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DEVELOPMENT AND THERMAL PERFORMANCE EVALUATION OF A PCM-ENHANCED CONCRETE PAVEMENT FOR SURFACE TEMPERATURE REDUCTION IN TROPICAL CONDITION

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***Abstract*— The urban heat island (UHI) effect is an important environmental challenge in rapidly developing urban areas, where built surfaces can reach substantially higher temperatures than surrounding areas. Pavement materials contribute to this phenomenon by absorbing and storing solar energy during daytime exposure. This study investigates the thermal and mechanical performance of a phase change material (PCM)-enhanced concrete pavement developed to reduce pavement surface temperatures under tropical outdoor conditions. Paraffin wax was selected as the PCM because of its phase-change temperature range suitable for the experimental conditions, while expanded clay aggregate (ECA) was used as a porous carrier for PCM incorporation. Four pavement mixtures containing 0%, 3%, 6%, and 9% PCM-integrated ECA were prepared, with the PCM-containing material incorporated within the upper surface layer of the pavement specimens. The thermal performance was evaluated through outdoor monitoring over a 15-day period at one-hour intervals. Compressive strength was evaluated at 7, 14, and 28 days, while flexural strength was evaluated at 28 days. The results showed that PCM incorporation reduced the peak pavement surface temperature compared with the control specimen. The 3%, 6%, and 9% PCM mixtures reduced the peak surface temperature by approximately 3.5 °C, 6.0 °C, and 6.5 °C, respectively. Although increasing PCM content improved thermal performance, the additional reduction between 6% and 9% was relatively small. The 6% PCM mixture provided a balance between thermal performance and mechanical strength, with a reported 28-day compressive strength of 27 MPa and flexural strength of 3.12 MPa. The findings indicate that PCM-integrated concrete pavement has potential for reducing pavement surface temperatures under tropical outdoor conditions. However, further investigation is required to evaluate long-term durability, environmental implications, thermal cycling behaviour, and the potential contribution of the technology to urban-scale UHI mitigation.**

Key words: Urban heat island; cooling pavement; phase change material; PCM; paraffin wax; expanded clay a ggregate; concrete pavement; thermal performance; mechanical performance.

I. INTRODUCTION

The urban heat island (UHI) effect occurs when urban areas experience higher temperatures than their surrounding rural areas. Rapid urban development, increased impervious surface coverage, reduction of vegetation, and the extensive use of heat-absorbing construction materials can contribute to this phenomenon (Anupam et al., 2022; Santamouris et al., 2020; Aflaki et al., 2021). Elevated urban temperatures can increase cooling energy demand, affect outdoor thermal comfort, and intensify heat-related environmental and infrastructure stresses (Cheval et al., 2024). UHI effects can generally be considered in terms of both air temperature and surface temperature. Air-temperature UHI refers to differences in near-surface air temperature between urban and rural environments, whereas surface-temperature UHI is associated with differences in the temperature of urban and surrounding land surfaces (Zhao et al., 2021; Santamouris et al., 2020; Meng et al., 2023). Surface temperature is strongly influenced by the thermal properties of construction materials, including solar reflectance, thermal conductivity, and heat-storage capacity. Under strong solar radiation, pavement surfaces can reach temperatures substantially higher than the surrounding air temperature (Anupam et al., 2022; Seifeddine et al., 2023; Kappou et al., 2022).

Because pavements occupy a considerable proportion of urban impervious surfaces, their thermal behaviour is relevant to urban heat management. Several pavement-cooling approaches have therefore been investigated, including reflective pavements and permeable pavement systems. Reflective pavements reduce solar heat absorption through increased surface reflectance, while permeable pavements can promote evaporative cooling. However, the effectiveness of these approaches depends on material characteristics and environmental conditions (Aflaki et al., 2021; Kong et al., 2021). Phase change materials (PCMs)

have recently received attention as a potential approach for regulating pavement temperatures. Unlike conventional materials that primarily store thermal energy through a rise in temperature, PCMs can absorb and store a substantial amount of thermal energy as latent heat during a phase transition while maintaining a relatively narrow temperature range (Drissi et al., 2019; Santamouris et al., 2020). During daytime heating, a PCM can absorb thermal energy as it undergoes melting. During subsequent cooling, the stored latent heat is gradually released as the PCM solidifies. This thermal buffering mechanism can delay temperature increases and modify the timing and magnitude of peak pavement temperatures.

PCMs can be classified into organic, inorganic, and eutectic materials. Organic PCMs include paraffin waxes and fatty acids and have been investigated for cement-based applications because of their chemical stability and relatively good compatibility with construction materials (Santamouris et al., 2020; Guo et al., 2024). Inorganic PCMs generally provide high thermal storage capacity but may present limitations associated with phase separation and corrosion. Eutectic PCMs consist of combinations of materials selected to achieve a desired phase-change temperature range. Different methods have been investigated for incorporating PCM into cement-based materials. Shape-stabilized PCM systems, in which the PCM is contained within a porous carrier material, are particularly relevant to pavement applications because the carrier can provide physical support for the PCM and reduce direct interaction between the PCM and the cementitious matrix. Expanded clay aggregate (ECA), with its porous structure, can therefore be considered as a potential carrier for PCM incorporation.

Previous research has primarily investigated PCM applications in building materials and asphalt pavement systems, while relatively fewer studies have examined PCM-enhanced concrete pavements under tropical climatic conditions.

