ISSN 2004-2965 Energy Proceedings, Vol. 17, 2021

Paper ID APEN-MIT-2021_202
Applied Energy Symposium: MIT A+B
August 11-13, 2021 • Cambridge, USA

An innovative method of integrating phase change materials in buildings for thermal energy storage via additive manufacturing

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Abstract— The incorporation of phase change material (PCM) into building fabrics would significantly enhance thermal energy storage, thereby enabling energy savings and CO_2 emission reductions. However, the integration method remains a major challenge with the detrimental effects on structural integrity, durability of building elements and performance. This paper proposes a way of integrating PCM into concrete building elements by utilizing additive manufacturing and construction automation technologies. Additive manufacturing of concrete allows the manufacture of non-rectilinear building elements that cannot be constructed using the traditional construction method, thanks to the three-dimensional (3D) concrete printing technology. The concrete elements were constructed as hollow-core using the 3D concrete printing method and PCM incorporated into the hollow-core for thermal energy storage enhancement. Subsequently, the paper assesses performance enhancement of PCM incorporated concrete elements using experimental simulated test rooms and numerical assessment on full-scale buildings. The results reveal that the hollow-core concrete enables a large amount of PCM incorporation of up to 9.88% by weight of concrete, with the increase of heat storage capacity by 7.02 kJ/kg. The simulated test rooms experiment reports that the PCM incorporated hollow-core panels reduced the peak indoor temperature of the test room by 3.86 ℃ while enhancing the thermal storage capacity by 181%. Moreover, the numerical study on buildings incorporated with the innovative PCM panels demonstrated significant energy savings of up to 48% for the Australian climatic conditions.

Keywords— Thermal energy storage, phase change materials, additive manufacturing, energy savings, buildings

I. Introduction

The building sector is responsible for 30-40% of the world's primary energy supply and one-third of the greenhouse gases (GHG) emissions, of which more than half accounts for space heating and cooling purposes [1, 2]. Yet, a significant portion of heating/cooling energy is lost through the building envelope due to the lack of adequate thermal resistance and thermal storage capacity. In particular, modern construction practices have urged rapid construction processes using lightweight building materials, which have very little thermal mass and thermal resistance [3]. Thermal storage and resistance are the primary properties that determine the energy performance of a building. The lack of thermal storage and resistance in buildings will result in the inability to mitigate dynamic thermal loads onto the building, leading to significant diurnal temperature variations and high energy demands. With the awareness of global energy crises and consequent energy policies, energy-efficient building design has become an important topic of research [4].

Among the various methods studied for performance enhancement of buildings, the thermal energy storage enhancement using the latent heat thermal energy storage (LHTES) systems have received significant attention in recent years due to the inherent merits of this system, including large volumetric storage capacity, isothermal energy storage nature and small volume changes. LHTES are operated using the phase transition process (i.e. solid-liquid, solid-solid or liquid gas) of so-called phase change materials (PCMs). Thus, incorporating PCM into building elements could enhance thermal energy storage, thereby mitigating the high diurnal indoor temperature fluctuations leading to building energy savings and improved thermal comfort.

The incorporation of PCM into building elements can be achieved by either integrating PCM into the concrete during the casting process or incorporating the PCM as a separate layer in buildings. While each method has its pros and cons, both methods have been reported to have adverse effects on structural integrity and durability of buildings elements [5]. This is mainly due to the phase transition process of PCM from solid to liquid, where the liquid phase is unstable, leading to leakage of PCM. Several methods have been proposed to prevent PCM leakage, and some of those methods have shown promising outcomes [6]. Nevertheless, the reliability of those leakage prevention methods has not been assessed, so that the commercialization of such technology is significantly delayed.

The additive manufacturing of concrete elements using concrete 3D printing is an emerging construction automation technology, creating a unique opportunity for a disruptive change and creating a platform towards a new way of integrating various sectors (design, architecture and fabrication). These construction methods have many merits over traditional construction in terms of productivity and efficiency, such as greater design freedom, less material and waste, fast construction, and improved worker safety [7]. For instance, 3D concrete printing using robots reduces the material consumption by 30-60% and build the structures at 50-80% faster. Among various additive manufacturing methods, Concrete 3D printing using the extrusion process is a class of digital construction technology, in which the structures are built by adding layers of materials over others. The layers are extruded through nozzles/ print heads mounted on the robotic arm that moves on the predefined paths to construct building elements.

