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Limiting Freeze/Thaw Damage in Cementitious Infrastructure Systems with Phase Change Materials (PCMs)

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Phase Change Materials (PCMs) are organic, inorganic, or eutectic compounds with a high heat of fusion, which enables them to store and release large amounts of energy. While PCMs have found a number of uses in commercial applications, such as specialty clothing, shipping containers, and mattresses, in building systems they are mainly used to increase the energy storage capacity of materials. PCM is solid at lower temperatures (i.e. at night); as ambient temperatures increase during the day, the PCM melts, absorbing heat. At the end of the day, as temperatures decrease, the PCM re-solidifies and releases heat. The emission and absorption of heat from PCMs has the effect of warming cold rooms and cooling warm rooms, essentially cutting the highs and lows off of temperature profiles of a structure. When PCMs are incorporated in concrete or wallboard, a room or structure spends more time in the 'comfort zone' (Fig. 1) and requires less heating or air-conditioning [1,2]. Such incorporation is relatively simple; a solution containing PCM microencapsulated in a polymer shell is simply mixed into the liquid cement, plaster, or mortar. PCMs thus have the potential to reduce electricity required for temperature maintenance [3].

Although PCMs in building materials are used almost solely for the purpose of comfort zone maintenance [4], they show promise in other applications, such as freeze/thaw damage limitation [5]. At low temperatures, the pore solutions in cements and concretes freeze, expand, and cause cracking. Cracking is one of the most prevalent deterioration mechanisms in concrete, reducing mechanical properties and accelerating the corrosion of reinforcing steel. If the phase transition temperature of the PCM is slightly above the freezing point of pore solution, the PCM will solidify first, releasing enough heat to delay freezing of the pore solution. This has the potential to not only limit cracking damage, but also improve skid/slip resistance and safety.

Little research has been devoted to the use of PCMs as a freeze/thaw damage limitation system. An initial investigation [5] used thermally conductive lightweight aggregate (LWA) as a carrier for PCM to maximize heat transfer. The difference between microencapsulated PCM and LWA/PCM is illustrated in Figure 2. LWA can be graded to have the same size distribution as sand and is simply used to replace a portion of the fine aggregate in a mortar or concrete. Through calorimetry and simulations, this investigation concluded that 350 kg/m^3 of PCM in a standard concrete would be sufficient to reduce freeze/thaw cycles experienced by some bridge decks by as much as 30 %.

Building on these initial results, a more extensive investigation of the practicality of using PCMs to limit freeze/thaw damage has been carried out. LWA was again used as the carrier so as to maximize thermal transfer. Differential scanning calorimetry and semi-adiabatic calorimetry were used to characterize thermal behavior of the LWA/PCM. A thermal capacitance (or 'slug') calorimeter in a water/glycol bath was used to characterize the transient performance of a mortar containing PCM under freezing conditions. Further standard mechanical tests revealed that the use of the LWA/PCM had minimal negative effects on properties such as compressive or flexural strength.

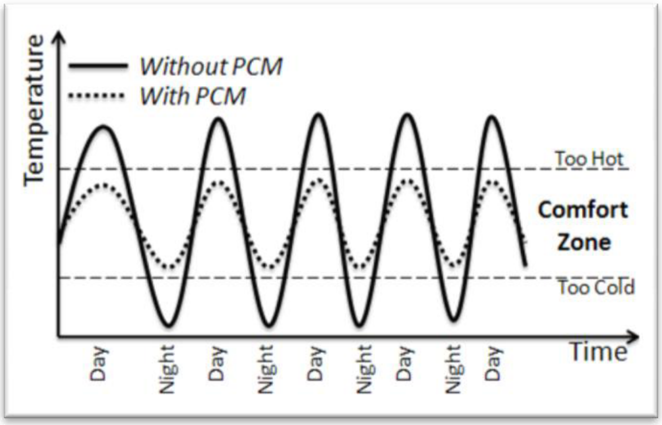

FIG 1 – Daily temperature cycles in a typical structure. Standard building materials (solid line) allow temperatures to become too hot or too cold. Building materials with PCM (dotted line) decrease such temperature excursions, lowering heating/air conditioning needs.

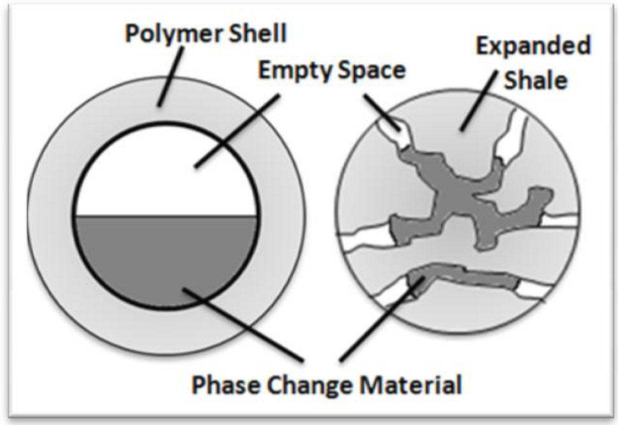

FIG 2 – Microencapsulated PCM (left) and PCM encapsulated in expanded shale, a lightweight aggregate (right). Empty space is meant to accommodate volumetric expansion during solidification.

Microstructural analysis in the form of optical- and electron microscopy, energy dispersive spectroscopy, resonant frequency analysis, and x-ray microtomography was carried out. Differences in the density and composition of natural aggregate (i.e. sand) and LWA enabled differentiation and observation of the two species with these techniques; chemical analyses showed that the inclusion of PCM did not negatively affect the hydration or final chemical composition of the hydrated cement.

On the basis of the experimental results, simulations using typical meteorological data collected across the U.S. were used to identify areas where infrastructure materials incorporating PCM would be most effective in reducing freeze/thaw damage. The previous investigation [5] examined 12 locations, in the least effective of which (Cheyenne, WY) freeze/thaw cycles experienced fell from 131 to 106 for a typical year, a 19.1 % decrease. The most effective location (excluding Tampa, FL, which saw a reduction from 4 freeze/thaw cycles to 0) was Tucson, AZ, where freeze/thaw cycles were reduced from 16 to 3, an 81.3 % decrease. This data set was expanded with the goal of producing a choropleth-type map, correlating region and potential reduction in freeze/thaw cycling.

Although the use of PCM in infrastructure systems to limit the damage caused by freeze/thaw cycling has not been fully developed, the results of this investigation show the promise to increase the durability of infrastructure systems. Though this approach is not appropriate in all locales, decreasing freeze/thaw cycles experienced by a structure by even 28.9 % (the average from the previous investigation [5]) translates into a large savings in the frequency and cost of maintenance.

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