

Increasing the Service Life of Bridge Decks by Incorporating Phase-Change Materials to Reduce Freeze-Thaw Cycles

Aaron R. Sakulich¹ and Dale P. Bentz²

Abstract: During a freezing event, pore solution in cementitious bodies expands and creates stresses that can cause damage; therefore, reducing the number of freeze/thaw cycles experienced by a structure will extend the structure's service life. The incorporation of phase-change materials (PCMs) to reduce the number of freeze/thaw cycles experienced by bridge decks has been investigated by modeling, mechanical testing, calorimetry, and X-ray microtomography. Models identified geographical regions in which freeze/thaw damage is not a significant concern and regions where this technology may be practical, increasing the service life of a bridge deck by at least 1 year. The incorporation of PCM reduces strength by varying amounts and for varying reasons, depending on which PCM is used and how it is introduced into the concrete. Because a variety of methods exist to address this loss in strength, PCM incorporation shows promise as a technique for addressing one aspect of worldwide infrastructure maintenance challenges. DOI: 10.1061/(ASCE)MT.1943-5533.0000381. © 2012 American Society of Civil Engineers.

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Introduction

Although bridge maintenance accounts for approximately 40% of national infrastructure maintenance costs (about U.S. \$10 billion annually), in 2009, the ASCE issued an overall grade of "C", or "mediocre", to the nation's bridges (ASCE 2010; Emmons and Sordyl 2006). That same year, AASHTO listed "age and deterioration" first on a list of the "top five problems for bridges" (AASHTO 2008). Over 150,000 bridges (approximately one in four) are either structurally deficient or functionally obsolete (Federal Highway Administration 2011). At an average price of U.S. \$500/m² (\$50/ft²), replacing the bridge decks of all structurally deficient or functionally obsolete bridges in the United States would cost nearly \$49 billion, although the ASCE estimates that an annual U.S. \$7 billion increase in funding every year would be required to "substantially improve bridge conditions" (Federal Highway Administration 2011; Hong and Hastak 2007; Lopez-Anido 2001). As infrastructure continues to age, the amount of money needed for maintenance is expected to rapidly increase; the average American bridge was constructed in 1966 and expected to last for 50 years (AASHTO 2008). Unless the nation is to face a similar crisis in the future, new technologies that extend the service life of bridge decks are needed.

One of the most important factors affecting the service life of a bridge deck is the corrosion of reinforcing steel (Berg et al. 2006). Exposure to freeze/thaw cycles can accelerate corrosion because solutions in the pores of concrete expand during a freezing event and exert pressures that lead to the creation of cracks. These cracks provide aggressive media, such as deicing salts, easy access to reinforcing steel (Kan et al. 2010). The presence of water in cracks then further increases the amount of deterioration caused by successive freeze/thaw cycles. Although cracking can be caused by a variety of other mechanisms, and a variety of techniques have been developed to prevent or mitigate the effects of cracking, freeze/thaw damage still plays a significant role in limiting bridge deck service life (Berg et al. 2006).

The number of freeze/thaw cycles experienced by a bridge deck can be reduced by incorporating phase change materials (PCMs), materials with high enthalpies of phase-change (ΔH_f^0) (Cabeza et al. 2011; Pasupathy et al. 2008; Schossig et al. 2005). Below a given temperature (T_{MELT}) PCMs solidify, releasing energy and maintaining surrounding temperatures at T_{MELT} . If enough energy can be released in this way (dictated by ΔH_f^0), a freezing event and the associated damage can be prevented (Hunger et al. 2009; Kuznik et al. 2011).

The PCM can easily be introduced into a system by a variety of methods, most commonly as macro/microencapsulated "pellets" (Cabeza et al. 2007; Stoll et al. 1996). These pellets are, essentially, polymer spheres containing PCM and an appropriate amount of empty space to accommodate volumetric changes with temperature. Alternatively, lightweight aggregate (LWA) can be used; LWA is a porous aggregate that can absorb and hold liquids by capillary action (Bentz and Turpin 2007). These aggregates are commonly used for internal curing (supplying additional water to the cement paste so as to encourage more complete hydration) and are graded in such a manner that fine aggregate (i.e., sand) can simply be replaced by similarly-sized LWA during mix design (Bentz and Weiss 2011).

¹Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899 (corresponding author). E-mail: a.sakulich@gmail.com

²Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899. E-mail: dale.bentz@nist.gov

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This study investigates the use of PCM as a means by which to increase bridge deck durability by reducing the number of freeze/thaw cycles. The effects of 12 different PCMs in 237 different locations (simulated on the basis of temperature history) were modeled by using a combination of the CONCTEMP program developed at the National Institute of Standards and Technology (NIST) and a service life prediction model developed for the Indiana DOT (INDOT). Mortars containing PCM were produced to investigate the effects of PCM incorporation on mechanical properties, on the rate of hydration, and to investigate the three-dimensional (3D) microstructure with X-ray microtomography.

Methodology

Experimental

Four mortars were investigated: a control, a mix containing a paraffin wax (PCM6) in LWA, a mix containing a vegetable oil (PT4) in LWA, and a formula containing PT4 encapsulated in polymer. The composition of each formula can be found in Table 1. The cement used was a commercially available ASTM C150 Type II cement. The aggregate was a mixture of four different normal-weight sands that has previously been used in studies involving LWA (Bentz et al. 2006). The LWA used was a commercially available expanded clay corresponding to standard ASTM C330, "Specification for Lightweight Aggregate for Structural Concrete" (2005). The mass ratio of water to cement was fixed at 0.35; the volume fraction of sand was 55%. Tap water was used throughout.

