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Fire behaviour of a mortar with different mass fractions of phase change material for use in radiant floor systems

Laia Haurie[a,*], Javier Mazo[b], Mónica Delgado[b], Belén Zalba[b]

[a] Department of Architectural Technology II, Universitat Politècnica de Catalunya, Av. Dr. Marañón 44-50, 08028 Barcelona, Spain
[b] Aragón Institute for Engineering Research (I3A), Thermal Engineering and Energy Systems Group, University of Zaragoza, Agustín Betancourt Building, C/María de Luna 3, 50018 Zaragoza, Spain

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ABSTRACT

The present work focuses on the reaction to fire of a cement mortar containing phase change material (PCM), which is embedded in a lightweight aggregate, for buildings. Several samples containing different PCM mass fractions have been prepared and tested in order to study the influence of the quantity of PCM on fire behaviour. The enthalpy–temperature of the PCM curve has been measured using the T-history method, and the effect of the PCM on the thermal behaviour of the cement mortar material has been studied using an experimental setup. With the aim of characterizing the reaction of the composite material to fire, various small scale laboratory tests have been carried out, paying special attention to the production of burning drops during combustion, smoke release and flame persistence.

1. Introduction

Phase change materials (PCMs) can be used to improve the energy efficiency of buildings as well as provide thermal comfort to their occupants. There are several diverse applications of PCMs in the building sector. PCMs can be incorporated in building envelopes, increasing their thermal inertia and reducing the fluctuation of the interior temperature of the building and therefore its thermal load. This is known as a passive application. These PCMs can also be part of the active installations of heating and cooling systems. Their storage capacity can be exploited to make it easier the use of energies of intermittent availability.

PCMs can be incorporated into building elements by their integration into conventional building materials. The main PCM materials used in buildings are composites of PCM and gypsum, composites of PCM and polymers, and composites of PCM and cement. Concrete elements have a high thermal mass in buildings. PCMs can be used to enhance this thermal mass with the objective of improving the thermal behaviour of buildings. Several techniques for incorporating PCMs in cement composite materials have been studied in the literature. PCM can be soaked into concrete blocks by an immersion process [1,2]. Due to the low porosity of concrete, the maximum amount of PCM that can be absorbed is around 5% in mass [1]. The main disadvantage of this technology is that PCM leakage is not avoided. However, incorporating microencapsulated material into concrete or mortar during its mixing phase can prevent PCM leakage. A significant number of studies on the characterization of these materials [3–8] and on testing their behaviour when incorporated into building elements [9] have been published. Using these integration techniques, 5% of PCM can be retained in concrete [3–6] and nearly 25% in mortars [7,8]. As a general rule, adding PCM reduces the bulk material density, thermal conductivity and compressive strength. In most cases PCM increases the thermal inertia of the material, though the reduction in density can reduce its thermal mass. PCM can also be integrated into cement composites by impregnation into lightweight aggregates. Its absorption into different materials and its subsequent incorporation into cement composites have been analyzed in several publications. Different kinds of porous materials have been studied, including expanded shale [1,10,11], pumice [1,12], expanded clay [11,12] and expanded graphite [13,14]. By using this technique, a maximum amount of PCM of 25% can be incorporated. As in the previously described technique, the PCM normally decreases thermal conductivity and mechanical resistance.

It is well-known that organic PCMs such as paraffins overcome problems such as corrosion, supercooling or segregation that hinder the use of hydrated salts in building materials [15]. Despite the benefits of these organic PCMs, several authors have reported the flammability of paraffins as one of the main drawbacks to extending the use of these PCMs to building materials [16]. The presence of organic PCMs in building materials increases the risks of fire even

* Corresponding author.
E-mail addresses: laia.haurie@upc.edu (L. Haurie), jmazo@unizar.es (J. Mazo), monica@unizar.es (M. Delgado), bzalba@unizar.es (B. Zalba).

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Nomenclature

Fo	Fourier number
HDPE	high-density polyethylene
HRR	heat released rate [W/g]
L	thickness of the mortar samples [m]
m	exponential decay constant, m [s^{-1}]
PCFC	pyrolysis combustion flow calorimeter
PCM	phase change material
Pt	platinum
T_∞	air flow temperature [°C]
T_1	external temperature of the mortar samples in the thermal diffusivity tests [°C]
T_2	intermediate temperature of the mortar samples in the thermal diffusivity tests [°C]
T_3	internal temperature of the mortar samples in the thermal diffusivity tests [°C]
T_{ini}	initial temperature of the mortar samples in the thermal diffusivity tests [°C]
TGA	thermogravimetric analysis
TTI	time to ignition [s]
t	time [s, min]

Greek symbols

α	Thermal diffusivity [mm^2 s]
ξ_1	First *eigenvalue* of heat transfer differential equation

when incorporated in a non-flammable matrix such as gypsum or cement. To date, few works have assessed the fire performance of composite building materials with PCM.

