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Potential applications of phase change materials to mitigate freeze-thaw deteriorations in concrete pavement

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HIGHLIGHTS

- Potential applications of PCM to mitigate frost damage in concrete pavement were examined.
- Paraffin-based organic PCM microencapsulated with melamine-formaldehyde resin was used.
- The mPCM reduced the magnitude of temperature drop by releasing stored heat upon solidification.
- The mPCM inclusion negatively affected the mechanical properties of cement mortar.

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ABSTRACT

A study was performed to evaluate the feasibility of using phase change materials (PCMs) to mitigate freeze-thaw deteriorations in concrete pavements. The approach taken in this paper was to reduce the expected number of freeze-thaw cycles by harnessing the latent heat of fusion of a paraffin-based organic PCM with a phase transition temperature of 4.5 °C (N-Tetradecane). To ensure stable and proper functioning of PCM in mortar, the PCM was coated with tiny melamine-formaldehyde resin shells using a microencapsulation technique. A preliminary study verified successful thermal storage/release functions of the PCM microencapsulated with a melamine-formaldehyde resin. Thermal response tests showed that the low-transition temperature PCM has a promising potential to extend the service life of concrete pavements against freeze-thaw deteriorations even though its effect became minimal with prolonged exposure to ambient temperature far below the transition temperature. A microencapsulated PCM (mPCM) inclusion was found to negatively affect the compressive and flexural strengths or mortar, whereas the volume stability at early ages was rather enhanced in the presence of mPCM.

1. Introduction

A large number of concrete infrastructures in cold regions such as pavements, bridge decks, side walk slabs, barrier walls, and railings are suffering from exposure to successive frost actions and deicing salt applications [1,2]. For example, the number of freezing days including snow events per year in the Korean peninsula, where a continental high atmospheric pressure prevails during winter, reportedly exceeds 100 on average. This phenomenon often leads to various premature to long-term distresses such as salt scaling, D-cracking, random cracking, and joint deterioration since water on freezing expands by 9% in volume, raising the internal pressure of the pores in concrete and coarse aggregate saturated above the critical level [1–4]. These deteriorations exacerbate the long-term performance and serviceability of infrastructures as the cracks and failures act as pathways for intrusion of various deleterious substances as well as moisture, which ultimately increases governmental expenditure needed for infrastructure maintenance. Over the years, various approaches have been proposed to handle such frost-related durability issues including the use of admixtures such as air-entraining agent [5,6], anti-freezing agent [7], and supplementary cementitious materials (SCMs) [8,9]. Recently, several studies [10,11] reported that the use of superabsorbent polymers (SAPs) can be an effective option to enhance the freeze-thaw resistance of concrete because they leave behind numerous engineered voids in the matrices upon release of water as air-entraining agents do.

Phase change materials (PCMs) are latent-heat substances that are capable of repeatedly storing and releasing a large amount of thermal energy upon melting and solidification, taking advantage of their much greater thermal mass than other media such as

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water, wood, masonry, and concrete. Owing to such characteristics, PCMs have been used in many industrial applications including building systems and materials [12–16], textiles [17], automobiles [18], and transportation [19]. In concrete technology, PCMs with a higher transition temperature have been mostly used in mitigation of thermal cracking by limiting early-age temperature rises in concrete [20–25]. In a similar way, if the latent thermal capacity of PCMs with a low phase transition temperature is properly exploited in concrete infrastructures subjected to cold climate conditions, the expected number of freezing events can be significantly reduced, which would eventually extend the service life of the infrastructures. Moreover, because such method does not require additional equipment and artificial energy supply for functioning but just utilizes energy sources available in nature in a less intensive manner, the use of PCMs can be considered fairly well in line with the sustainable development goals compared to other methods.

Several studies pioneered the potential applications of PCMs in freeze-thaw mitigation and snow melting in concrete bridge decks/pavements. Stoll et al. [26] reported that passive thermal treatments using PCMs can substantially reduce the hazard of bridge freezing although a large-scale investigation failed to validate the effectiveness. Bentz and Turpin [20] performed a computer simulation to estimate the expected freeze-thaw cycles for bridge decks in 12 different climates using the modified CONCTEMP computer model and found that the number of freeze-thaw events was reduced by 30% on average. Another study by Sakulich and Bentz [27] demonstrated that incorporation of PCM in bridge decks can be a practical method that would extend the service life of bridge decks even though further attempts are required to tackle the strength reductions issue. Lately, Farnam et al. [28] assessed the thermal properties of two types of PCMs (paraffin oil and methyl laurate) and PCM-incorporated mortars treated with different methods (lightweight aggregate filling and tube filling) by means of a low-temperature differential scanning calorimeter and a longitudinal guarded comparative calorimeter. They concluded that both paraffin oil and methyl laurate yielded superior performance when filled in embedded tubes.