This study exploits the benefits of additive manufacturing in constructing complex building elements, where the building elements are formed as hollow-core 3D printed filaments. A sophisticated nozzle is designed to extrude hollow-core filament such that the filaments have voids in the core produced by the subtraction of concrete. The voids of these elements are impregnated with PCM for enhancing thermal energy storage. The maximum PCM loading and the leakage of PCM after multiple thermal cycles were assessed first. The PCM impregnated hollow-core elements were then used to evaluate the thermal performance using the simulated test room experiments. The building energy savings and corresponding emission reduction were also calculated using numerical modelling of a three-story building incorporated with PCM integrated hollow-core elements.

II. Methodology

A. Additive manufacturing of hollow-core elements

The hollow-core elements were constructed using the concrete 3D printing method by using 3D printable concrete mixes. For this purpose, Ordinary Portland cement (OPC) complying with AS 3972 general-purpose cement (Type GP) and two grades of silica sand (fine sand and TGS sand) were used. Commercial-grade water-reducing admixture (WRA) and retarder, supplied by BASF Australia, were used to adjust printable concrete's setting and workability characteristics. Highly purified Magnesium Alumino Silicate (MAS) provided by Active Minerals International, LLC was used as a thixotropic additive in this study. Table 1 reports the mix proportion of materials for 3D printing of hollow filament structures.

A gantry style 3D printer along with the custom-designed nozzle attachments was used to print the different types of hollow filament structures. The nozzles have an opening of 40 x 15 mm^2 with the wedge to make the required cross-section of the printed specimen. Figure 1 shows the gantry printer used for 3D printing and two different nozzle types used for printing. The printing speed was kept at 10 mm/s for all mixes. Figure 2 shows the wall element with the dimensions of 600 x 400 mm^2 printed for testing purposes. After printing, all specimens were covered with builders' plastic to prevent moisture loss from exposed surfaces and kept for 24 hours. After 24 hours, the specimens were moved to a lime saturated water bath at 23 °C ± 0.5 °C and cured until the test date. The thermal performance test was conducted after 28 days of curing.

B. PCM loading and TES of hollow-core elements

After 28 days, 3D concrete printed elements were removed from the water bath, and an epoxy based waterproofing layer was applied on the exterior surface to prevent PCM leakage. Once the waterproofing layer is cured, the melted paraffin was impregnated into the hollow network allowing it to achieve complete saturation in the voids. The stability of PCM in the hollow-core network was ensured by subjecting the 3D printed elements to multiple thermal cycles operated well below and above the PCM melting temperature. The maximum loading capacity was determined by the weight change of 3D printed elements after subjected to multiple thermal cycles. The thermal energy storage of hollow-core panels was determined by conducting the DSC analysis for paraffin and then converting the heat storage capacity of the panel using the following formulae:

$$TES_{panel} = H_l \times (W_s - W_p) \quad (1)$$

Where H_l is the latent heat capacity of paraffin; W_p and W_s are the weight of the panel before and after PCM incorporation, respectively.

C. Thermal performance test

The thermal performance of PCM incorporated hollow-core panel was studied using the simulated test room experiment. The schematic diagram of the test set up is shown in Figure 3. The test room consists of five adiabatic surfaces and the sixth surface being as the test panel, which is also functioned as a removable lid to facilitate access into the cube. This experimental set up will assure the one-dimensional heat transfer process through the test panel only.

The simulated test rooms were subjected to heating using an infrared heat lamp operated from a height of 300 mm above the specimen as shown in Figure 3. The heater was run for 2 hours followed by natural cooling at ambient conditions. The ambient temperature and relative humidity were kept at 25°C and 50% throughout the experiment. The temperature accuracy of the environmental chamber is 0.1 °C. The K type temperature sensors with the accuracy of 0.01°C and heat flux sensors (5% accuracy) were attached to the test panels' interior and exterior surface. The parameters considered for thermal performance assessment were the interior temperature of the test rooms and inner surface convective heat gain rate. Here, the convective heat gain rate represents the amount heat transferred to the indoor as a result of thermal irradiance on the exterior surface.

TABLE I. Mix proportion of materials

OPC (kg)	Water/ cement	Sand (kg)		WRA (g)	Retarder (g)	MAS (g)
		Fine	TGS			
1	0.285	1	0.5	4.71	5	2