The quantity of LWA used was based on the LWA's previously determined maximum absorption of 26.5% by mass. The LWA was incorporated into the formulas simply by replacing normal-weight sand, ensuring that the gradation of aggregate particle sizes in all mortars was the same. Theoretically, the amount of LWA used could absorb up to 22 g more liquid than the amount of PCM used. Therefore, in the two mixes containing LWA-PCM, an additional 30 g of mix water was used to ensure that the LWA did not dehydrate the system. Although this additional water is likely to have some effect on final properties, the effect of not including the water (thus allowing unsaturated LWA to dehydrate the system) would likely be much greater. The LWA was saturated with PCM by immersion and agitation on a shaker-mixer for 1 h. Whether the LWA can absorb the same amount of PCM as it does water was not investigated at this time. The amount of encapsulated PCM to be used was calculated with the knowledge that each pellet contains the mass ratio of PCM to encapsulation media of 4:1.

Table 1. Mix Compositions. 'Microenc' Refers to the Mortar Containing PCM Encapsulated in a Polymer Pellet

Component	Mass (g)			
	Control	PT4	PCM 6	Microenc
Type II Cement	1,250	1,250	1,250	1,250
Water	437.5	467.5	467.5	437.5
F95 fine sand	659.1	620.9	620.9	659.1
Graded sand (C778)	500.9	432.1	432.1	500.9
20–30 sand (C778)	500.9	355.7	355.7	500.9
S16 coarse sand	975.4	463.4	463.4	975.4
LWA	—	439.2	439.2	—
PCM	—	92.0	92.0	—
Encapsulated PCM	—	—	—	108

Mortar preparation was performed in accordance with ASTM C109 (2007) with two exceptions: first, when used, the PCM (in either LWA-PCM or encapsulated form) was added immediately after the aggregate; and second, the prescribed mixture proportions were not used. Specimens were placed in steel molds in plastic bags, placed in an environmental chamber, removed from the molds after 24 h, and submerged in lime-saturated water in a temperature-controlled cabinet. Compression tests were performed at 3, 7, and 28 days on no fewer than 5 specimens.

Isothermal calorimetry tests, in which the rate of heat release from a hydrating mortar is measured, were carried out to identify the possible retardant effects of PCM. The tests were generally carried out over the course of 7 days, using between 7.4 g and 8.1 g of mortar, depending on mix. The mortar specimens were taken from batches used to make specimens for compression testing, placed in a glass calorimetry specimen vial, sealed, and loaded in the calorimeter.

One cube specimen of each mortar was placed in a sealed plastic bag after failure in the compression test. Compressed samples were used because of logistical constraints and are not expected to greatly affect measured values. The specimen was sawn into three equal sections by using oil as the cutting lubricant, wiped dry, and placed in a plastic bag. The two outer sections of the specimen were used to determine thermal properties using transient plane source (TPS) analysis, which has been described in Gustafsson (1991) and He (2005). A 6.403 mm radius probe (Ni foil encased in Kapton) was sandwiched between two faces of the specimen (to minimize possible artifacts caused during the sawing, the outer surface faces were used in every experiment). Measurements were taken every 45 min after an equilibration time of 45 min. Five measurements of thermal conductivity and volumetric heat capacity were recorded. Measurements were taken at ambient temperatures (either 22 or 23°C) with a power of 0.3 W applied over 10 s. The volumetric heat capacity, provided by the system, was then converted to specific heat capacity (mass basis) by dividing by average density (calculated by weighing and measuring cubes before compression tests). According to the manufacturer, thermal conductivity measurements on homogeneous materials are reproducible within $\pm 2\%$, whereas heat capacity is reproducible within $\pm 7\%$. After the dry measurements were made, sections were placed in a lime-water bath for 7 days. The sections were removed, patted dry, and remeasured, with the entire apparatus placed inside a plastic bag to minimize drying over time.

The middle section of the specimen was further sawn down to produce a small sample for analysis by X-ray microtomography. These tests were performed at a voltage of 100 kV and a tube current of 100 μA , at an output resolution of 4,000 pixels \times 2,096 pixels in the radial plane, a spatial resolution of about 5 $\mu\text{m}/\text{pixel}$, scanned at 0.3° per step, 5 frames averaged, and a full 360° rotation.

Modeling

Bridge deck modeling was performed by using the CONCTEMP program developed at NIST [20]. The model predicts time-of-wetness (caused by both precipitation and condensation), surface temperature, and time-of-freezing for bridge decks on the basis of a one-dimensional (1D) finite difference scheme that includes heat transfer by convection, conduction, and radiation. Radiation considers both solar radiation as a source and radiative cooling to the sky (greater at night) as a sink. A full description of CONCTEMP can be found in (Bentz 2000).

CONCTEMP requires the user to define several variables, including thermal and physical properties of both the concrete and PCM. The values for the concrete (heat capacity, thermal

conductivity, and density) were set at 1,000 J/kg•K, 1.5 W/m•K, and 2,350 kg/m³, respectively. The latter two values are particularly conservative (as seen subsequently). Of the 12 different PCMs investigated, two (PT4 and PCM6) are commercially available products for which ΔH_F^o and T_{MELT} were supplied by the manufacturer. (Certain commercial equipment, instruments, or materials are identified in this report to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the NIST, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.) The ΔH_F^o and T_{MELT} values used for the other 10 PCMs were based on a recent review by Cabeza et al. (2011) (Table 2). When a range was reported for a value in that review, a simple average was used in this study. The 12 PCMs represent a relatively broad range of both ΔH_F^o (153 to 295 J/g) and T_{MELT} (0 to 8°C). The final user-defined variable is the PCM concentration in the concrete, set at 0 kg/m³ (control bridge deck), 50 kg/m³ (expected typical PCM loading), or 120 kg/m³ (estimated maximum possible PCM loading if this specific LWA is used to replace fine aggregate).

