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Comprehensive Assessment of PCM-Integrated Cool Concrete Sidewalks: Thermal, Mechanical, and Field Performance

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Abstract:

Urban Heat Island (UHI) conditions intensify urban warming, increasing cooling energy demand and reducing outdoor comfort. This study evaluates microencapsulated organic paraffin phase change material (PCM, MPCM28D) as a sand-replacement additive in rigid concrete pavement for sidewalk applications as a scalable UHI mitigation strategy. Thermal characterization confirmed the material's latent heat storage capacity, while compressive strength tests assessed mechanical performance relative to Texas Department of Transportation (TxDOT) sidewalk concrete requirements. Indoor testing under an 8-hour heating-cooling cycle produced surface temperature reductions of up to 2–4 °C for the 10% PCM mixture, and similar trends were observed in 8-hour outdoor exposure tests, with a maximum reduction of 4 °C. A Six-month sidewalk pilot with one control slab and five cooling treatments ; 5% PCM, reflective finishes, and hybrid configurations, showed the best cooling performance in slabs incorporating 2.5% PCM with diamond grinding or sandblasting. These hybrid treatments provided the most stable temperature reductions, as measured by the Monthly Cooling Benefit Index (MCBI). Overall, the results confirm that sand-replacement PCM combined with surface enhancement is a viable approach for improving the thermal performance of urban concrete pavements.

Background

Urban areas commonly experience higher air and surface temperatures than nearby rural regions because built materials and human activities modify the local surface energy balance, producing the Urban Heat Island (UHI) effect (Oke, 1982, 1988; Arnfield, 2003). Concrete pavements are important contributors to this phenomenon because their high thermal mass, relatively low albedo, and limited evaporative capacity allow them to absorb and retain substantial solar energy, increasing sensible heat release to the surrounding environment (Grimmond and Oke, 1999; Fortuniak, 2008; Qin and Hiller, 2014). Since pavements can cover 20–40% of urban surfaces, cool pavement technologies have been widely explored as a UHI mitigation strategy, including reflective, evaporative, and heat-harnessing systems (Akbari and Rose, 2001; Akbari et al., 1999; Akbari, 2003). More recently, phase change materials (PCMs) have attracted attention as thermal modifiers in cementitious materials because they can absorb and release heat during phase transition, thereby reducing temperature fluctuations and improving thermal regulation (Cabeza et al., 2011; Sarı et al., 2009). Previous studies have incorporated PCMs into concrete through microencapsulation, lightweight aggregate impregnation, and other containment methods, with reported benefits such as reduced peak temperatures, delayed heat buildup, and mitigation of thermal cracking and freeze–thaw damage (Wei et al., 2017; Lin et al., 2005; Bentz and Turpin, 2007). However, pavement-related PCM research has mainly focused on anti-icing and snow-melting applications (Farnam et al., 2017; Hunger et al., 2009; Ramakrishnan et al., 2017; Jayalath et al., 2016), while their use in rigid concrete sidewalks for UHI mitigation remains limited. This study investigates microencapsulated organic paraffin PCM as a sand replacement in concrete sidewalk mixtures to evaluate its potential as a practical cooling strategy for urban pavements.

Methodology

The research approach focused on incorporating microencapsulated organic paraffin PCM (MPCM28D) into rigid concrete pavement, with sidewalks selected as the primary application for (UHI) mitigation. **Figure 1** shows the PCM is embedded in the concrete in powder form and functions by undergoing a solid–liquid phase transition within a narrow temperature range, absorbing heat as latent energy during heating and releasing it during cooling, thereby helping moderate pavement temperature fluctuations. The PCM supplied as a white, free-flowing dry powder in sealed containers. This material is microencapsulated within polymer shells, which prevent leakage during phase transition and improve handling, stability, durability, and compatibility with cement-based mixtures. It has a nominal melting temperature of 28 °C, a latent heat capacity of about 175 J/g, a particle size of 15–30 µm, and a high solidscontent of 97%, which supports uniform distribution in the concrete without affecting the water content.

