the thermal mass of buildings during melting and solidification process and hence, they can reduce inner temperature oscillations or even eliminate the need of mechanical air conditioning in some climates [4].

Thermal response of gypsum with PCM has been extensively studied during the past years [5–13], experimentally or by using numerical models, and successful results were achieved. Nevertheless, physical and mechanical characterization is also important [14,15] in order to evaluate the PCM homogeneity, the porosity of the material, and the variation of compressive and flexural strength, among others. In Oliver [5], the author concluded that mechanical and physical properties required by regulations can be maintained when 44.5% in weight of PCM is added into gypsum with additives. In contrast, although minimum physical and mechanical properties established in regulations are reached in Oliver-Ramirez et al. [16], bending and compressive strength is substantially decreased by the addition of 45% in weight of PCM in gypsum panels.

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A wide range of PCMs have been investigated and used, including paraffin wax, salt hydrates, fatty acids, and ester compounds [3]. However, the most common PCM used is paraffin wax because they are cheap and abundant with enough thermal storage densities (up to 200 kJ/kg), negligible subcooling, chemically inert and stable with no phase segregation [17]. However, as it is well known and some studies demonstrate, paraffin has poor behaviour against fire. For example, as Asimakopoulou et al. [18] stated, PCM paraffin wax evaporates, escapes andignites increasing the effective fire load. Some fire retardants (such as magnesium hydroxide, aluminium hydroxide, expanded graphite, ammonium polyphosphate, pentaerythritol, and treated montmorillonite [19]; or high density polyethylene, intumescent flame retardant and iron [20]) are added into the material to improve fire behaviour of PCM paraffin wax. In contrast, they increase the cost of the material and has a potential environmental impact after the building has been demolished.

In the present study, multi-layered PCM gypsum materials have been manufactured and tested with the aim of improving fire reaction behaviour without the addition of additives. To reach this goal an external thin layer of common gypsum (low tech and cheap solution without extra environmental impact) has been added in the outer face of the coating. Three types of PCM inclusion methods have been used in order to add 10% in weight of PCM into common gypsum E-35. Some relevant physical, mechanical and thermal properties as the PCM distribution among gypsum, water absorption in low pressure conditions, modulus of elasticity, compressive and flexural strength as physical and mechanical properties are tested. Moreover, thermal conductivity, thermal transmittance and heat capacity as thermal properties are evaluated to determine the suitability of the material to be implemented in the building envelope as inner coating.

2. Materials

Hemihydrate gypsum with high purity E-35, commercialized by PlacoSaintGobain® and supplied by Joaquim Closas Sabadell, minimum flexural resistance of 3.5 N/mm^2 [21], without fire contribution (Euroclass A1) according to 89/106/CEE Directive was used during the experimentation procedure of this study.

Approximately 10% in weight of PCM paraffin wax was added into E-35 using three different methods: in the first one, microencapsulated PCM Micronal® DS5008 from BASF is used, and, in the other two compositions, non-encapsulated RT-21 PCM from Rubitherm is added into the formulations. In the first method microencapsulated PCM and gypsum powders are first mixed and afterwards the water is added. In the second method a suspension mixture of the required water to hydrate the gypsum and the PCM in liquid phase is done before powder gypsum addition. Finally, in the third method PCM is added into hardened gypsum samples using vacuum impregnation.

According to manufacturers, RT-21 has around 21 °C melting point and 155 kJ/kg melting enthalpy, and Micronal DS5008 has a melting point around 23 °C and its melting enthalpy is 100 kJ/kg.

The nomenclature and sample formulations used during the experimentation are detailed in Table 1. Gypsum and water (without PCM) is used to quantify the variation of properties once PCM is added into the material, therefore, regular gypsum is used as reference material.

3. Methodology

The European standard UNE-EN 13279-2 [22] states minimum requirements for gypsum coatings used in buildings as higher densities than 600 kg/m^3, minimum compression strengths of 2 N/mm^2, and minimum flexural strength of 1 N/mm^2. The first part of the study consist on verify that gypsum achieves these requirements once PCM is added using different inclusion methods. Furthermore, authors consider that there are other important physical and thermal properties that can condition the usage of gypsum with PCM as inner coating in buildings like porosity, water vapour absorption, velocity of water absorption in low pressure (especially in wet rooms, as bathrooms or not conditioned areas), dynamic modulus of elasticity, flexural and compressive strength, thermal transmittance, thermal conductivity and heat capacity.

Table 1
Nomenclature and sample formulations (percentages in weight).

Type	Abbreviation	Gypsum (%)	PCM (%)	Water (%)
Reference	REF	60	0	40
Microencapsulated Micronal ® DS5008 + Gypsum	M	45.5	10	44.5
Suspension RT-21 + Gypsum	S	50	10	40
Impregnation RT-21 + Gypsum	I	54	10	36

As it is well known, the addition of paraffin wax worsens fire response of materials [18]. For this reason, an external thin layer of gypsum without PCM is added into gypsum with PCM. Then, multi-layered gypsums are tested in order to check if it acts correctly as fire barrier material. To reach this goal, a fire reaction test is used (dripping test) that consists of calculating the number of ignitions/extinctions and the duration of flame when a heating source is applied. This test demonstrates the self-extinguishing capability of materials.

3.1. Physical characterization

Authors consider that the methodology used in UNE 1936:2006 Standard [23] to calculate apparent porosity and bulk density can be very useful for gypsum materials. In [23], bulk density and apparent porosity are calculated following Eqs. (1) and (2), respectively, where ρ_b is bulk density [kg/m^3], ρ_0 is apparent porosity [%], m_d is the sample dry mass [g], m_s is sample saturated mass [g], m_h is the mass sample covered with water [g], and ρ_{rb} is the water mass [kg/m^3].

$$\rho_b = \frac{m_d}{m_s - m_h} \times \rho_{rh} \quad (1)$$

$$\rho_o = \frac{m_s - m_d}{m_s - m_h} \times 100 \quad (2)$$

On the other hand, authors consider that the behaviour of gypsum with PCM against the presence of vapour or water is mandatory in inner coatings; however, there is no standardized methodology to evaluate these properties. For this reason, an adaptation of the following building materials standards is done and consistent results are successfully achieved. Vapour permeability is evaluated in a climatic chamber with constant temperature (20 ± 5 °C) and humidity (50 ± 5%) in different ambient conditions, 20% (with NaOH) and 83% (with Na_2SO_4) of relative humidity. This test is also an adaptation of UNE-EN 1015-19 Standard [24] that has the aim of creating different pressures between inner and outer samples containers, which tend to balance by absorbing vapour water. Moreover, the amount of water (in cm^3) that the material is able to absorb per minute in low pressure conditions is determined by Karsten tube penetration test (RILEM Test Method II.4 [25]). RILEM Test Method allows measuring the water diffusion rate through porous materials such as gypsum. Three repetitions of each experiment are analysed to determine the physical properties of each gypsum type.