Typical Meteorological Year 2 (TMY2) datasets, produced by the Analytic Studies Division of the National Renewable Energy Laboratory (Marion and Urban 1995), provided the program with data relating to weather factors. The TMY2 data sets are hourly values of various weather factors that would be experienced over a typical year for a given location, determined statistically from weather recorded between 1961 and 1990 and provided time, ambient and dewpoint temperatures, relative humidity, wind speed, precipitation levels, incident global horizontal solar radiation, and percentage of cloud cover. Across 46 states, 4 commonwealths, and the unincorporated organized territories of Guam and the Commonwealth of Puerto Rico 237 locations were investigated.

To estimate bridge deck service life, a model developed by Barde et al. for the INDOT was used, which is briefly reviewed in this paper and detailed in Barde et al. (2009). This model considers two factors: LIFE_{INITIAL}, the length of time required for a bridge deck to reach a critical saturation (after which damage will begin to accumulate), and LIFE_{SECONDARY}, the length of time required for a bridge deck to reach a user-defined level of damage.

Table 2. PCMs Investigated

PCM	Code	T_{MELT} (°C)	ΔH (J/g)	Locations where effective at $D_S = 0.6$, #
H ₂ O + polyacrylamide	HPAA	0	295	32
91.67% tetradecane +8.33% hexadecane	T/H	1.7	156	29
Tetradecane + docosane	TD	3.55	234	47
Paraffin C14	P2	4	153	35
<i>Proprietary vegetable oil</i>	PT4	4	195	41
Tetradecane + geneicosane	TG	4.55	200	39
Tetrahydrofuran	THF	5	280	48
paraffin C14	P1	5.5	228	40
<i>Proprietary, paraffin</i>	PCM6	6	162	33
n-Tetradecane	nT	6	230	39
Formic acid	FA	7.8	247	29
Hydrated lithium chlorate	HLC	8	253	28

Note: Italics indicate commercially available products used in mechanical characterization experiments. All others use data reported in Cabeza et al. (2011).

The LIFE_{INITIAL} is influenced by the nick-point time, which represents the time at which the sorptivity of the concrete changes from initial sorptivity to secondary sorptivity (Martys and Ferraris 1997). During initial sorptivity, only capillary and gel pores fill with solution. The volumetric expansion of this solution as it freezes can be accommodated by the air void system; thus, no damage occurs during freeze/thaw cycling. During secondary sorptivity, the air void system itself begins to fill with solution, can no longer accommodate the volumetric expansion of solution during freezing, and damage will occur during a freeze/thaw cycle. The LIFE_{INITIAL} is, essentially, the amount of time it will take for the air void system to fill with solution, divided by the amount of time that the air void system spends filling each year. In very dry areas, there will be few wetting events lasting longer than nick-point time, the air void system will take a long time to fill, and LIFE_{INITIAL} will be relatively high.

The LIFE_{INITIAL} is approximated by using the time required to reach a critical saturation value (t_w , in h) and the cumulative length of wetness events lasting longer than the nick-point time ($T_{w/nickpt}$, in h/year) (Martys and Ferraris 1997)

$$LIFE_{INITIAL} = \frac{t_w}{T_{w/nickpt}} = \frac{\left(\frac{S_{CR}-S_b}{e}\right)^2}{T_{w/nickpt}} \quad (1)$$

The time required to reach a critical saturation value, t_w , is a function of critical saturation level and the saturation at the nick-point time (S_{CR} and S_b , respectively, in %) and a factor e , which is a function of the volumes of entrained air and porosity (V_{AIR} and V_p , respectively, in %), bridge deck depth (D , in mm), and the secondary sorptivity (R_s , in mm/s^{0.5})

$$e = \frac{R_s}{(V_p + V_{AIR})D} \quad (2)$$

Saturation at the nick-point time (S_b , in %) is calculated by using an additional fitting factor (b , 5.5 mm), an initial saturation value ($S_{INITIAL}$, in %), an initial sorptivity value (R_i , in mm/s^{0.5}), and the nick-point time [t_{npt} , 21,600 s (i.e., 6 h)]

$$S_b = S_{INITIAL} + \frac{R_i \sqrt{t_{npt}} + b}{(V_p + V_{AIR})D} \quad (3)$$

The $S_{INITIAL}$ can be estimated for concrete in a given location on the basis of absorption isotherms and the relative humidity (RH) immediately preceding a wetting event. The RH is supplied in the TMY2 data sets. Because the 237 locations investigated here have approximately similar values of RH before a wetting event ($84 \pm 6.6\%$) and because a range of absorption isotherms have been published, a single estimated value for $S_{INITIAL}$ of 0.56 was used for all locations, rather than reestimating initial saturation at each location. The method used to estimate $S_{INITIAL}$ and the absorption isotherms can be found in Barde et al. (2009). As recommended, the nick-point time was set at 6 h; because the TMY2 datasets do not report fractions, the cumulative length of wetting events longer than the nick-point time per year was calculated including wetting events that lasted exactly 6 h, rather than more than 6 h.

The second factor in service life, LIFE_{SECONDARY}, is a measure of the length of time required for the properties of the concrete (e.g., compressive/flexural/tensile strength and resonant frequency) to fall to a user-defined damage level (D_S , in %)

$$LIFE_{SECONDARY} = \left(\frac{D_S}{A\Delta S}\right) \frac{1}{n} \quad (4)$$

where A = unitless fitting factor; ΔS = change in sorptivity from initial to secondary sorptivity; and n = number of annual freeze/thaw cycles experienced by the structure in a typical year (provided by the TMY2 data sets).

Total service life is simply the sum of $LIFE_{INITIAL}$ and $LIFE_{SECONDARY}$

$$TOTAL\ SERVICE\ LIFE = \left[\frac{(S_{CR} - S_B)^2}{T_{w/nickpt}} \right] + \left(\frac{D_S}{A\Delta S} \right) \frac{1}{n} \quad (5)$$

The user-defined values used here (Table 3) are generally the same as those selected by Barde et al. (2009).

