Construction and Building Materials 181 (2018) 638–649

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Developing a PCM-enhanced mortar for thermally active precast walls

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HIGHLIGHTS

- Thermal properties of mortars incorporating Phase Change Materials are analysed.
- A good balance between thermal diffusivity and effusivity is essential.
- The best thermal properties are obtained using silica aggregates and antifoaming.
- The amount of PCM reduces conductivity and diffusivity but effusivity is invariant.
- The mortar design has to focus on diffusivity to reach proper heat diffusion rates.

ARTICLE INFO

Article history:
Received 7 December 2017
Received in revised form 1 June 2018
Accepted 2 June 2018
Available online 15 June 2018

Keywords:
Phase Change Material
Thermal energy storage
Thermal diffusivity
Thermal effusivity
Cementitious mortar

ABSTRACT

This work presents an experimental research on the thermal properties of novel cementitious mortars incorporating microencapsulated Phase Change Materials intended to be used as the innermost layer in a precast radiant building component actively controlled by an integrated hydronic system.

The characterization was developed in two steps: the first one focused on the effects of different fine aggregates and admixtures for a fixed PCM content and the second one on the effect of changing the amount of PCM. Results show that using silica aggregates and antifoaming admixture outperform the other options, producing mortars with statistically significant higher thermal conductivities, diffusivities and effusivities. Besides, increasing the amount of PCM significantly reduces conductivity and diffusivity, but the effusivity is practically invariant. This suggests that the mortar design has to be defined by predominantly focusing on diffusivity, in order to achieve appropriate heat penetration rates and activation times for an efficient system operation.

1. Introduction

The total final energy demand of the European Union member states was approximately 1084 Mtoe (Million Tonnes of Oil Equivalent) in 2015, according to the latest data published by Eurostat [1]. Building-related sectors such as residential and services were the most energy-intensive demanding sectors producing together a demand of 422 Mtoe corresponding to 39% of the total, with about two-thirds corresponding to the residential sector [1,2]. Despite the increasing interest in promoting energy-efficient buildings and the current energy policies aimed to reduce the energy impact of the construction sector [3–5], the weight of building-related sectors on the European final energy balance has slightly increased from 35% in 1990 to 39% in 2015. Looking at the energy end-uses in buildings, space heating is the most energy consuming one in the residential sector, representing 71% of the total consumption of households, whereas cooling represents almost 10% of the total energy consumption in Southern countries mainly due to a rapid penetration of air conditioning systems [2,6].

In this context, strategies focused on achieving thermal comfort in buildings, while reducing heating and cooling energy demand, such as Thermal Energy Storage (TES) systems and Thermally Activated Building Systems (TABS), have gained interest proving high energy savings potential [7]. Building integration of TES technologies improves the building energy efficiency by reducing peak loads, uncoupling the energy demand from its availability, allowing the integration of renewable energy sources and providing an

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https://doi.org/10.1016/j.conbuildmat.2018.06.013
0950-0618/

efficient management of thermal energy [8–10]. TABS consist of hydronic pipes embedded in building elements and actively used to transfer heat and/or cold to building components such as walls, ceiling or floors [10]. The thermal mass activation of building components has a big potential for energy use reduction in buildings mainly due to its low temperature operation (low temperature heating and high temperature cooling, as a result of the large heat exchange surfaces) and the high thermal inertia that enables shaving peak loads and shifting energy consumption to low energy cost periods [11,12]. Furthermore, radiative heat exchange of TABS provides comfort conditions, avoiding typical draught problems of convective systems [13–15].

Thermal characteristics of conventional cement-based mixtures without PCM have been analysed by several authors. Although the values vary considerably depending on the specific composition of the mixtures, typical values are in the range from 1.5 to 3.4 W m^{-1} K^{-1} for thermal conductivity [16–19], from 0.38 to 0.90 mm^2 $s^{-1}$for thermal diffusivity [17,19,20] and from 323 to 1800 W·$s^{0.5}$·m^{-2}·K^{-1} for thermal effusivity [18,20]. Available literature on building materials incorporating Phase Change Materials (PCM) is extensive since a wide range of different materials and building products, such as gypsum plaster, gypsum boards, concrete, panels, bricks, membranes and insulating materials, have been considered as matrix materials to include PCM. The main objective of these studies was to improve the thermal behaviour of passive construction systems by increasing the thermal storage capacity of the building envelope [17,21–27].

However, research on the use of latent heat storage materials in active building components is not very extensive, likely because TABS and PCM in most cases have been investigated as individual technologies.