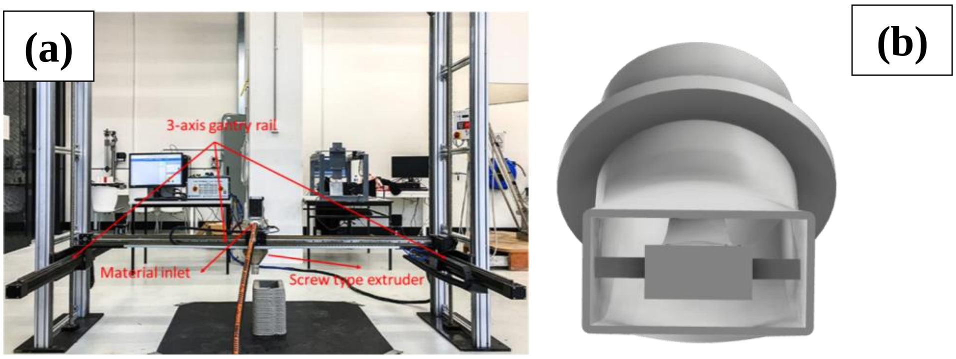

Fig. 1. Additive manufacturing of hollow-core element (a) 3D printer (b) nozzle for hollow-core printing

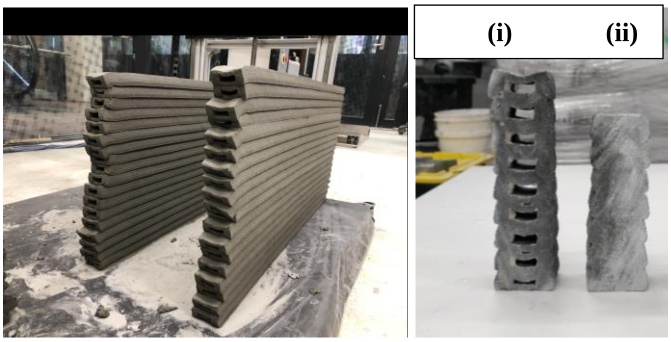

Fig. 2. Hollow-core printed specimens (i) hollow-core (ii) solid core

D. Energy savings of PCM hollow-core panels in buildings

While the simulated test room experiments show a preliminary assessment of PCM integrated hollow-core elements, they cannot be used to assess the performance of buildings due to significantly high scaled-down experiments conducted in simulated test rooms. Thus, thermal performance enhancement of hollow-core PCM panels in real scale buildings was investigated with the aid of numerical approach. A multi-zone office building as shown in Fig. 5 was considered for the building refurbishment with hollow-core PCM panels. It is considered as a module of a typical office building construction, where the building consists of a concrete structure frame enclosed by large glazed facades with concrete infill partition walls separating the offices.

Dynamic thermal simulations were performed with the aid of building energy and thermal load simulation software EnergyPlus v8.9, developed by the U.S. Department of Energy (DOE). EnergyPlus is a highly accredited thermal simulation tool and it has been successfully used for the evaluation of energy efficiency and thermal performance of buildings incorporated with PCMs [40]. The simulations were conducted for two major climate zones of Melbourne and Sydney in Australia.

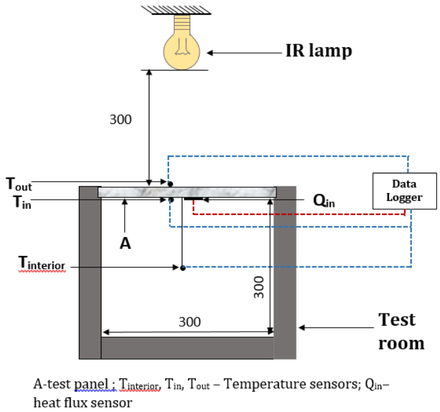

Fig. 3. Schematic diagram of simulated test room experiment

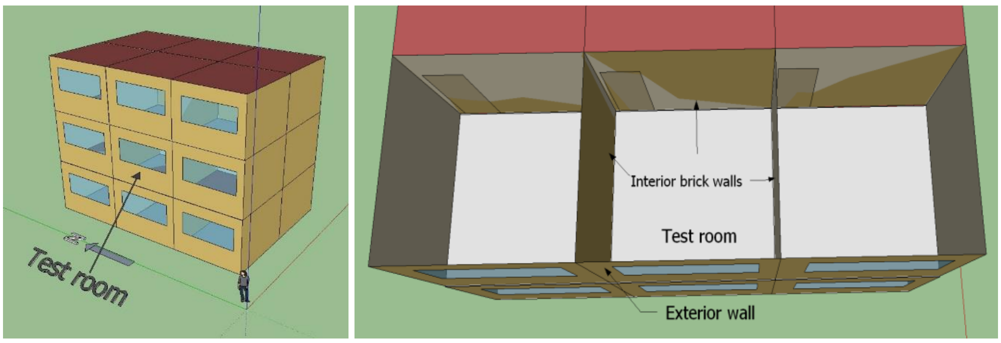

Fig. 4. Simulated building model (a) Thermal zones of the house (b) test room details