Results and Discussion

Four mortars were produced for physical and thermal characterization: a control formula and formulas containing PT4 in LWA, PCM6 in LWA, or microencapsulated PT4. If the incorporation of PCM has a significant effect on physical properties, such as strength, heat evolution, and thermal conductivity, the system will not be viable, regardless of the modeling results.

Compressive Strength

When compared to the control mortar, the three mortars containing PCM attained lower compressive strengths at all ages (Fig. 1). After 3 days, the control mortar reached a compressive strength of (49.1 ± 1.9) MPa [(7116 ± 281) psi]; the incorporation of PT4 in LWA, PCM6 in LWA, and microencapsulated PT4 reduced compressive strength by 38, 18, and 15%, respectively. At 7 days, the control mortar reached a compressive strength of (55.8 ± 1.7) MPa [(8093 ± 241) psi], and the three encapsulation methods reduced strength 39, 16, and 20 %, respectively. Finally, at 28 days, the control mortar reached a compressive strength of (60.3 ± 3.1) MPa [(8754 ± 462) psi], and was reduced by 29, and 18%, by the three encapsulation methods, respectively.

In the mortar containing encapsulated PT4, the lower compressive strength observed is likely caused by mechanical reasons because the capsules are relatively weak and encourage the nucleation of cracks. This effect will likely be a function of the size of the PCM capsules employed, and it is unlikely that the current product

Table 3. Variables Selected for Use in CONCTEMP and the INDOT Service Life Model

Variable	Symbol	Units	Value
Concrete heat capacity	C	J/(kg•K)	1,000
Concrete thermal conductivity	k_{cond}	W/(m•K)	1.5, 3
Concrete density	ρ	kg/m ³	2,350
PCM density in concrete	ρ_{PCM}	kg/m ³	0, 50, 120
Critical saturation	S_{CR}	%	0.85
Initial saturation	$S_{INITIAL}$	%	0.56
Initial sorptivity	R_i	mm/s ^{0.5}	0.002
Secondary sorptivity	R_s	mm/s ^{0.5}	0.001
Porosity	V_P	%	8
Entrained air	V_{AIR}	%	6.5
Fitting factor B	b	mm	5.5
Nick-point time	t_{nickpt}	s	21,600
Deck depth	D	mm	200
Damage level	D_S	%	0.6
Fitting factor A	A	—	12
Change in sorptivity	ΔS	mm/s ^{0.5}	0.0001

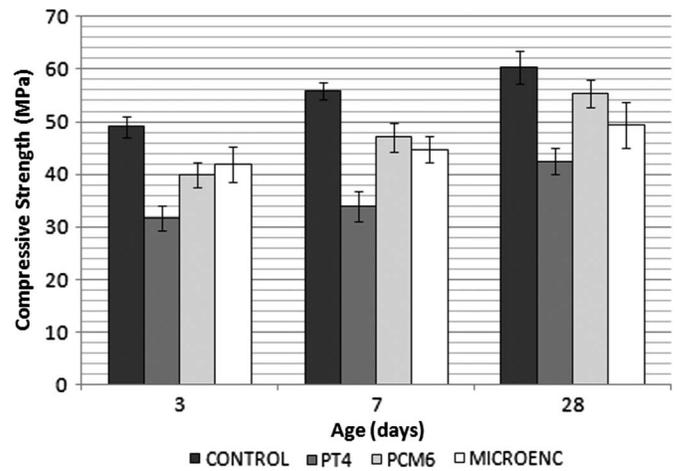


Fig. 1. The 3, 7, and 28 day strengths of (from darkest to lightest) a control mortar and mortars containing PT4 in LWA, PCM6 in LWA, and encapsulated PT4; error bars represent one standard deviation

was optimized for such utilization in mortars and concretes. For the two mortars containing PCM in LWA, the reduced compressive strengths are likely caused by a combination of several of the following factors:

- If the LWA exchanges PCM with water from the cementitious matrix, it may dehydrate the system, resulting in a lower degree of hydration;
- If the LWA releases PCM into the cementitious matrix, the PCM could act as a retardant by coating cement particles, hampering the transport of water into those particles, and thus, reducing the rate and degree of hydration; and
- The LWA is simply a weaker aggregate than sand, partially caused by the fact that LWA is rather porous.

It is possible that simply adding an additional dose of LWA soaked in water, to act as internal curing agent, will counteract system dehydration. The only way to counteract the retardant effects of PCM is to ensure that either (1) the LWA does not release any of the PCM, or (2) a PCM is used that does not have a retardant effect on cement hydration. The effects of LWA as a weaker aggregate can only be addressed by either finding a different LWA or a different incorporation method. What portion of the reduction in strength is caused by which mechanism is not entirely clear, however, and requires further study. Strength reductions of 20% or less might be offset by a reduction in the water to cement ratio, for example.

Isothermal Calorimetry

In light of the strength results, isothermal calorimetry was used to quantify heat evolution, which is directly related to hydration reactions in cement. The two mortars containing LWA-PCM and the control mortar were investigated; the more heterogeneous nature of the encapsulated PCM made analysis difficult.

The results indicate that the lowered compressive strengths are caused by two distinct mechanisms (Fig. 2). The heat evolution curves of the control and the formula containing PCM6 are almost identical; this indicates that hydration was not retarded or reduced by the presence of PCM6, either because the LWA does not release PCM or, if released, the PCM does not act as a retardant. The reduced strength, therefore, is likely caused by a purely mechanical reason, that is, the weakness of the LWA as an aggregate. This conclusion is supported by the observation that, at any age, the strength of the formula containing PCM6 is similar to the strength of the formula containing microencapsulated PT4, in which the reduced

