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Investigation on thermal and mechanical characteristics of concrete mixed with shape stabilized phase change material for mix design

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HIGHLIGHTS

- SSPCM (Shape stabilized phase change material) is applied for structural concrete.
- Strength of concrete with SSPCM can be predicted from mass fraction of SSPCM.
- An equation to calculate strength of concrete mixture with SSPCM is proposed.

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ABSTRACT

This paper aims at evaluating thermal and mechanical behaviors of concrete mixed with shape stabilized phase change material (SSPCM) in order to apply the concrete mixed with SSPCM for structural members. Toward that goal, material tests are performed on cylindrically shaped specimens having different water to cement ratios, SSPCM content, and temperature conditions. In addition, two different mixture methods are tested; the first is to add SSPCM to the concrete mixture, and the second is to replace the fine aggregate with the same amount of SSPCM. From the tests for thermal behaviors, it is observed that the thermal conductivity decreases and specific heat increases as SSPCM content increases. Regarding mechanical behaviors, the compressive strength and elastic modulus of concrete mixed with SSPCM decrease with SSPCM content, and the reduction rate is linearly proportional to the mass fraction of SSPCM to concrete. When the specimens are exposed to temperature higher than the melting point of the SSPCM, the compressive strength of the concrete is decreased. However, full recovery of the decreased strength is also observed when the heated specimens are cooled down to room temperature. Based on the experimental findings, an equation for calculating strength of concrete mixture is proposed and used to design mix proportions of concrete mixed with SSPCM. The material tests show that the specimens fabricated according to the proposed method satisfy the target strength.

1. Introduction

Recently, phase change materials (PCMs) have been applied to building materials due to their high thermal storage capacity. There are different PCM types, such as salt hydrates, fatty acids/esters, and paraffin, and each type of PCM has its own thermal and mechanical characteristics. Paraffin and fatty acids have the advantages of physical and chemical stability, while salt hydrates show high energy storage density and are inexpensive [1]. New types of PCMs have been continuously developed to enhance thermal storage capacity and resolved the leakage problem of liquidized PCMs [2–7]. In addition, studies to save energy consumption of buildings have been performed by mixing PCMs with classical building materials such as mortar, cement composite, and gypsum board [8–16]. To be used as building materials, a proper type of PCM needs to be chosen with careful consideration of indoor temperature ranges. Kim et al. [10] propose the use of octadecane, $C_{18}H_{38}$, based shape stabilized PCM (SSPCM) to save energy consumption and prevent leakage problems in buildings. The melting point and heat storage capacity of SSPCM are 28 °C and 256.5 J/g, respectively. In this study, the SSPCM is prepared using vacuum impregnation method, which guarantees the high heat storage of the PCM. Because the vacuum impregnation method induces capillary forces and surface tension forces during the incorporation process, the PCM can maintain its shape as incorporated with porous materials such as exfoliated graphite. Therefore, the leakage problem can be resolved in the SSPCM.

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Moreover, the SSPCM shows improved thermal behaviors because of the high thermal conductivity of exfoliated graphite. [10] Studies on the thermal and mechanical properties of concrete mixed with PCMs have been reported by Jayalath et al. [17], Meshgin and Xi [18], and Fenollera et al. [19]. Jayalath et al. [17] present extensive reviews of thermal energy storage capacity depending on the type of PCM and the strength of the concrete mixed with encapsulated PCM. Their paper concludes that the thermal storage capacity of concrete can be enhanced by adding PCM. However, they raise concerns about strength reduction due to PCM. Meshgin and Xi [18] report experimental studies for mechanical behaviors of concrete mixed with PCM. From their study, obvious reductions of compressive and flexural strength are observed, when 5–20% of the fine aggregates are replaced by the same amount of PCM. In addition, drying shrinkage increases with PCM content, because the PCM used in the study has low stiffness and high moisture content. Fenollera et al. [19] perform experiments on the slump flow and density of self-compacting concrete mixed with paraffin type of PCM, and report that slump flow increases with PCM content, while density decreases with PCM content. However, in order to safely use concrete mixed with PCM as structural members, studies about the effects of mix proportions and temperature changes on mechanical behaviors are still needed.

This paper investigates the thermal and mechanical behaviors of concrete mixed with SSPCM considering various parameters such as the water to cement ratios, temperature changes, and SSPCM contents. With material tests on cylindrically shaped specimens, the thermal conductivity, specific heat, 28-day compressive and tensile strength, strength gain during curing, and elastic modulus are measured. In addition, an equation for calculating strength of concrete mixture is proposed, which can be used for mix design of concrete mixed with SSPCM. For the validation, the material tests are performed on the specimens fabricated by the proposed method.

Fig. 1. Tested materials, (a) Shape stabilized PCM (SSPCM), and (b) Concrete mixed with SSPCM.

2. Experimental methods

2.1. Specimen preparation

This study uses SSPCM, which is octadecane based PCM impregnated into the structure of xGnP. Physical properties of octadecane and xGnP under room temperature are listed in Table 1(a) and (b), respectively [10]. As shown in Fig. 1(a), the SSPCM is form of black fine aggregate, made using vacuum impregnation method. The chosen SSPCM has a melting point of 28 °C, which is appropriately positioned relative to acceptable ranges of indoor temperatures. Octadecane, $C_{18}H_{38}$, belongs to the organic PCMs and xGnP is a graphitic carbon based material made by Asbury Graphite Mills, Inc., NJ, USA. It has been reported that the SSPCM is very cost effective and can simultaneously provide physical and chemical property enhancements [9,10].

Table 1
Physical properties of octadecane/xGnP SSPCM [10].

(a) Physical properties of octadecane	
Melting temperature (°C)	28.0
Heat storage capacity (J/g)	256.5
Specific heat capacity (J/gK)	92.0
Thermal conductivity (W/mK)	0.3
Density (kg/m^3) at 25 °C	777.0
(b) Physical properties of xGnP	
Surface area (m^2/g)	20.4
Bulk density (g/cm^3)	0.0053–0.010
Pore volume (cm^3/g)	0.1
Thermal conductivity (W/mK)	2–300
Specific heat capacity (J/kgK)	710.0

Concrete specimens are prepared in order to investigate the effects of various mix proportions and temperatures on the mechanical behaviors of concrete mixed with octadecane/xGnP SSPCM. Water to cement ratios are varied as 35.42% and 48% by weight, in order to satisfy two different design strengths of plain concrete. That is, the design strengths of plain concrete without SSPCM are 40 MPa and 24 MPa, for water to cement ratios of 35.42% and 48%, respectively. Mix proportions of plain concrete are calculated according to Korean Concrete Standard Specification [11]. There are two different methods for adding SSPCM to concrete mixture; the first is to simply add SSPCM to the plain concrete mixture, and the second is to replace the fine aggregate of plain concrete mixture with the same amount of SSPCM. Tables 2 and 3 are lists of test variables and corresponding mix proportions, respectively. In order to avoid chemical reactions between SSPCM and admixtures, any chemical admixtures such as fly ash or air entraining and water reducing agents are not added even for the concrete having the lowest water to cement ratio. In accordance with the standard method for making and curing concrete specimens provided by Korean Agency for Technology and Standards (KATS) [20], cylindrical specimens with a diameter of 100 mm and height of 200 mm are fabricated. When preparing concrete mixture, SSPCM is mixed with cement and aggregates prior to be mixed with water, and the mixing is conducted for enough time to make sure that the SSPCM is well dispersed within the concrete mixture. During the mixing, the SSPCM particles are easily dispersed within the concrete due to its spherical shape and smooth surface, and no binding between the SSPCM particles is observed.