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Mechanical behavior, energy-storing properties and thermal reliability of phase-changing energy-storing concrete

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HIGHLIGHTS

- Studied phase-changing energy-storing concrete (PCESC) experimentally.
- The microstructure of PCESC was investigated.
- The energy storage of PCESC is calculated by the specific heat capacity.
- Studied the thermal reliability of PCESC by thermal cycle test.

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ABSTRACT

Phase-changing energy-storing concrete (PCESC) was prepared by phase-changing energy-storing aggregates (PCESA) replacing a certain percentage of sand. The compressive strength test evaluated the mechanical behavior of PCESC. The SEM imaging and DSC analysis were performed to identify the microstructure and energy-storing properties of PCESC, respectively. The thermal cycle test was used to determine the thermal reliability of PCESC. The test results showed that the PCESA remain intact in PCESC. The compressive strength of PCESC with 20% PCESA is 45.08 MPa, and its equivalent energy storage increases by 82.73%. Besides, the compressive strength of PCESC after 100 thermal cycles is 48.29 MPa, and the equivalent energy storage decrease by 10.55%. Therefore, the PCESC with 20% PCESA maintains satisfactory performance in terms of energy-storing properties and thermal reliability.

1. Introduction

A series of environmental problems, such as fog and haze, extreme weather and global warming, have increasingly threatened the survival of mankind. People pay more and more attention to the rational use of energy and the sustainable development of environment. Global energy consumption increased by 23% between 1990 and 2005, and space heating accounts for 53% of the energy consumed by households [1]. And an important proportion of energy consumption by households refers to the heating and cooling necessities, so that an adequate attention is paid to the energy conservation and saving for buildings [2]. Different systems have been designed for improving the energy efficiency in building sectors related to space heating and cooling [3–5], thermal energy storage has received renewed emphasis and is considered as more effective energy technology for improving the thermal isolation performance of building. Thermal energy storage methods can be released as sensible heat thermal energy storage and latent heat thermal energy storage, latent heat thermal storage is a efficient method of storing thermal energy, and it relies on the phase change materials (PCMs) absorbing or releasing heat as it undergoes a phase transition [6,7]. Latent heat thermal energy storage method plays a critical role for regulating the time discrepancy between the energy demand and supply in building [8,9]. When ambient temperature is higher than the melting point, the PCMs in building sectors endure the corresponding phase transition and absorb heat, and it could retarding the external heat penetrating into the building. When ambient temperature is lower than the freezing point, it will release the stored heat into the building [2,3].The latent thermal heat storage with PCMs is used for off peak storage of thermal energy in buildings.

Concrete as a kind of universally used construction materials can be employed as a matrix for embedment of PCMs in building thermal energy storage [8,10]. D. Zhang et al. [11] prepared phase

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change concrete by two-step method. Firstly, liquid PCMs were impregnated into porous materials. Secondly, the porous materials were incorporated into concrete. The test result of concrete with porous materials show that adequate amount of liquid PCMs can be stored in concrete. P. H. Qin et al. [12] obtained shape stabilized PCMs concrete by high density polyethylene containing PCMs. The apparent specific heat capacity of phase change concrete can be much higher than that of common concrete. H. W. Min et al. [13] reported that the phase change concrete specific heat capacity increases and thermal conductivity decrease as shape stabilized PCMs content increasing, the elastic modulus decrease and compressive strength of phase change concrete decrease with shape stabilized PCMs content increasing. When the concrete is exposed to the environment where temperature is higher than the melting point of shape stabilized PCMs, the concrete compressive strength is decreased. S. Pilehvar et al. [14] investigated the effect of PCMs in solid and liquid states on the mechanical properties of concrete. The compressive strength of concrete with different amounts of PCMs decreases with the addition of PCMs, and the melting PCMs is found to reduce the compressive strength of concrete. The phase change concrete with active carbon energy storage aggregates and graphite was studied by Y. S. Yang et al. [15], and its specific heat capacity and thermal conductivity increases, while the compressive strength drop quickly.

According to the previous literature [11–21], it can be seen that the incorporation of PCMs influences not only the thermal properties but also mechanical properties of concrete. In spite of extensive efforts, only a few studies have examined the thermal reliability of phase change concrete [21,22]. If PCMs are incorporated into concrete, the concrete to resist rupture during thermal cycle and the PCMs must retain its phase change enthalpy over service life [23]. Thus, it is of great importance to prepare a kind of phase change concrete, which is equally amenable to bearing capacity and building energy conservation during long service life.

The main purpose of this study is to investigate the mechanical behavior, energy-storing properties and thermal reliability of phase-changing energy-storing concrete (PCESC). Firstly, phase-changing energy-storing aggregates (PCESA) were prepared by expanded perilte adsorbing butyl stearate. Secondly, PCESC was prepared by PCESA replacing a certain percentage of sand. Finally, the microstructure, mechanical properties and energy-storing properties of PCESC were studied by scanning electron microscopy (SEM) imaging, compressive strength test and differential scanning calorimetric (DSC) analysis, respectively. Besides, the thermal reliability of PCESC was determined by compressive strength test and DSC analysis after thermal cycle test.