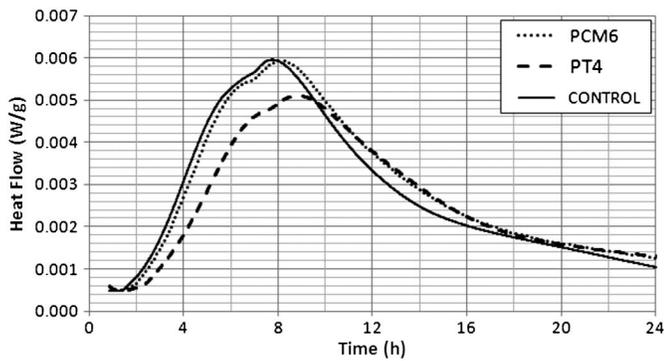


Fig. 2. Heat evolution with time, as determined by isothermal calorimetry; two replicates were tested per mortar and showed minimal variation; one curve is shown; after 24 h, curves equilibrate and are indistinguishable

strength is clearly an effect of adding the relatively weak polymer pellets. The slightly higher heat release in the PCM6 formula, when compared to the control, may be caused by internal curing effects caused by the small amount (30 g or 6% of the total water) of additional water included to ensure LWA saturation.

The heat evolution curve of the mortar containing PT4 is quite distinct from that of the control mortar. Heat evolution is not only delayed, but the maximum heat flow is reduced. This indicates that the incorporation of PT4 is having a significant effect on hydration because the PCM is acting as a retardant, the LWA is dehydrating

Table 4. Thermal Conductivity (k) and Specific Heat by Mass (C_m) of Mortars in Dry and Wet Conditions

Mix	State	k_{cond} (W/m \cdot K)	C_m (J/g \cdot K)
Control	Dry	2.67 ± 0.041	0.62 ± 0.049
	Wet	2.94 ± 0.054	0.74 ± 0.032
PCM6	Dry	1.63 ± 0.005	0.47 ± 0.004
	Wet	2.01 ± 0.053	0.76 ± 0.141
PT4	Dry	1.37 ± 0.008	0.63 ± 0.009
	Wet	1.78 ± 0.018	0.8 ± 0.059
PT4-ENC	Dry	2.47 ± 0.145	0.87 ± 0.106
	Wet	2.68 ± 0.034	1.01 ± 0.056

Note: Uncertainty represents the measured standard deviation.

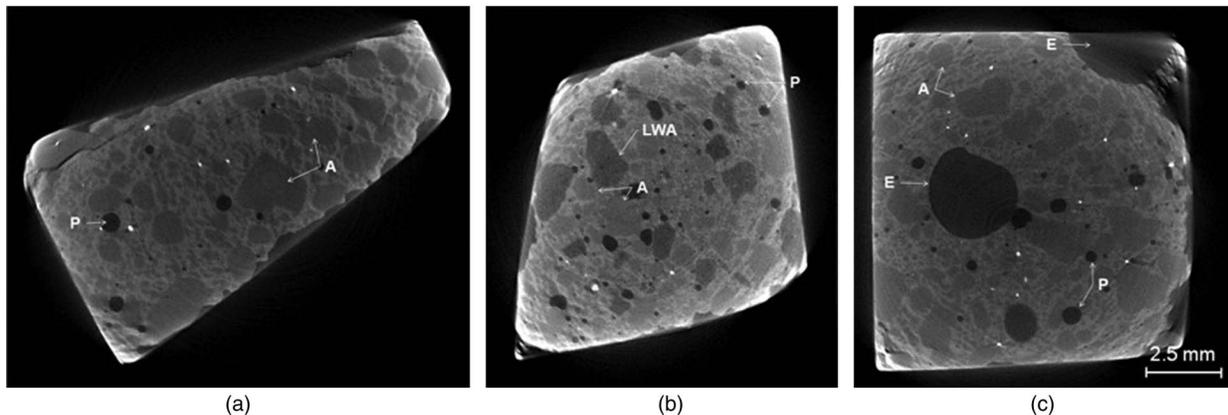


Fig. 3. Microtomographs of investigated mortars: (a) control mortar without PCM, in which quartz aggregate (A) and pores/air voids (P) are easily visible; (b) mortar containing LWA-PCM, which appears similar to quartz aggregate but darker because of its lower density; and (c) mortar containing encapsulated PCM pellets (E)

the system, or the PT4 may be encouraging the production of reaction products that produce less heat. It is likely that the first two mechanisms are occurring because the first encourages the second. The third mechanism is possible but has not been investigated in this paper.

Thermal Conductivity and Heat Capacity

Stoll et al. (1996) reported that the incorporation of PCM in concretes lowered the thermal conductivity of the system, negatively affecting overall performance by reducing heat transfer from the core to the surface and from solar energy to the core to 'recharge' the PCM. Reduced thermal conductivity was identified as a possible substantial, practical hurdle.

In dry conditions, the mortars incorporating PT4 in LWA, PCM6 in LWA, and encapsulated PT4 had thermal conductivities of 51, 61, and 93%, respectively, of that of the control mortar (2.67 ± 0.041) W/m \cdot K, Table 4. The presence of water in saturated surface dry conditions, which are more representative of the conditions under which freeze/thaw damage will occur, increased the thermal conductivity of all mixes by approximately 0.3 W/m \cdot K (i.e., 10%), but the same general trend was evident: the thermal conductivities of PT4 in LWA, PCM6 in LWA, and encapsulated PT4 were 61, 69, and 92%, respectively, of the control mix (2.935 ± 0.739) W/m \cdot K.

Specific heat, which was simultaneously measured, showed no apparent trend; the three mortars, respectively, had specific heats that were 101, 75, and 140% that of the control mortar in dry conditions. When saturated, the three respective mortars had specific heats of 107, 103, and 136% that of the control mix, suggesting a higher specific heat for the encapsulated PCM itself.

