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Thermal energy storage and release of a new component with PCM for integration in floors for thermal management of buildings

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ABSTRACT

Lightweight envelopes (used primarily for economic reasons) are widely used in modern buildings but their low thermal capacity does not allow an optimal thermal comfort situation to be obtained in summer period. A solution is proposed here by using phase change materials (PCMs) incorporated in building structures to increase their thermal inertia without increasing their volume. A new polymer composite PCM containing 85% of paraffin, with a latent heat of melting of 110 kJ/kg and a melting point at about 27 °C, is incorporated in a hollow concrete floor panel. Experimental investigation on thermal behavior is presented to study the response to a temperature variation. Results clearly show the influence of PCM, namely a decrease of the surface wall temperature amplitude and an increase of thermal energy stored. A numerical simulation with COMSOL Multiphysics® software confirms the enhancement of the floor inertia by the incorporation of the PCM. The simulation provides design guidelines for the thermal management system to minimize the quantity and size of PCM.

1. Introduction

In the context of continuously increasing fuel prices and CO_2 emissions, it has become necessary to seek effective means of reducing peaks in power consumption. However, reducing power consumption can affect thermal comfort in buildings. The development of improved methods of managing power consumption whilst insuring comfortable indoor conditions is a challenge for the future knowing that the integration of these new solutions in a sustainable architecture must consider the effects on people and the environment.

One way to reduce energy consumption is to use thermal storage devices, especially in climates where daily temperature variations require both heating and cooling over the same 24 h period. The utilization of phase change materials (PCMs) in active and passive cooling/heating of buildings is one of the most efficient ways to store thermal energy [1]. Different research projects have been developed since the last decade including (i) direct incorporation or impregnation of the construction material, (ii) incorporation of PCM capsules in building components, (iii) manufacturing new panels with PCMs to replace classic wallboards, and (iv) incorporation in a plate heat exchanger to improve performance of a HVAC system. The main projects can be found in recent reviews [1–5].

Nevertheless, different techniques presented in literature have limited success because it is difficult to incorporate these phase change materials into existing building materials. The main cause is the conditioning of the phase-change element, which must be completely sealed to prevent leakage of the product during the melting process.

An attractive method is to include PCMs inside cavities which could exist in construction components. This is the case of hollow bricks and several studies have proven such a method useful to increase thermal inertia of buildings [6–8].

One of the objectives of the present study is to implement either of the following two ways to ensure good protection against leaks (i) to utilize existing cavities in construction elements to confine PCMs and (ii) to use a composite which does not flow when the phase-change material is in the liquid state and we propose a novel PCM which does not need any conditioning. The first part of this work is a presentation of the new polymer–paraffin composite material and its thermo-mechanical and thermo-physical properties.

Though the integration of PCMs into light building components has been investigated in numerous studies, these components were essentially devoted to walls. To our knowledge the integration in floors or ceilings has rarely been studied [9–12]. Some authors also have studied performances of ceilings cooled with PCM slurries [13].

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Nomenclature

Latin letters

a	thermal diffusivity ($m^2\,s^{-1}$)
A	coefficient in Eq. (2) (K, °C)
C_p	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
E	energy stored per surface unit ($J\,m^{-2}$)
f	frequency (Hz)
G', G''	viscoelastic moduli (Pa)
h	convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	length (m)
Nu	Nusselt number
t	time (s)
T	temperature (K, °C)
Ra	Rayleigh number

Greek letters

β	volumetric expansion (K^{-1})
γ	strain
ν	kinematic viscosity ($m^2\,s^{-1}$)
ρ	density (kg/m^3)
τ	characteristic time (s)
φ	heat flux ($W\,m^{-2}$)
σ	Stefan–Boltzman constant ($W\,m^{-2}\,K^{-4}$)

Subscripts

max	maximum
i	internal, indoor
e	external, outdoor
a	ambient
m	mean

So, the second part of this study concerns a new construction element: a hollow concrete floor panel filled with a newly devised PCM composite. An experimental setup has been developed to study its thermal response with prescribed periodic boundary conditions. Experimental results are analyzed and demonstrate the suitability of the new component to guarantee significant thermal inertia of a building. Finally, comparison has been made with a numerical simulation developed with COMSOL Multiphysics® software and a good agreement with experimental results confirms its validity.

