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Potential applications of phase change materials in concrete technology

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Abstract

In internal curing, pre-wetted lightweight aggregates (LWA) serve as internal reservoirs to supply the extra water needed by the cementitious and pozzolanic components of the concrete during their hydration processes. Due to their porous nature and reasonably high absorption capacity, the LWA can also be filled with other materials, such as phase change materials (PCMs). In this paper, three potential applications of PCM-filled LWA in concrete technology are presented. In addition to the previously explored application of increasing the energy storage capacity of concrete in residential and commercial construction by using a PCM with a transition temperature near room temperature, applications for higher and lower temperature PCMs also exist. In the former case, a PCM can be used to reduce the temperature rise (and subsequent rate of temperature decrease) of a large concrete section during (semi)adiabatic curing, to minimize thermal cracking, etc. In the latter case, a PCM can perhaps reduce the number or intensity of freeze/thaw cycles experienced by a bridge deck or other concrete exposed to a winter environment. In this paper, these latter two applications are preliminarily explored from both experimental and modeling viewpoints.

Keywords: Building technology; Concrete; Enthalpy; Freezing; Phase change materials; Temperature

1. Introduction

In many areas of the world, concrete is used extensively for residential as well as for commercial construction. In moderate climates, the relatively large thermal mass of the concrete walls can be an advantage, as they store up energy during the day and release it at night, reducing the need for auxiliary cooling/heating. Of course, in more tropical climates, this nocturnal release of energy can be most unwelcome to residents trying to sleep in a room without forced cooling. However, the energy storage capacity of concrete can be further modified by the incorporation of phase change materials (PCMs) into the concrete mixture [1–4]. Two potential applications of PCMs in concrete have been highlighted in the recent works of Zhang et al. [4] and of Mihashi et al. [3]. In the former case, porous lightweight aggregates (LWA) were successfully impregnated with a butyl stearate PCM that melts at around 18 °C. Such a concrete could be used in construction to maintain interior temperatures near 18 °C, as the melting and solidification of the PCM would delay and, perhaps, avoid temperature excursions above/below this value. Even when a temperature excursion can not be avoided, its delay can be extremely beneficial if it shifts heating/cooling loads to time periods when power is available at a lower cost. Such a technology is now being commercially employed in aerated cement blocks, using microencapsulated PCMs, and plaster, using wax-filled spheres [5], for example.

In the second application [3], a paraffin microcapsule that contains a hydration retarder was incorporated into concrete to drastically reduce the temperature rise experienced during the early-age curing of massive concrete structures. The melting of the wax absorbs energy (partially

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reducing the temperature rise) and the release of the hydration retarder further reduces hydration rates and concurrent heat release from the mixture. Maximum achieved temperatures under (semi)adiabatic curing were significantly reduced in both small cement paste and larger concrete specimens. While early age concrete strengths were significantly reduced, 91 d strengths were actually increased by the incorporation of the PCM/retarder microcapsules, as it is well known that higher curing temperatures, while significantly accelerating hydration and strength gain at early ages, can actually lead to lower long term concrete strengths [6].

Because numerous PCMs are readily available with a wide range of transition temperatures, as summarized extensively in [7], a third (but untried to date) application of PCMs in concrete would be to utilize a PCM with a transition temperature of around 5 °C to avoid a fraction of the freeze/thaw cycles normally experienced by a concrete bridge deck or pavement. This could improve both the durability of the concrete and provide improved skid resistance, improving safety in cold climates. In this paper, the physical properties of a variety of PCMs of potential usage in concrete will be presented and the latter two of the three proposed applications will be explored in more detail.

2. Experimental and computer modeling

2.1. Differential scanning calorimetry

The following PCMs were obtained from chemical suppliers: three different polyethylene glycols (of different average molecular masses, MM), octodecane, and paraffin wax. All of the materials were evaluated in bulk form and two of them (the paraffin wax and one of the polyethylene glycols) were also impregnated into (porous) lightweight fine aggregates (expanded shale) nominally 3 mm in diameter. The "saturation" of the aggregates was performed by simply first drying them at 40 °C and then immersing them in a (melted) solution of the appropriate PCM for a minimum of 24 h. Small samples of each PCM (or of the PCM embedded in LWA) were used for each differential scanning calorimetry (DSC) experiment. In a given experiment, sample mass was typically between 10 mg and 100 mg. For each DSC experiment, the sample was placed in a small open stainless steel pan. The pan with the sample, along with an empty reference pan of similar mass to the empty sample pan, was placed in the calorimeter cell. A temperature range expected to encompass the transition temperature(s) of the specific PCM was selected and a cyclic cooling/heating/cooling scan conducted at a scan rate of 0.5 °C/min, with a 10 min isothermal hold at both the minimum and maximum temperatures comprising the scan. For temperatures between −100 °C and 500 °C, the equipment manufacturer has specified a constant calorimetric sensitivity of ±2.5% and a root-mean-square baseline noise of 1.5 μW. For comparison, typical measured peak signals for the PCM phase transitions were on the order of several milliwatts. Enthalpies of melting and solidification were quantitatively estimated by manually identifying each peak in the DSC scan and using a linear approximation for the baseline below/above the peaks.

2.2. Semi-adiabatic calorimetry

A home-built semi-adiabatic calorimeter was used to preliminarily evaluate the second proposed application of PCMs in concrete, namely reductions in the temperature rise and subsequent rate of temperature decrease during the first few days of hydration. For this portion of the experiment, mortar specimens with a water-to-cement ratio by mass of 0.4 were prepared and mixed by hand according to the proportions provided in Table 1. In the control mortars, a nonporous coarse silica sand was employed and the proportions were adjusted to obtain a temperature rise to near 70 °C in the semi-adiabatic calorimeter setup. In the LWA/PCM mortar, the paraffin wax PCM was first absorbed into the expanded shale LWA, with an obtained absorption of 13.8% by mass of dry LWA. The LWA/PCM was then used to replace the sand on a volumetric basis. Finally, in the pure PCM mortar, the paraffin wax particles (about 1 mm in size) were added directly to the cement paste, totally replacing the coarse sand on a volumetric basis. Each mortar was cast into a cylindrical plastic mold with an inner diameter of 47 mm and a height of 97 mm. The mold could thus hold about 330 g of the control mortar. By performing volumetric replacements for the sand, each mold should contain the same mass of hydrating (heat generating) cement paste to enable a realistic comparison amongst the three investigated mixtures. A filled mold was immediately placed in an insulative holder (constructed of microporous insulation) and a single Type J thermocouple inserted into the center of the mortar volume. The temperature was then monitored during the course of several days of "semi-adiabatic" hydration.

2.3. Concrete temperature modeling (CONCTEMP)

For the third potential application of PCMs, namely limiting the number of freeze/thaw cycles of bridge deck concretes (and pavements), a computer simulation approach was employed to evaluate its potential feasibility. An existing one-dimensional finite difference computer code (CONCTEMP) that predicts the temperature distri-

Table 1
Mixture proportions for the mortars employed in the semi-adiabatic calorimetry experiments

Material	Mass (g)
Type I cement	210
Distilled water	84
Coarse sand or #8 LWA with PCM or PCM	70 g sand or 48 g LWA/PCM or 27 g PCM