X-Ray Microtomography

Several phases were easily discernible in X-ray microtomographs, including (in order of increasing density and thus, brightness): pores, encapsulated PCM pellets, LWA, quartz aggregate, and cement paste matrix (Fig. 3). The pores and encapsulated PCM have similar brightness but can be distinguished by size. The diameter of an encapsulated PCM pellet is on the order of 3 mm, whereas the largest pores identified were well below the millimeter scale. The LWA and quartz aggregate were generally similar in size and shape, although the size distribution of the LWA tends toward slightly larger particles. The LWA is also substantially darker in X-ray microtomographs. Unfortunately, the densities of dry LWA, LWA with absorbed PCM, and LWA with absorbed water are similar enough

that the three cannot be easily differentiated on the basis of brightness (assuming that all three phases were present in the sample). X-ray microtomography has, however, been previously used to identify the movement of water from LWA to the cement paste (Bentz et al. 2006); because the LWA and the quartz aggregate are distinct from each other, this technique may be useful in future studies of the rate at which LWA releases PCM.

Modeling: Determination of Practical Locations

In general, the 237 locations investigated can be split into two groups: locations where freeze/thaw damage significantly affects the service life of a bridge deck, and locations where it does not. Freeze/thaw damage may not significantly affect the service life of a bridge deck either because the area is too dry (i.e., $LIFE_{INITIAL}$ is relatively high) or because the area is too warm (i.e., $LIFE_{SECONDARY}$ is relatively high). Locations in which freeze/thaw damage does have a significant effect on service life can be further broken into two categories: locations where the incorporation of PCM is likely to be practical, and those where it is not (Fig. 4).

Lopez-Anido (2001), in a survey of data from various DOTs, found that bridge decks in “moderate climate regions,” “in which the main deterioration mechanism is unrelated to freeze/thaw damage, require initial maintenance after an average of 20 years. This value was chosen as an upper limit; if either $LIFE_{INITIAL}$ or $LIFE_{SECONDARY}$ are greater than 20 years, reducing freeze/thaw cycles through the incorporation of PCMs is not necessary because freeze/thaw damage is not likely to be a predominant deterioration mechanism. A total of 41 locations receive so little precipitation that $LIFE_{INITIAL}$ was calculated to be greater than 20 years [Fig. 5(a)]. These locations are predominantly in the Mountain West states stretching from North Dakota to Arizona. Further, 21 locations experienced so few freezing events that $LIFE_{SECONDARY}$ was calculated to be greater than 20 years [Fig. 5(a)]; these are generally limited to points along the gulf coast, California, and all points in Hawaii, Guam, and Puerto Rico.

Although incorporation of PCM should increase the service life of a bridge deck in the remaining 175 locations, the increase in service life is not necessarily significant. Selection of 1 year

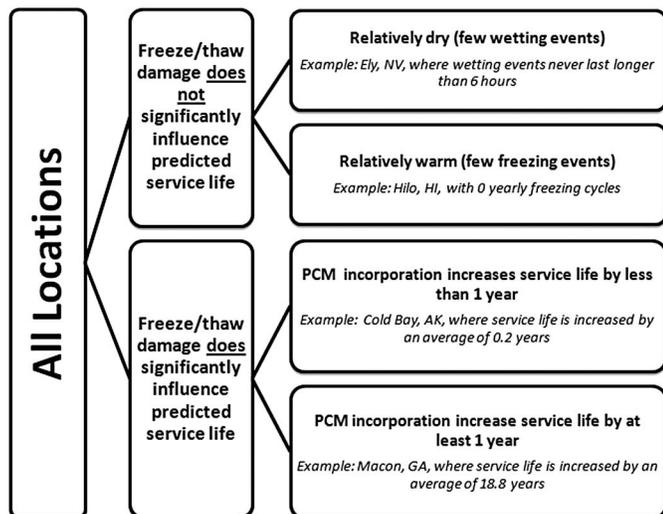


Fig. 4. Breakdown of all locations into two groups and four subgroups, on the basis of the effect of freeze/thaw damage and the effect of PCM incorporation