2. Experimental

2.1. Materials

In this study, butyl stearate obtained from Beiduobei company in P. R. China was used as PCMs. Fig. 1 shows the DSC thermograms for butyl stearate, and its thermo physical properties are given in Table 1. The melting temperature and the freezing temperature of butyl stearate were determined as 13.99 °C and 19.72 °C, respectively, while the latent heat of melting and freezing were determined as 107.30 J·g^{-1} and 105.41 J·g^{-1}, respectively.

In this study, expanded perlite was chosen for impregnation with PCMs because of its chemical compatibility and pore structure, and it has been considered suitable for impregnation in previous works [24–26]. Expanded perlite was supplied from Henan in P. R. China, and its characteristic parameters are given in Table 2. The SEM image of expanded perlite is shown in Fig. 2, and the expanded perlite has rough and accidental microstructure.

An ordinary portland cement (cement P·O 42.5) in accordance with China National Standard GB175-2009 was used, which was obtained from Huainan. A silica fume was supplied from Gansu, its characteristic parameters are given in Table 3. The chemically pure limestone powder was purchased from Beijing, its chemical constituents are given in Table 4. A water reducing admixture was used in this study, which is polycarboxylate superplasticizer produced by Hebei. A common sand was used, and its particle size ranged from 20 μm to 3 mm and fineness modulus were 2.6. Coarse aggregate was crushed gravel, with particle size ranged from 5 mm to 10 mm. Distilled water was used in this study.

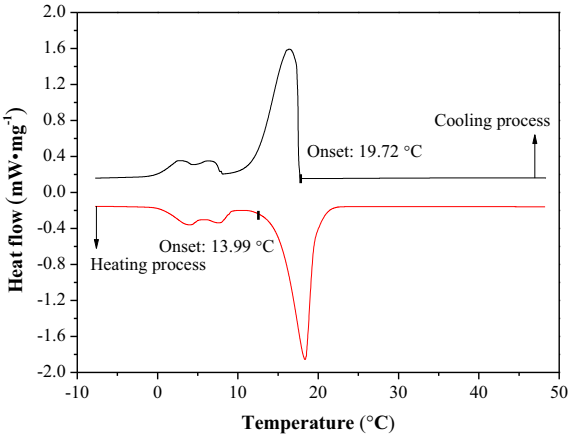

Fig. 1. DSC thermograms of butyl stearate.

Table 1
Thermo physical properties of butyl stearate and PCESA.

Thermo physical properties	Butyl stearate	PCESA
Melting temperature (°C)	13.99	12.56
Latent heat of melting (J·g^{-1})	107.30	29.26
Freezing temperature (°C)	19.72	18.15
Latent heat of freezing (J·g^{-1})	105.41	30.01
Corrosion	Chemically inert	

2.2. Preparation of PCESA

The PCESA were prepared by impregnation technique. In the first stage, the expanded perlite was dried in a ventilated oven at 105 °C until a constant weight was achieved. Secondly, the dry expanded perlite was completely immersed in liquid butyl stearate, and the adsorption process lasted for 24 h with the temperature of 30 °C. After reaching maximum adsorption, the expanded perlite was set aside to draw off excessive butyl stearate and left for drying 12 h. Finally, the impregnated expanded perlite was subsequently wrapped up in limestone powder which is twice the weight of the impregnated expanded perlite. The final PCESA were weighted, and the mass fraction of butyl stearate was calculated. The butyl stearate was absorbed into expanded perlite as much as 25.81% of total weight of PCESA. The unit weight of PCESA was 720.31 kg·m^{-3}, and its particle size ranged from 0.5 mm to 2.0 mm. Fig. 3 shows the DSC thermograms for PCESA, and its thermo physical properties are given in Table 1. The melting temperature and freezing temperature of butyl stearate were measured as 12.56 °C and 18.15 °C, respectively. And the latent heat of melting and freezing were measured as 29.26 J·g^{-1} and 30.01 J·g^{-1}, respectively.

2.3. Preparation of PCESC

The mix designs of the investigated concrete together with their adopted designations are listed in Table 5. The percentages of PCESA used in this study are 0% (CC), 10% (PC-10), 20% (PC-20) and 30% (PC-30) in relation to the volume of sand. In addition, the PC-20 repeated 30 (PCT-30), 60 (PCT-60) and 100 (PCT-100) times of thermal cycle, respectively.

To obtain PCESC containing different amount of PCESA, a four-step mixing process was followed: Firstly, the PCESA and sand were manual mixed to ensure homogeneity of the mixture. Secondly, the gravels were added to the mixture and mixing for 30 s by concrete mixer. And thirdly, the cement and silica fume were added to the mixture and mixing for 60 s. Finally, the already prepared water containing superplasticizer was added to the mixture and mixing for 120 s. The PCESC was carried out at the room temperature.

Immediately after mixing, the PCESC was cast into cubic molds at a size of 100 mm × 100 mm × 100 mm. Then, they were shaken on a vibrating platform for 90 s. After that all the specimens were placed in a laboratory with the room temperature. After 24 h, the specimens were removed from their molds, and placed in the standard curing chamber for concrete until 28 d.