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Energy efficient concrete with n-octadecane/xGnP SSPCM for energy conservation in infrastructure

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HIGHLIGHTS

- SSPCM brought high heat storage property and high enthalpy accumulation of concrete.
- Peak temperature reduction and time lag effect was confirmed through dynamic heat transfer analysis.
- SSPCM concrete has high thermal conductivity in comparison with general concrete.
- SSPCM concrete can be applied to various sectors in building for reducing heating and cooling load.

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ABSTRACT

Among the preparation methods of shape-stabilized PCMs (SSPCMs), incorporation of a PCM into construction materials has been proposed as a passive means of decreasing the overall heating and cooling demand of a building. PCMs can be incorporated in a variety of construction materials, such as gypsum plaster boards, concrete and plaster. In this study, we prepared concrete with a high heat storage property by using n-octadecane based SSPCM for application to building. The prepared SSPCM was applied to the concrete as a fine aggregate because its shape is grain type. Then we prepared the SSPCM concrete by compositing SSPCM to concrete. The physical property of SSPCM concrete was analyzed density analysis. And thermal properties of the SSPCM concrete were analyzed by differential scanning calorimeter (DSC), enthalpy analysis and thermogravimetric analysis (TGA). Finally, we carried out dynamic heat transfer analysis of the SSPCM concrete for evaluation of peak temperature reduction time lag effect of the prepared samples. From this research, we confirmed the high thermal properties and possibility to apply SSPCM concrete to heat storage structures and various other fields. We expect SSPCM concrete would be useful in heat storage building materials and to establish a heat storage structure for enhancing thermal efficiency.

1. Introduction

Thermal energy storage (TES) can be an attractive concept to reduce the cost of heating and cooling buildings [1,2]. TES systems could also be used to reduce buildings' dependency on fossil fuels, to contribute to more efficient energy use and to supply heat reliably. The main advantage of thermal storage is that it can contribute to the matching of supply and demand at times when they do not happen to coincide [3,4].

PCM is divided into three kinds, which are organic PCM, inorganic PCM and eutectic PCM. These are used as storage media in latent thermal energy storage, which can be classified into two major categories: organic and inorganic compounds. Inorganic PCMs include salt hydrates, salts, metals and alloys; whereas organic PCMs are comprised of n-hexadecane, n-octadecane, paraffin and fatty acids/esters etc. Also, eutectic PCMs mean mixtures of PCM, which are made by composition of organic-organic, organic-inorganic and inorganic-inorganic PCMs. During daytime, the PCM melts and absorbs part of the heat gain through the melting process; at night, the PCM solidifies and releases the stored heat [5]. PCMs have been widely used in many applications, such as passive cooling for electronic devices, protection systems in aircraft,

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food processing, and energy conservation in buildings, because of their high latent heat, chemical stability, suitable phase-change temperature, and reasonable price [6].

The selection of the PCM is mainly based on its melting temperature. The melting temperature should be within the temperature range of the weather to ensure melting and solidification cycles. In addition, low cost, non-toxic, non-flammable and chemically stable materials are the preferred PCMs [5].

Despite their high potential, PCMs have a couple of problems: leakage during the solid-to-liquid phase change, lower thermal conductivity, and limited cycles of melting and solidification. Some investigators have studied the possibility of a container that can prevent the leaking of liquid PCMs, to solve these problems [7].

In recent years, a new kind of compound PCMs, the so-called shape-stabilized PCMs (SSPCMs), have attracted the interest of many researchers [8–15] due to their large apparent specific heat, suitable thermal conductivity, ability to keep the shape of the PCM stabilized during the phase-change process, and good performance over long-term multiple thermal cycles [16].

Among the SSPCM preparation methods, incorporation of PCMs into construction materials has been proposed as a passive means of decreasing the overall heating and cooling energy demands of a building [17,18]. The high latent heat of PCMs increases the overall thermal mass of building elements, resulting in lower diurnal indoor temperature fluctuations and reduced heat losses to the ambient [19]. PCMs can be incorporated in a variety of construction materials, such as gypsum plaster boards, concrete and plaster [20].

In previous research we prepared an n-octadecane based SSPCM by using exfoliated graphite nanoplatelets (xGnP) to solve the leakage problem, retaining their efficient thermal storage quantity, and improving the thermal conductivity. From the research, the prepared SSPCM brought about a very effective time lag performance in the areas of thermal comfort, indoor temperature and quick releasing heat [7].

Therefore, in this study, we prepared concrete with a high heat storage property by using n-octadecane based SSPCM for application to building. The prepared SSPCM was applied to the concrete as a fine aggregate. Then we prepared the SSPCM concrete by compositing SSPCM to concrete. The physical and thermal properties of the SSPCM concrete were analyzed by density analysis, differential scanning calorimeter (DSC), enthalpy analysis and thermogravimetric analysis (TGA). Finally, we carried out dynamic heat transfer analysis of SSPCM concrete for evaluation of peak temperature reduction and time lag effect of prepared samples.

2. Experimental

2.1. Materials and preparation

The SSPCM was prepared by vacuum impregnation method, and it was composed of n-octadecane as the PCM and xGnP as the container [21]. The n-octadecane, $C_{18}H_{38}$, is made of the alkane series, and belongs to the organic PCMs. Its melting temperature and latent heat capacity are 28 °C and 256.5 J/g, respectively. The 28 °C of phase change temperature is adequate for application to buildings and it is very comfort temperature for humans. So we selected the n-octadecane which has 28 °C of temperature as phase change material.