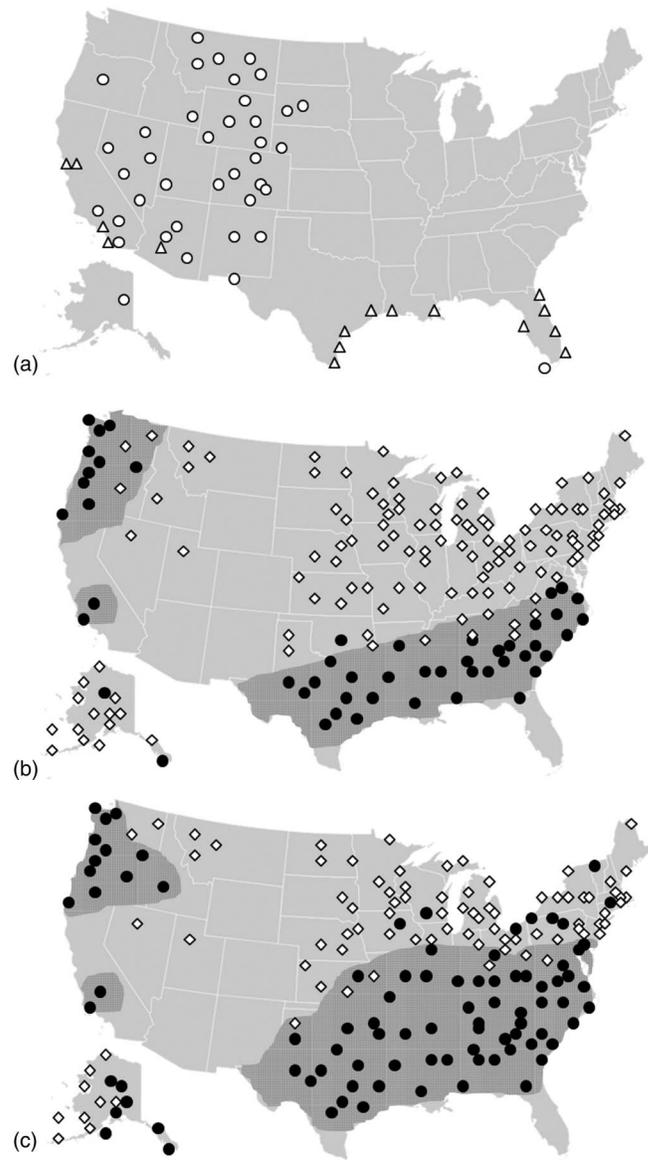


Fig. 5. (a) Locations in which freeze/thaw damage does not limit bridge deck service life because either $LIFE_{INITIAL}$ (○) or $LIFE_{SECONDARY}$ (△) is greater than 20 years; not shown: all points in Hawaii, Guam, and Puerto Rico; (b) locations in which incorporation of 50 kg/m³ of PCM increases bridge deck service life by less than 1 year (◇) or more than 1 year (●); and (c) locations in which incorporation of the maximum 120 kg/m³ of PCM increases bridge deck service life by less than 1 year (◇) or more than 1 year (●); shaded areas indicate a rough estimate of the regions in which PCM incorporation is practical for extending bridge deck service lives

was used to separate significant and insignificant increases, partially because construction is a seasonal activity; extending a bridge deck service life by a few months, or necessitating replacement in winter instead of summer, is not practical. In 125 of the remaining locations (generally in Alaska, the Midwest, and New England) none of the 12 PCMs investigated were able to increase service life by at least 1 year at a PCM loading of 50 kg/m³ [Fig. 5(b)].

The final 50 locations meet two criteria: freeze/thaw cycles are likely to significantly influence the lifespan of a bridge deck, and at least one of the 12 PCMs investigated increased the estimated

service life of a bridge deck by at least 1 year at a PCM loading of 50 kg/m³. These 50 [Fig. 5(b)] locations are found in a band across the southeast (south of the line Richmond-Knoxville-Oklahoma City but north of the line Tallahassee-Mobile-San Antonio) and along the northwest coast (west of the line Fresno-Eugene-Seattle).

Although 50 kg/m³ (approximately 2% by mass) is a feasible, conservative estimate, on the basis of the absorptive properties and particle size gradation of the LWA used here, approximately 120 kg/m³ is the maximum amount of PCM that could be incorporated by simply substituting the LWA used here for regular aggregate. When CONCTEMP was run using this maximum concentration, an additional 41 locations were identified in which service life would be increased by at least 1 year [Fig. 5(c)]. The minority of these locations are in Alaska and the Pacific Northwest, whereas the majority are north of the previously identified band across the southeast. At a PCM density of 120 kg/m³, the northern limit of this band runs along the general line of Baltimore-Lexington-Topeka.

Modeling: Effects of Material Properties

The effects of ΔH_f^o , melting temperature, and thermal conductivity are closely related. The ΔH dictates how much energy is available to be transferred from the PCM to the bridge deck; melting temperature determines the temperature at which the bridge deck will be maintained as the ambient temperature drops; and thermal conductivity determines how the bridge deck will react once the energy available from the PCM has been expended.

A larger ΔH_f^o is always more effective at preventing freeze/thaw cycling because it represents a larger amount of energy that can be used to keep the bridge deck at T_{MELT} . For example, P2 and PT4 both have a melting temperature of 4°C, but have different values of ΔH_f^o : 153 and 195 J/g, respectively. (By convention, ΔH is positive for exothermic reactions, such as fusion, and negative for endothermic reactions, such as melting, although both reactions will occur at T_{MELT} . The values discussed in this paper refer specifically to ΔH_{FUSION} . P2 increases service life by at least 1 year in 35 locations, whereas PT4 increases service life by at least 1 year in 41 locations.

An optimal range for T_{MELT} exists between approximately 3.55 and 6°C. For example, although HLC has the third highest ΔH_f^o , it increased service life by at least 1 year in only 28 locations, the fewest of any of the PCMs investigated, because it has a very high T_{MELT} (8°C). At the other end of the scale, despite having the highest ΔH_f^o (295 J/g) of any PCM, HPAAs increases service life by at least 1 year in only 32 locations, because of its very low T_{MELT} of 0°C.

This optimum range of T_{MELT} exists because of the way in which bodies are cooled, which depends heavily on the system's thermal conductivity. The models show that increasing the thermal conductivity of the composite from 1.5 to 3 W/m•K will result in improved performance (i.e., fewer freeze/thaw cycles) only if the phase transition temperature of the PCM is within the optimal range (Table 5). Outside the optimal range of T_{MELT} , increasing the thermal conductivity will actually increase the number of freeze/thaw cycles that the bridge deck experiences.

Cooling of a hot body (i.e., a bridge deck whose temperature is maintained at T_{MELT} as the ambient temperature drops) will occur primarily because of either convection or conduction. These are similar phenomena whose rates of cooling depend on surface area, a coefficient (either h_{conv} , the convection heat transfer coefficient, or k_{cond} , the thermal conductivity), and a thermal differential (Cengel and Boles 2002). A greater thermal differential leads to more rapid cooling; a greater thermal conductivity leads to a more rapid transfer of heat from the interior of the body to the surface and even cooling. In systems in which the PCM has a high T_{MELT} , the

Table 5. Number of Locations in Which the Service Life of Bridge is Predicted to be Increased by at Least 1 Year with the Inclusion of PCM with Total Composite Thermal Conductivity (k_{conc}) of 3 or 1.5W/m•K

PCM (Code)	T_{MELT} (°C)	Locations effective, #		Difference
		3W/m•K	1.5W/m•K	
<i>HP AA</i>	0	29	30	-1
<i>T/H</i>	1.7	45	27	18
<i>TD</i>	3.55	64	45	19
<i>P2</i>	4	41	33	8
<i>PT4</i>	4	49	39	10
<i>TG</i>	4.55	43	37	6
<i>THF</i>	5	54	46	8
<i>P1</i>	5.5	37	38	-1
<i>nT</i>	6	32	37	-5
<i>PCM6</i>	6.1	28	31	-3
<i>FA</i>	7.8	25	27	-2
<i>HLC</i>	8	24	26	-2