III. RESULTS AND DISCUSSIONS

A. PCM loading and thermal energy storage of panels

The results pertaining the PCM loading and thermal energy storage of different hollow-core panels are given in Table 1. The hollow core panels shows 9.88% of PCM loading with an insignificant reduction in loading after the thermal cycling. The slight reduction in PCM loading during the thermal cycling could be due to the evaporation of PCM. On the other hand, the thermal energy storage of PCM incorporated hollow-core panel was enhanced by 16.27 kJ/kg due to the latent heat capacity of PCM. While the loading rate of PCM is low, the heat storage capacity of concrete is significantly enhanced by the PCM, compared to the specific heat capacity of concrete reported in the order of 0.89 kJ/kg. The significant increase in the TES will expected to enhance the thermal performance of hollow-core panels when incorporated as building elements.

TABLE II. PROPERTIES OF HOLLOW-CORE ELEMENTS WITH PCM

Properties of 0.3 x0.3 m^2 panel	***Hollow-core***
Weight of hollow-core panel (kg)	5.1792
Weight of hollow-core + PCM (kg)	5.7024
Weight of hollow-core + PCM after thermal cycles (kg)	5.6906
PCM loading rate (%)	9.88%
Heat of fusion of paraffin (kJ/kg)	164.8
TES of hollow-core panel (kJ/kg)	16.27

B. Thermal performance of PCM hollow-core panels using simulated test rooms

The thermal performance of PCM incorporated hollow-core panels assessed using the simulated test rooms is shown in Fig. 5 and Fig. 6, representing the indoor air temperature and inner surface convective heat gain rate, respectively. Here, the indoor air temperature gives a direct comparison of hollow-core panel on improving indoor thermal comfort, and heat gain rate provides an thermal storage performance of PCM incorporated in hollow-core elements.

As shown in Fig. 5, in comparison to solid-core panel, the hollow-core PCM panel showed a reduced peak indoor temperature with a reduction of 4.88°C with the time lag of 12 minutes. It is also noted that the hollow-core panel without PCM showed high peak temperature than solid-core panel with the maximum temperature difference of 2.62°C. This behavior is attributed to the lack of thermal energy storage in hollow-core panel although it has high thermal resistance due to air voids, compared to solid-core panels. This observation suggests that the thermal storage is important in building elements for improving indoor thermal comfort conditions.

The inner surface convective heat gain rate of the panels shown in Fig. 6 reveals that the incorporation of PCM into the hollow-core significantly reduces the heat gain rates of the panels. For instance, the peak heat gain rate recorded for hollow-core PCM panel was 37.3 W/m^2, compared to 63.3 W/m^2 and 69.3 W/m^2 recorded for solid-core and hollow-core panels respectively. It is also interesting to note that the PCM incorporated hollow-core panels have shown slightly different behavior during the heating process. While the solid-core and hollow-core panels showing approximately linear increase in the heat gain rate, the hollow-core PCM panel showed a mild increase followed by a steep growth in the heat gain rate. This behavior can be explained by the initiation of the melting heat transfer of PCM, and during the melting process, the heat gain rate was slowly increasing followed by rapid increase after complete melting of PCM. This reveals the thermal mass enhancement of hollow-core panel when incorporated with PCM.

C. Energy saving potential of PCM hollow-core panels in buildings

Fig. 7 shows the monthly cooling energy saving potential of building refurbished with PCM incorporated hollow-core panels as a replacement to standard building wall panels in major Australian cities of Melbourne and Sydney. As can be seen, a significant amount of energy savings can be achieved with the PCM hollow-core refurbishment, particularly in the spring and autumn months. Meanwhile, the monthly cooling energy savings during the summer months were plateaued with a minor difference due to the very high solar irradiance during these months. On this basis, the total annual cooling energy savings were estimated as 48% and 38% for the climate zones of Melbourne and Sydney, respectively, when building refurbished with hollow-core + PCM panels.