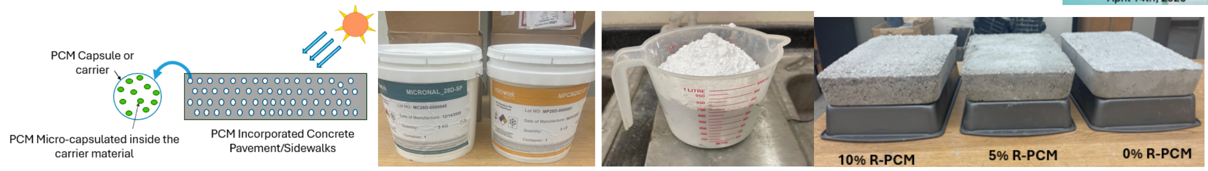


Figure 1: Research Methodology; PCM Powder Form; Three Conc-PCM slabs

Experimentation

For the thermal testing program, three concrete mixtures were produced with PCM replacement levels of 0%, 5%, and 10% by weight of the fine aggregate. The control sidewalk mixture was originally proportioned to satisfy Texas Department of Transportation (TxDOT) specifications for sidewalk concrete.

Indoor, Outdoor, and Material Properties Experimentation

For the sand-replacement program, slabs containing 0%, 5%, and 10% PCM were tested indoors under an 8-hour cycle of 4 hours of heating followed by 4 hours of cooling after the lamps were turned off. Only one slab was placed under each lamp stand to avoid shading and cross-heating, and the controlled chamber with a fixed lamp arrangement ensured comparable radiative and convective boundary conditions for all mixtures, allowing direct comparison of peak temperature, time to peak, and cooling response. Outdoor testing followed the same pavement-based concept, with the 0%, 5%, and 10% PCM slabs placed side by side and exposed to natural solar radiation and ambient weather from 1:00 p.m. to 9:00 p.m., covering peak daytime heating and evening cooling. The slabs were supported on wooden strips to minimize conductive heat transfer from the ground so that solar radiation and convection remained the dominant heat-transfer mechanisms (**Figure 3**). In addition to temperature monitoring, the thermal properties of the concrete–PCM mixtures were measured by determining apparent heat capacity with a Netzsch 404F1 Pegasus DSC, thermal diffusivity with a Netzsch 467HT LFA system, and density with an Anton Paar Ultrapyc 3000 helium pycnometer; these results were used to quantify the PCM effect (**Figure 3**). Mechanical testing was also performed to confirm that the PCM sand-replacement mixtures satisfy TxDOT-type sidewalk concrete requirements. Cylinders measuring 4 in. × 8 in. were cast from the control, 5% PCM, and 10% PCM mixtures, with three replicates per mixture. The cylinders were cured in lime-saturated water following ASTM C39/C39M-23 before compressive strength was measured and compared with TxDOT expectations (**Figure 3**). To assess field performance, a full-scale sidewalk pilot was constructed on the UTSA campus using six adjacent 4 ft × 4 ft segments, each 3 in. thick, over the same base and subbase, including a control, 5% PCM, sand-blasted concrete, 2.5% PCM with sandblasting, diamond-ground concrete, and 2.5% PCM with diamond grinding (**Figure 3**). Because each segment produced continuous 24-hour temperature records over multiple weeks and months, a **Monthly Cooling Benefit Index (MCBI)** was defined as the difference between the control mean surface temperature and the corresponding segment mean surface temperature during the critical afternoon period, so that a positive value indicates cooler performance than the control, zero indicates similar behavior, and a negative value indicates a warmer response.