Hawes [1] used an experimental setup to make preliminary tests on different PCM concrete samples. The observed fire resistance was good and the flame spread was minimal. A moderate fume discharge was also observed in some PCM concrete samples. Salyer and Sircar [17] analyzed how to retard fire in PCM-plasterboards. The authors proposed the addition of a non-flammable surface to the plasterboard, treatment with insoluble liquid fire retardant and the use of fire retardant surface coatings to prevent the wicking action of the plasterboard paper covers. Banu et al. [18] also carried out flammability tests on gypsum wallboard with approximately 24% organic PCM. Specifically, they determined the flame spread and smoke development from experiments in a Steiner tunnel, and the heat and smoke release rates using a cone calorimeter. The results showed that this PCM building material does not meet all the requirements of the National Building Code of Canada on fire characteristics for building materials. They pointed out the possibility of adding flame retardant to reduce its flammability.

On the other hand, several works have analyzed the flammability reduction of a form-stable phase change material based on paraffin and high density polyethylene (HDPE) when adding different types of flame retardants [19–23]. Thermogravimetric analysis and cone calorimeter tests were used. It can be concluded from the results obtained that the incorporation of flame retardants into the form-stable PCM reduces its flammability, as it was observed in the reduction of the HRR peak, having little effect on the stored thermal energy.

Although in recent years many works have been presented on preparation and on thermal and mechanical properties determination of materials with cement and PCM, none of them has dealt with the fire response characterization of these materials since Hawes [1] first studied this issue in the early 1990s. Nowadays, fire safety has become an important aspect for society and this is reflected in the building regulation. In this sense, fire behaviour of building materials must be tested and materials must fulfil some requirements in order to be used in certain applications. The organic nature of commonly used PCM makes necessary to include the fire performance among the parameters evaluated in studies of materials incorporating PCM. Testing methodology has to be adapted from the tests required in the standards to the laboratory scale.

In this work, the fire behaviour of a mortar formulation containing granulated PCM is tested. This material has been designed for a radiant floor application, similar to that described in [24]. The addition of PCM to the radiant floor slabs increases significantly their thermal storage capacity in the temperature range in which it usually works. This effect can be used in applications where there is a high delay between thermal energy supply and demand or in case of integration energy sources with intermittent time availability such as renewable energy. In previous works [24,25] the thermal performance and economic feasibility of a radiant floor coupled to a heat pump was studied. In this case, thermal energy storage is used in order to level the energy demand, shifting electric energy consumption to night hours. The influence of PCM mass fraction in radiant floor slab on the operation of the system was analyzed. It was concluded that the amount of PCM included in the radiant slab composite material has a relevant influence on the profitability of the investment [25]. Therefore, the effect of the quantity of PCM in the composite material on its reaction to fire is analyzed; for this purpose, different PCM mass fractions have been tested. The fire testing methodology as well as the trends observed when paraffin based PCM are incorporated in non-combustible materials could be used and extrapolated when other combinations of paraffin PCM and building material matrix are used.

2. Materials

The mortar samples were prepared using Portland cement with limestone, with denomination CEM II/B-L 32.5N, according to the standard UNE-EN 197-1:2000 [26], fine sand as aggregate, the granulated PCM GR27 supplied by Rubitherm [27], and water. The granulated PCM (GR) is a compound in which the phase change material is bound by a clayey matrix. The compound material forms granules of a size between 1 and 3 mm whose phase change temperature is near 27 °C. The enthalpy–temperature curve of the granulated material has been measured. Since the sample must be representative of the material that is being investigated, the volume of the sample should be of at least a few cubic centimetres or more if possible [28]. For this reason an installation of the T-history method was chosen. This method was originally proposed by Zhang et al. [29] and later improved by Marín et al. [30] and Lázaro et al. [28]. The basic characteristics are the following: one-dimensional heat transfer in the radial direction; the system formed by the container, the reference substance and the PCM are lumped heat capacity systems; and the heat transfer from the containers of the reference substance and the PCM to the air in the chamber is by natural convection. The experiment proposed by Zhang entails recording the chamber temperature and the temperatures during the phase change of the PCM inside two equal tubes that contain respectively the substance that changes phase and the reference substance whose specific heat is known. After obtaining the temperature–time curves of the PCM and of the reference substance, these data can be used to estimate the thermophysical properties. Fig. 1 shows the enthalpy–temperature curve of GR27 obtained with an installation of the T-history method. The sample was ground and compacted in the sample holder for an accurate measurement.

The composition of the mortar follows the prescription of the heating floor manufacturer Uponor [31]. In the reference formulation, the cement to aggregate ratio is around 1:4 and the