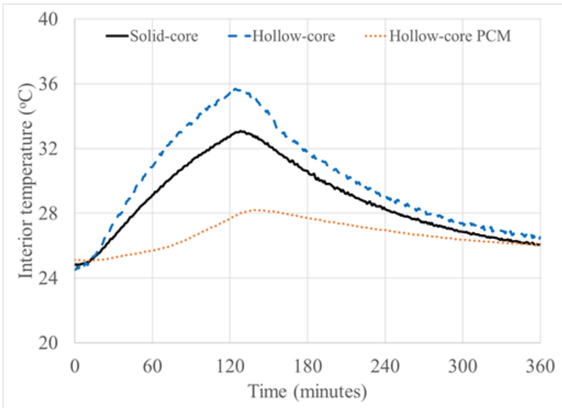

Fig. 5. Indoor temperature variation of simulated test rooms

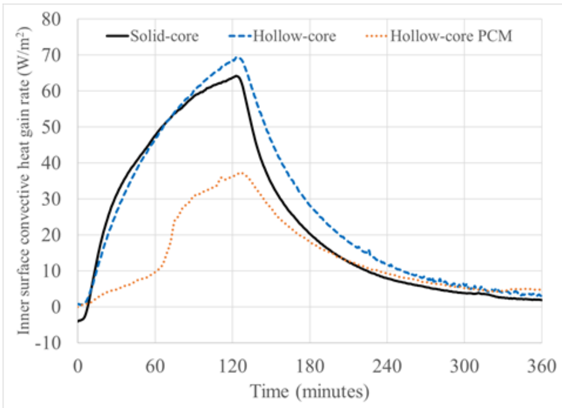

Fig. 6. Convective heat gain rates of panels

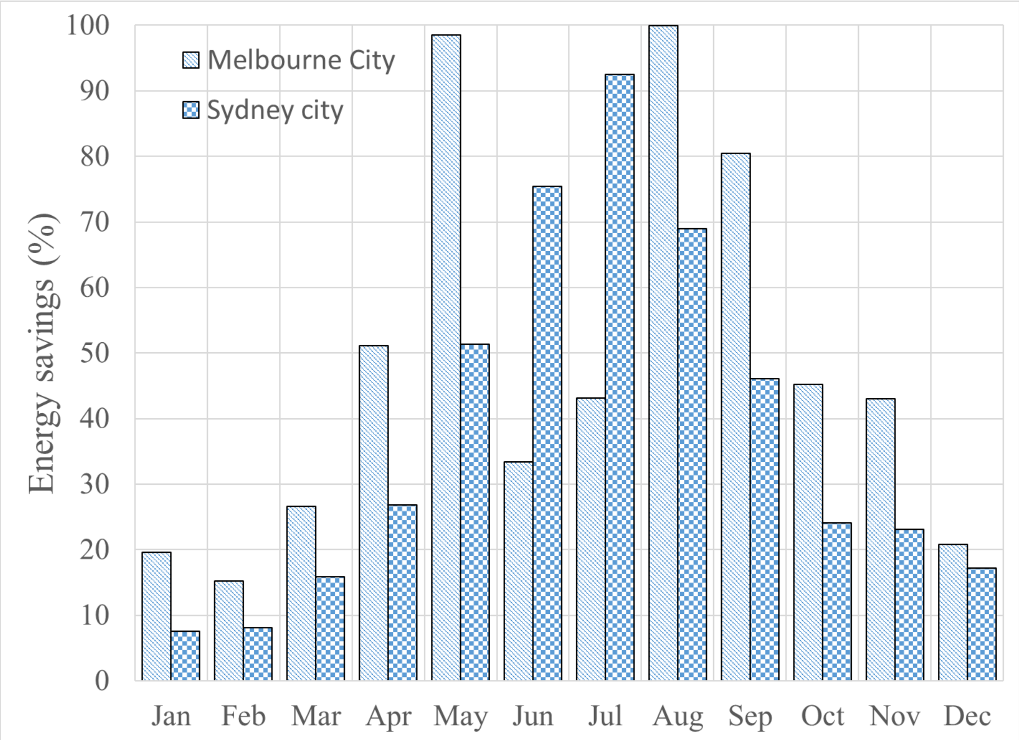

Fig. 7. Monthly cooling energy savings of hollow-core PCM panels incorporated buildings

IV. Conclusions

In this study, additive manufacturing of hollow-core building elements was investigated as a way to incorporate PCM for thermal energy storage applications. Based on the experimental study, the following conclusions can be drawn:

1. The hollow-core building elements manufactured using the additive manufacturing method could facilitate up to 9.88% PCM loading and an enhancement of 16.27 kJ/kg.
2. The simulated test room experiment reported the peak indoor temperature reduction of up to 3.85 ℃ when PCM incorporated hollow core elements are used.
3. The convective heat gain rates on the internal surface of PCM incorporated panels were reduced by 46%, compared to hollow-core without PCM.
4. The annual building energy savings determined using dynamic thermal simulation tests reveals 48% and 38% of energy savings for building incorporated with PCM hollow-core elements in the major climate zones of Melbourne and Sydney, respectively.

Acknowledgment

The authors acknowledge the support received from the Australian Research Council Discovery Early Career Researcher Award DE190100646.

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