Figure 3: Indoor, Outdoor, and Field Experimentation

Results And Discussion

The 8-hour slab tests confirmed that PCM incorporation by sand replacement modifies the thermal response of concrete, although the magnitude of cooling depends strongly on the loading regime. Under indoor heating–cooling conditions, the control slab reached the highest temperatures, while the 5% PCM mixture produced only a small reduction in peak temperature and the 10% PCM mixture provided the greatest benefit, lowering the peak by about 2 °C and slightly delaying the time to peak (**Figure 8**). During cooling, the PCM slabs retained heat longer than the control, especially at 10% PCM, indicating release of stored latent heat and a smoother thermal response. Under outdoor exposure, the PCM effect became more pronounced: the 5% mixture reduced peak temperature by about 1.5–2 °C, while the 10% mixture achieved a maximum reduction of about 4 °C relative to the control (**Figure 4**). This indicates that PCM performs more effectively under diurnal outdoor conditions, where the pavement temperature repeatedly passes through the PCM melting range rather than remaining under sustained high heating. The material-property results explain this behavior. As shown in **Figure 5a**, the 5% and 10% PCM mixtures exhibited a clear increase in apparent specific heat capacity near the PCM melting range, reflecting latent heat absorption during phase transition. At the same time, thermal conductivity and thermal diffusivity decreased with increasing PCM content (**Figure 5b–c**), showing that the PCM capsules reduced the rate of heat transfer through the concrete. Together, these effects enabled the PCM mixtures to buffer temperature rise and delay peak heating, especially outdoors. Mechanically, however, PCM addition introduced a clear tradeoff. The control mixture had the highest compressive strength, the 5% PCM mixture still exceeded the TxDOT minimum requirement for sidewalk concrete, and the 10% PCM mixture fell below the required threshold (**Figure 6**). The strength loss at 10% PCM shows that higher replacement levels are not suitable for structural sidewalk applications without mix redesign. Field monitoring of the full-scale sidewalk sections further showed that PCM alone was not the most reliable cooling strategy; instead, surface treatment played the dominant role (**Figure 6**). The 5% PCM segment by itself was warmer than the control during the first two months and showed only a slight benefit in the third month. In contrast, the sand-blasted and hybrid sections, especially sand-blasted concrete with 2.5% PCM, provided the most stable and meaningful cooling performance, with the highest positive Monthly Cooling Benefit Index (MCBI) values over time (**Figure 6**). Diamond-ground sections showed more variable performance, while the hybrid sand-blasted configuration consistently ranked among the best treatments. Overall, the results show that sand-replacement PCM can improve thermal performance, particularly under outdoor cyclic heating, but its benefit is moderate and dosage-dependent. For practical sidewalk applications, a modest PCM content combined with high-albedo or roughened surface treatment offers the most effective balance between cooling benefit, constructability, and mechanical performance.

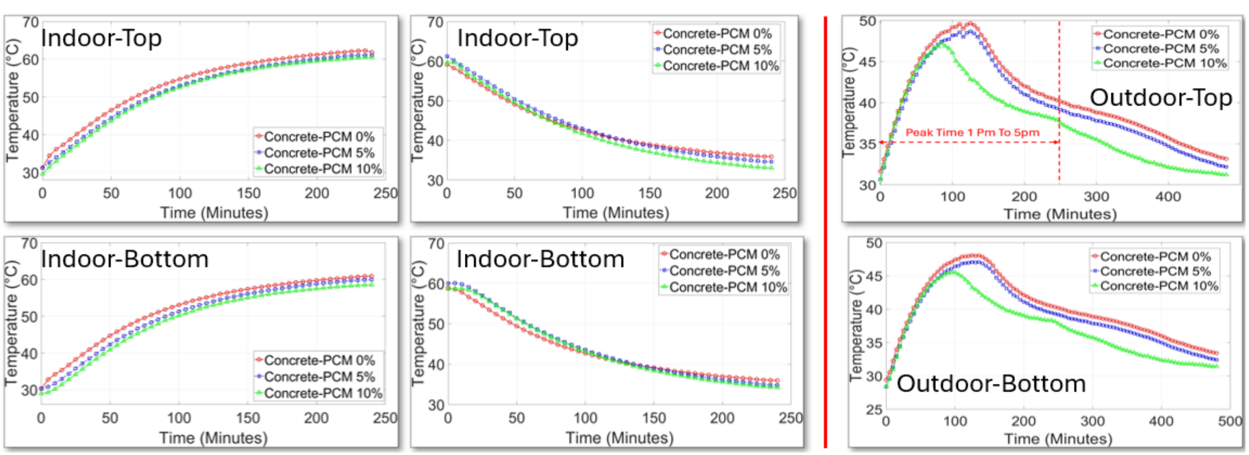


Figure 4: Heating cycle for 8 hours Indoor and Outdoor for Both Top and Bottom Surfaces