In previous work, we determined that none leakage phenomenon of SSPCM which was made by vacuum impregnation had been occurred in above melting temperature condition [22].

The used xGnP is a graphitic carbon-based material obtained from Asbury Graphite Mills, Inc., New Jersey, USA, and was applied using a cost-effective and time-effective exfoliation process initially proposed by the Drzal group [23]. xGnP, which combines the layered structure and low price of nanoclays with the superior mechanical, electrical and thermal properties of carbon nanotubes, is very cost-effective, and can simultaneously provide a multitude of physical and chemical property enhancements [24,25].

In previous work, we confirmed the latent heats of the n-octadecane/xGnP SSPCM approach as 110.9 J/g for heating and 104.5 J/g for cooling, which is about half of the heat storage performance of pure n-octadecane [7]. And its melting temperature is 28 °C. The SSPCM concrete was prepared to a 40 MPa design strength. All samples were made by composition of concrete and 10, 20 and 30 wt% of SSPCM, in comparison with the cement weight. For the preparation of SSPCM concrete, we set the water cement ratio at 30%, with 120 mm of slump value, 25 mm maximum size of coarse aggregate and 1.5% of air contents. We made the cylindrical test piece specimens of prepared SSPCM concrete and of size 6 cm in diameter and 12 cm in height. After the mixing process, the concrete mixtures were cured at 20 °C for 28 days in a water bath.

2.2. Characterization techniques

The density analysis of the SSPCM concrete was carried out using the testing method for apparent porosity, water absorption and specific gravity of fire bricks according to KS L 3114:2010. The density property of SSPCM was measured under conditions of 22 ± 1 °C of temperature and 41 ± 1% relative humidity.

Thermal conductivity of the SSPCM concrete was measured by TCi thermal conductivity analyzer, with a size of 20 mm diameter and 10 mm thickness, at 20.0 °C. The TCi can measure the thermal conductivity of a small specimen, using the Modified Transient Plane Source (MTPS) method. Unlike other devices, TCi can measure the thermal conductivity of materials in solid, liquid, powder, or mixed states. In addition, it can measure the thermal conductivity using only one side [26].

Thermal properties of the SSPCM concrete, such as the melting temperature and latent heat capacity, were ascertained using differential scanning calorimetry (DSC: Q 1000). DSC measurements were performed at a 5 °C/min heating and cooling rates over temperature ranges of 0–80 °C, and 80–0 °C. And we used nitrogen as purge gas. The melting temperature was measured by drawing a line at the point of maximum slope of the leading edge of the peak, and extrapolating to the base line. The latent heat of the SSPCM concrete was determined by numerical integration of the area under the peaks that represent the solid–solid and solid–liquid phase transitions.

The enthalpy value of the SSPCM concrete was obtained from a universal analysis program and cp-calculation program, which converts the heat flow of DSC data to a specific heat value. The final enthalpy value was obtained from the sum of specific heat values up to 80 °C.

Thermogravimetric analysis measurements of the SSPCM concrete were carried out using a thermogravimetric analyser, or TGA (TA Instruments, TGA Q5000) on samples of approximately 2–4 mg, over the temperature range 25–600 °C, at a heating rate of 10 °C/min, under a nitrogen flow of 20 ml/min. TGA was carried out with the composites placed in a high-quality nitrogen atmosphere (99.5% nitrogen, 0.5% oxygen content), to prevent unwanted oxidation.

For the dynamic heat transfer analysis of the SSPCM concrete, we set up a mold 0.1 m × 0.1 m × 0.05 m (length × width × height), made of wood and then encased with insulating material. We used the XPS (Extruded polystyrene sheet) as insulation. The used XPS has 0.028 W/m · K of thermal conductivity and 18 N/cm^2 of compressive strength. And then the insulation mold was put on a heat plate. We prepared two such insulation molds which contained concrete, and concrete with 30 wt% of SSPCM. In the dynamic heat transfer analysis, we adjusted the set temperature of the heat plate to 40, 50 and 60 °C. The heating and cooling times were set at four hours and 12 h, for a total of 16 h to finish this test. Thermocouples were inserted at the top, middle and bottom of the concrete and the SSPCM concrete in the insulation molds, to measure the temperature during the heating and cooling periods. Data acquisition took place by using a data logger, Logger GL800 by Graphtec, in combination with a personal computer to store the data. The schematic image of dynamic heat transfer analysis of the SSPCM concrete is shown in Fig. 1.

3. Results and discussion

3.1. Basic thermal properties of SSPCM concrete

The density analysis of the SSPCM concrete was measured three times and the results are shown in Fig. 2. In the experiment, the concrete had an average density of 2.44 g/cm^3, which is 2.4–2.5 times denser than water. The SSPCM is composed of oil-based substances, and that means that the density of SSPCM concrete reduces as more SSPCM is added. In the case of the 10 wt% SSPCM added to concrete, it had a density of 2.21 g/cm^3, and the 20 and 30 wt% SSPCM loaded concretes had densities of 2.05 and 2.01 g/cm^3.

From this result, we noted that the average density of 30 wt% SSPCM loaded concrete was apparently higher than the 20 wt% SSPCM loaded concrete. However, in the process of sample extraction, a lot of concrete might be contained to the extract heat storage concrete, because the extracted sample is a very small amount. For this reason, one of density of 30 wt% of SSPCM loaded concrete showed 2.27 g/cm^3 of density value in the density measurement.