Note: Table is sorted by increasing T_{MELT} ; locations where increased thermal conductivity decreases the number of effective locations are shown in italics.

thermal differential is relatively high when the energy from the PCM is expended, leading to rapid cooling. If the thermal conductivity is high, heat from the interior of the body will be rapidly drawn to the surface and dissipated into the environment, meaning that the entire body will cool rapidly (and likely undergo a freeze/thaw cycle). If the thermal conductivity is low, heat cannot flow from the interior to the surface as easily, so although the surface may rapidly cool, the interior of the body will be maintained at a higher temperature and remain undamaged. For bodies incorporating a PCM that has a T_{MELT} in the optimal range, the temperature differential is not as great and cooling is, thus, much slower. A higher thermal conductivity will encourage an even temperature distribution, preventing freezing at the surface. This explanation assumes that the ambient temperature has fallen to, or close to, its minimum temperature before the thermal energy of the PCM is expended. In situations where both PCMs have a relatively high T_{MELT} , or the freezing cycle has a very low minimum temperature, the thermal differential will likely be the similar for both PCM systems, and they will behave accordingly.

The concern that reduced thermal conductivity caused by PCM incorporation may negatively affect the composite's effectiveness depends, therefore, on the specific properties of the PCM selected. To refine PCM-concrete composites into practical systems for real-world applications, increasing the thermal conductivity of the

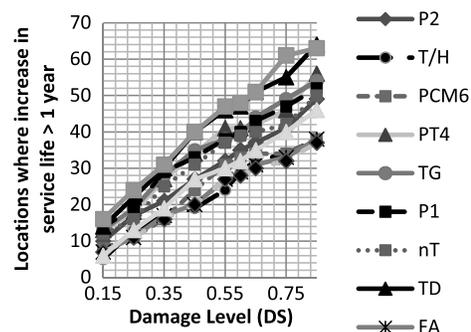


Fig. 6. Number of locations where the incorporation of 2% PCM increases the service life of a bridge deck by at least 1 year; in the key, PCMs are listed in order of ascending ΔH

composite (or, for that matter, reducing it if a PCM with a suboptimal T_{MELT} is used) is likely to be an important area of inquiry.

Modeling: Effects of Weather

Freezing events can vary in how long the event lasts (length) and the minimum temperature reached during the event (depth). The longer the freezing event, the less likely that PCM will be able to keep the temperature of the bridge deck above freezing; the supply of energy from the phase change is not infinite. Deeper freezing events have a similar effect by increasing the temperature differential between the bridge deck and the environment, leading to more rapid cooling once that energy is expended.

In the 25 locations with the shortest freezing events, at least 11 of the PCMs increased service life by an average of 4.8 years. In the 25 locations with the longest freezing events, only 8 of the PCMs increased service life by an average of 1.2 years. The depth of freezing cycles has a less pronounced effect; in the 25 locations with the deepest freezing cycles, an average of approximately 8 of the PCMs increased service life by at least 1 year; in the 25 locations with the least deep freezing cycles, an average of approximately 11 of the PCMs increase service life by at least 1 year.

Modeling: Effects of User-Defined Damage Level

In the INDOT model, a bridge deck is considered to have reached the end of its service life when some quantifiable property falls below a user-defined damage level (D_S). Barde et al. (2009) performed calculations by using $D_S = 0.6$; however, the ideal value of D_S may vary from location to location. Bridge deck service life was therefore calculated by using damage levels ranging from $D_S = 0.15$ (least damage) to $D_S = 0.85$ (most damage) for the 175 locations in which freeze/thaw has a significant effect on service life (Fig. 6). Clearly, allowing more damage to occur before replacing the bridge deck will increase the service life of that bridge deck; as D_S increases, the number of locations in which at least one PCM would prove practical increased in a roughly linear fashion. At $D_S = 0.15$, service life was increased by at least 1 year in an average of 10 ± 4 locations; at $D_S = 0.85$, the average was 48 ± 9 locations. As such, minor variations in the allowed D_S are not likely to have a significant effect on the practicality of the PCM/concrete system.

Conclusions

New technologies that increase infrastructure service life are needed to successfully address the maintenance challenges that the world currently faces. These results show that incorporation of PCM in bridge decks is one such technology that could increase the service lives of bridge decks used by a significant portion of the American population. The effects of PCM incorporation on early age properties, such as strength, will need to be addressed before this technology can be considered truly practical.

Freeze/thaw damage is not a predominant deterioration mechanism in all locations, either because they are too dry or too warm. In the remaining locations, PCM may improve service life by significant amounts in two general areas: the Pacific Northwest and across the southeast. These regions encompass several major metropolitan areas, including Portland, Seattle, Houston, and Atlanta, which alone have a combined population of 3.5 million people. A number of generalizations can be made regarding the use of PCM in bridge decks

- Incorporation of PCM will reduce compressive strength unless preventative measures are taken, either because of the weakness of the incorporation method (e.g., LWA) or retarding behavior displayed by the PCM;

- Increasing ΔH_F of the PCM or the level of damage that the structure can tolerate, selecting a PCM with a T_{MELT} within the optimal range, and decreasing the length and/or depth of freezing events will all increase effectiveness (i.e., reduce freeze/thaw cycling);
- Increasing the thermal conductivity of the composite will increase effectiveness only if the T_{MELT} of the PCM is within the optimal range; outside the optimal range, increasing thermal conductivity will actually lower effectiveness; and
- For PCM incorporation to be proven practical, more work is needed, especially in preventing mechanical property reduction, optimizing composite thermal conductivity, refining the system composition, understanding long-term behavior, and investigating PCM use in real-world multilayered deck systems.

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