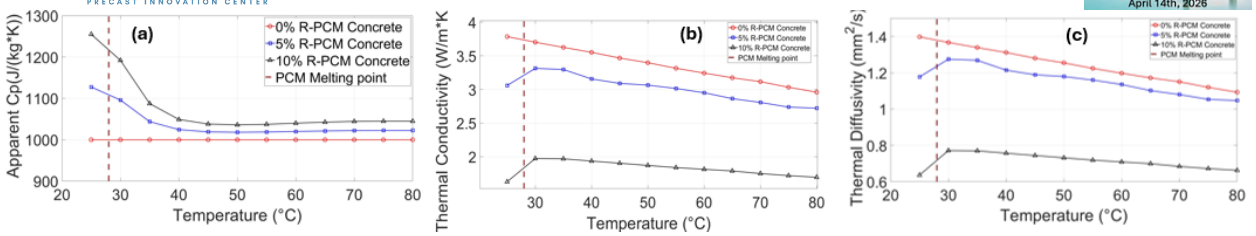
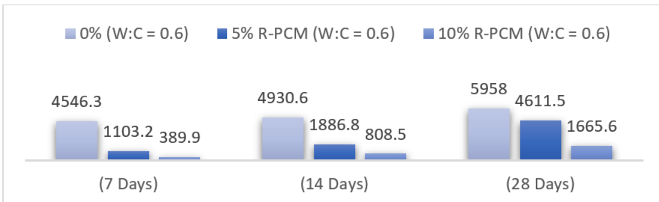


Figure 5: (a) Apparent Specific Heat Capacity; (b) Thermal Conductivity; (c) Thermal Diffusivity.



Cooling Effect (Heating → Cooling)	MCBI 1st Month	MCBI 2nd Month	MCBI 3rd Month	MCBI 4th Month	MCBI 5th Month	MCBI 6th Month
Control Concrete	0.00	0.00	0.00	0.00	0.00	0.00
5% PCM Concrete	-1.95	-0.75	0.30	-0.44	-0.13	-0.10
Sand Blasted Surface Concrete	-0.50	0.07	1.95	0.52	0.30	0.97
Sand Blasted-2.5% PCM Concrete	0.14	0.33	1.71	1.74	1.36	1.56
Dimond Grinded Surface Concrete	-0.63	-0.97	0.61	0.82	0.79	0.98
Dimond Grinded-2.5% PCM Concrete	-0.22	-1.30	-0.08	-0.51	-0.38	0.03

$$\bar{T}_{s,m} = \frac{1}{N} \sum_{t \in (12:00-22:00)} T_{s,m}(t)$$

$$\bar{T}_{control,m} = \frac{1}{N} \sum_{t \in (12:00-22:00)} T_{control,m}(t)$$

$$\text{MCBI}_{s,m} = \bar{T}_{control,m} - \bar{T}_{s,m}$$

Figure 6: Compressive Strength; Heat-Map of Monthly Cooling Benefit Indices

Conclusion

This study evaluated the use of microencapsulated organic paraffin phase change material (PCM, MPCM28D) as a sand replacement in concrete pavement for sidewalk applications aimed at (UHI) mitigation. The results showed that PCM incorporation modified the thermal response of concrete by increasing apparent heat capacity near the phase-change range and reducing thermal conductivity and diffusivity, which enabled the slabs to buffer temperature rise and delay peak heating. In the indoor 8-hour heating–cooling tests, the cooling benefit was modest, with the 10% PCM mixture reducing peak surface temperature by about 2 °C, while the 5% PCM mixture produced only limited improvement. Under outdoor exposure, however, the PCM effect became more noticeable, and the 10% mixture achieved a peak surface temperature reduction of about 4 °C, confirming that PCM performs more effectively under cyclic diurnal conditions than under sustained high heat input. From a mechanical standpoint, the 5% PCM mixture maintained acceptable workability and compressive strength above the TxDOT requirement for sidewalk concrete, whereas the 10% mixture showed a significant strength reduction and did not satisfy the minimum design requirement. Field monitoring of the full-scale sidewalk pilot further demonstrated that PCM alone was not the most reliable cooling strategy. Instead, the best overall performance was achieved by hybrid configurations combining modest PCM content with surface treatments, particularly sandblasting and diamond grinding. Among the tested sections, the sand-blasted and sand-blasted + 2.5% PCM segments provided the most stable and meaningful cooling benefit over time. Overall, the findings indicate that sand-replacement PCM can contribute to cooler concrete sidewalks, but its effectiveness depends on dosage, thermal loading conditions, and integration with complementary surface treatments. For practical sidewalk implementation, moderate PCM contents combined with optimized surface finishing offer the most promising balance between thermal benefit, constructability, and mechanical performance.

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