2. The new polymer–paraffin composite material

2.1. Material preparation

Two compounds are used to prepare the composite PCM: commercial blended paraffin (Rubitherm RT 27), supplied from the Rubitherm Company and a styrene–butadiene–styrene (SEBS) block, supplied from the Sigma Aldrich Company. It is composed of a mixture of solid saturated hydrocarbons with the following molecular formula: C_nH_{2n+2} (4% $C_{17}H_{32}$; 45% $C_{18}H_{34}$; 36% $C_{19}H_{36}$; 12% $C_{20}H_{38}$; 2% $C_{21}H_{40}$ and 1% other alkanes). The basic idea is to mix, at high temperature (>100 °C), the paraffin which serves as a latent heat storage material and SEBS block copolymer leading to a matrix acting as a supporting material. After cooling at room temperature, we obtain a shape-stabilized paraffin material. Several samples with different weight percentages of paraffin were prepared to determine the maximum ratio of the paraffin under which there is no leakage of the paraffin when it melts. With a mass percentage of paraffin into the composite of 85 wt%, it can keep its shape, although the material is heated above the melting point of the paraffin. Observations with optical microscopy show that the nucleation phenomena is heterogeneous and that wax crystals produced in the presence of polymer tend to be spherical as presented in Fig. 1. When the mass percentage of polymer is under 15%, the mechanical strength of the PCM composite is decreased, and thus, the polymer network cannot prevent leakage of the melted paraffin for temperature above the melting point.

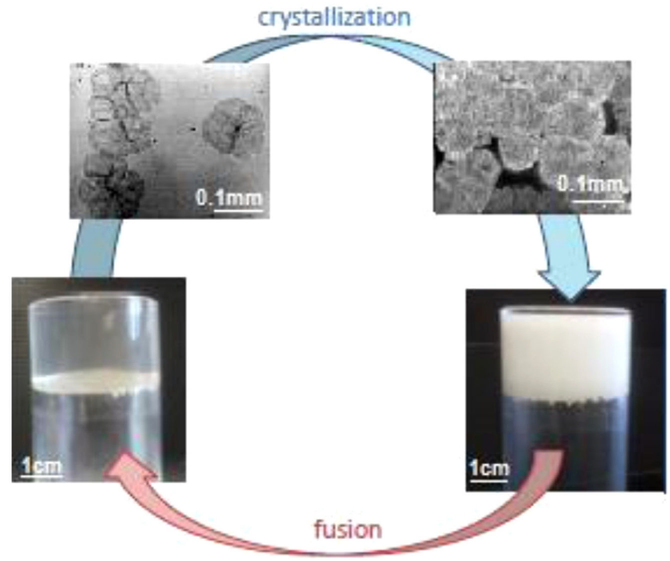

Fig. 1. Photographs of a sample of the material during a freezing–thawing cycle.

2.2. Thermo-mechanical properties of the composite PCM

Thermo-rheological properties were determined as a function of temperature using a Physica MCR 500 (Anton Paar, USA) fitted with a cone-plate fixture. The diameter and angle of the cone were 50 mm and 1° respectively. A continuous temperature sweep (from 20 to 70 °C and back) was undertaken at a rate of 1 °C/min, an angular frequency f of 1 Hz and a strain γ of 1%, which was within the linear viscoelastic region of the polymer solution.

Fig. 2 shows the temperature dependence of viscoelastic moduli (G' and G'' which are the real and imaginary part of

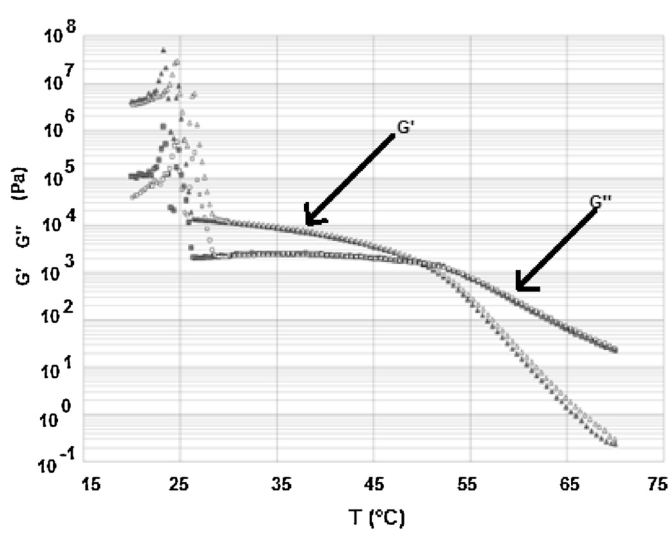

Fig. 2. Viscoelastic moduli (G' and G'') as function of temperature at 1 Hz and γ = 1% for a heating ramp (△) and cooling ramp (■) respectively.