In this paper, a feasibility study is performed to verify the practical contributions of PCM inclusion to freeze-thaw durability enhancement for potential applications in concrete pavements. The focus of this study is primarily on monitoring thermal responses of mortar with a low-transition temperature PCM under freeze-thaw cycles. Of the various PCMs available, this study employed a paraffin-based organic PCM due to its relatively excellent durability, phase change stability, and less reactivity with other components in concrete.

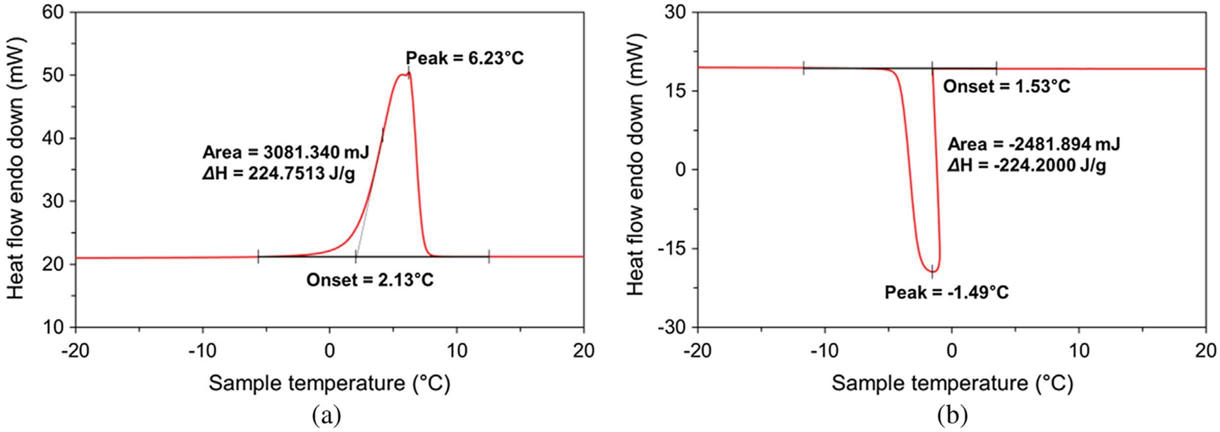
2. Experimental

2.1. Materials

Type I ordinary Portland cement (OPC) with a specific gravity of 3.15 and a fineness of 3700 cm^2/g was used. The chemical composition of the cement was 61.5% CaO, 19.7% SiO_2, 5.33% Al_2O_3, 2.90% Fe_2O_3, 3.81% MgO, 2.54% SO_3, 0.86% K_2O, and 0.18% Na_2O.

Standard sand conforming to KS L 5100 (*Standard sand for testing strength of hydraulic cement mortars*) with a specific gravity of 2.65, a fineness modulus of 2.87, an absorption capacity of 1.02%, a SiO_2 content of 98.4%, and D10, D50, and D90 of 0.388, 0.533, and 0.731 mm, respectively, was used as fine aggregate.

A paraffin-based organic PCM (N-Tetradecane ($C_{14}H_{30}$); 198.39 g/mol) with a transition temperature of 4.5 °C, a heat conductivity of 0.2 W/m·K, and a specific gravity of 0.756 was employed as a latent heat storage/release material. The latent heat of fusion for the raw PCM was found to be about 224.5 J/g based on the heat flow measurements via differential scanning calorimetry (DSC) (DSC 4000; PerkinElmer, Inc.), as shown in Fig. 1. The heating and cooling rate and sample weight for the DSC measurements were 2.0 °C/min and 11.070–13.710 mg, respectively. In this study, the PCM was microencapsulated with a melamine-formaldehyde resin by means of the emulsification method (1) to prevent the leakage of PCM when presented in the form of liquid at room temperature; (2) to avoid the direct exposure of PCM to hydration products in concrete; and (3) to maximize the thermal efficiency of PCM by well-distributing the mPCM particulates (increasing the specific surface area) in the matrix. Since the drying process to obtain mPCM powder raises the unit cost of PCM by up to 5 times, a slurry type mPCM was used in this study. The fundamental properties of the mPCM slurry used are presented in Table 1.



(a) (b)

Fig. 1. Heat flow measurements of raw PCM in bulk: (a) heating cycle; and (b) cooling cycle.

Table 1
Properties of mPCM slurry used.

Appearance	Composition	Core material	Polymer shell size	Purity	Thermal stability	Thermal cycling
White slurry 	10 wt% polymer shell; 27.5 wt% raw PCM; and 62.5 wt% liquid	Paraffin (N-Tetradecane)	5–20 μm	Min. 90–97 wt%	Stable with negligible leakage and supercooling	Multiple