In spite of this, TABS in combination with PCM might result in an improvement of the thermal comfort in buildings and at the same time in a reduction of the HVAC energy consumption, mainly due to (i) the increased energy storage density of latent heat storage systems that contributes to the peak loads shifting, including in the case of lightweight buildings, (ii) the flexible operation of the hydronic pipes that provide active charging and discharging of the PCM depending on the actual heating or cooling needs, and (iii) the possibility to be efficiently coupled with heat pumps and solar-assisted systems, being a low-temperature heating and high-temperature cooling system [28–30].

Regarding the hydronic thermal activation of building components incorporating PCM, a first study was proposed by Koschenz and Lehmann [31]. They designed a ceiling panel incorporating a 5 cm thick layer made of gypsum and microencapsulated PCM (25% by weight) with embedded capillary tubes for the night cooling of lightweight buildings. One of the findings of the development process was the significant thermal conductivity reduction of gypsum after the PCM addition and the need of incorporate aluminium fins to compensate for the decrease of the gypsum thermal conductivity from the expected value of 0.8–1.0 W·m^{-1}·K^{-1} to 0.2 W·m^{-1}·K^{-1} caused by PCM addition.

Another study on the thermal mass activation of a concrete slab including PCM by means of embedded hydronic pipes was proposed by Jin and Zhang [32]. The proposed system consists of a radiant floor with two layers of PCM with different melting temperatures to cover both heating and cooling periods. The objective of the paper was to define the optimal melting temperatures of the layers in order to store heat or cold energy in off-peak period and release the energy in peak period. Authors found by numerical analysis that the fluctuations of the floor surface temperature and heat flux were reduced by using PCM, not only for the direct effect of latent heat capacity but also as a consequence of the low thermal conductivity of the PCM layers. Moreover, they found that the optimal melting temperatures were 38 °C and 18 °C for heating and cooling respectively, and that the energy released by the floor with PCM in peak period was increased by 41% for heating and 38% for cooling in comparison with the radiant floor without PCM.

A similar study on the development of radiant floor panels incorporating granulated PCM and activated by water pipes was presented by Arsuini et al. [33]. Results showed that the integrated PCM layer improved the thermal performance of the floor during summer cooling regimes by storing the internal gains without temperature increase. However, the heating performance was not as good as expected mainly due to the inefficient heat exchange between the water and the environment produced by the increased thermal resistance of the melted granular PCM. In order to lower the contact resistance between the pipes and the PCM, a steel matrix was inserted in the PCM layer providing the necessary conductivity to bypass the parasitic resistances introduced by the PCM.

Regarding the thermal properties of self-compacting concrete including different amounts of microencapsulated PCM, a study was performed by Hunger et al. [16]. They found out that increasing the amount of PCM significantly increases the specific heat capacity as expected. However, the thermal mass presents an upper limit, corresponding to 4–5% PCM in weight, due to the decreasing concrete density. Furthermore, they found out that the addition of PCM results in a substantial reduction of thermal conductivity (of about 40% for the concrete with 5% of PCM by mass in comparison with the reference mix) that improves the concrete insulation properties, but makes the PCM thermal activation more difficult. In the same research line, Pomianowski et al. [34] presented an experimental method to determine the specific heat capacity of concrete materials incorporating PCM as a function of the temperature for the melting process. In this work, the authors emphasise that an efficient application of PCM-enhanced concretes in buildings is strongly limited by their low thermal conductivity that hinders the PCM thermal activation, as also indicated in Ref. [18].

In light of these results, it seems clear that the thermal properties of PCM-added materials have a fundamental role in the development of efficient TABS solutions. In fact, the very high latent heat storage capacity of the PCM can be unexploited if the thermal activation of the material cannot be reached due to the low thermal conduction in the composite. Likewise, the low thermal conductivity and density of cementitious material including PCM can decrease the building element thermal inertia and thus the performance of TABS [18,31]. In fact, in order to fully exploit the improved thermal storage capacity of the PCM-based material in comparison with the conventional one, it is crucial that the addition of the PCM does not produce a substantial drop in density and thermal conductivity, as has been highlighted by several studies [16,18,31,34]. Bearing in mind these premises, the general objective of this work is the formulation of a PCM-enhanced mortar to be used as the inside layer in precast thermally activated façade components. More specifically, this work presents the experimental research carried out to assess the thermal properties of different cementitious mortars added with microencapsulated PCM in order to point out the optimum solution in terms of mix components for this specific application.

2. Methodology

2.1. General approach

This study analyses five properties of different cementitious mortars containing microencapsulated PCM; density, air content, thermal conductivity, thermal diffusivity, and thermal effusivity