II. MATERIAL AND METHOD

Ordinary Portland cement was used as the primary binder for all concrete mixes. Natural river sand was the fine aggregate while crushed stone size in 20mm were used as the coarse aggregate for the experiment. Expanded clay aggregate was selected as the PCM carrier since their high porous structure facilitated effective absorption of PCM.

Commercially available paraffine wax was selected as the PCM for this study. Since their properties are well suited to tropical climate conditions. Its owning a melting temperature in between 30-32C which corresponds to tropical pavement surface temperature. And on the other hand, paraffin wax has high latent heat storage capacity, good thermal stability, chemical integrity, and compatibility with cementitious materials.

Preparation of PCM integrated expanded clay aggregates.

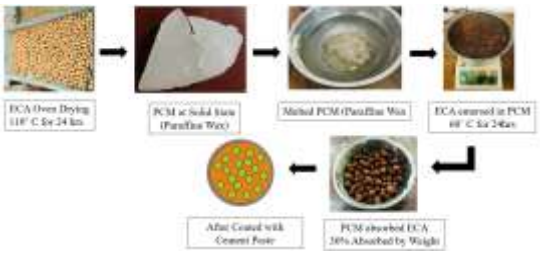


Figure 1. PCM integration process.

At the initial stage expanded clay aggregates were oven-dried at 105 ± 5 °C for 24 hrs. to remove any moisture trapped inside the porous structure and increase the PCM absorption capacity. The dried aggregates were subsequently cooled to room temperature and weighed. After paraffin wax were heated above its melting temperature to achieve homogeneous liquid phase. Dried expanded clay aggregate were immersed in the liquid paraffin wax for 24 hours to fully fill the porous by capillary action. After the soaking period PCM absorbed expanded clay aggregate were removed from the paraffin liquid and allowed drain out excess paraffin wax. The PCM absorption capacity was determined gravimetrically by comparing the aggregate mass before and after impregnation using Equation.

$$\text{PCM Absorbed } \% = \frac{Wpcm - Wdry}{Wdry} \times 100\% \qquad (1)$$

The PCM absorption capacity of the ECA was determined gravimetrically from the difference between the dry mass of the ECA and its mass after PCM impregnation and removal of excess surface PCM. The measured PCM absorption was approximately 30% of the dry ECA mass. Following PCM impregnation, the ECA particles were coated with a thin layer of cement paste and allowed to dry for 24 h before incorporation into the concrete mixture. The coating was intended to provide physical containment of the impregnated PCM and reduce the potential for PCM migration during concrete mixing and subsequent phase-change cycles.

A. Concrete mix design and specimen preparation

Four concrete mixtures were prepared by following grade 25 mix design strategy; control mix with zero PCM content and three PCM enhanced mixes 3%, 6% and 9% respectively partially replaced by the coarse aggregate into PCM integrated ECA. This replacement percentages were selected based on previous studies prior to the balance between thermal and mechanical performance. 150mm×100mm×100mm in size slab specimens were prepared to evaluate the thermal performance. PCM integrated ECA were placed as a layer withing the top 20mm-30mm surface area of the specimens since the top surface area is generally getting the highest temperature due to direct exposure to the sunlight. To measure the mechanical performance 150mm×150mm×150mm in size 36 number of cubes were prepared to test the compressive strength in 7 days

14day and 28days while 150mm×150mm×500mm size specimen were prepared to test the flexural strength.

B. Thermal Performance evaluation

Thermal performance evaluation was conducted under the outdoor environment exposure for 15 days monitoring period starting from 1st of August to 15th August 2025. Surface temperature measurements were taken 1hr interval. Thermal performance of the PCM enhanced cooling pavement was evaluated based on the peak surface temperature reduction and the impact of PCM content on the thermal behavior.

C. Mechanical performance evaluation

To evaluate the mechanical performance at curing ages of 7-, 14-, and 28-day compressive strength testing was performed under the SLS 1144 while at 28 days flexural strength testing was conducted under ASTM C78 to measure the load bearing performance of the PCM enhanced cooling pavement.

III. RESULTS AND DISCUSSION

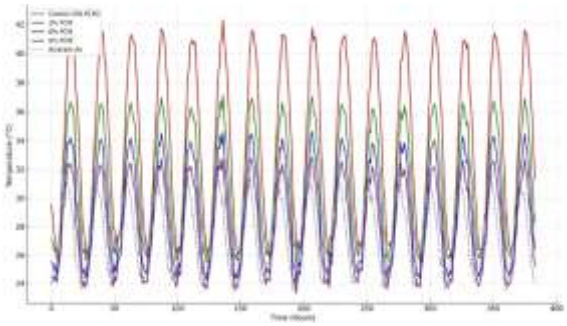


Figure 2. Surface temperature variation.

Figure 2 presents the surface-temperature variation of the control and PCM-enhanced pavement specimens during the outdoor monitoring period. The control specimen reached a peak surface temperature of approximately 42.0 °C. In comparison, the PCM-enhanced specimens recorded lower peak surface temperatures. The 3%, 6%, and 9% PCM mixtures recorded peak surface temperatures of approximately 38.5 °C, 36.0 °C, and 35.5 °C, respectively. These correspond to reductions of approximately 3.5 °C, 6.0 °C, and 6.5 °C relative to the control specimen.

The reduction in peak surface temperature can be associated with the latent heat storage behaviour of the incorporated paraffin wax. When the pavement temperature approaches the phase-change temperature of the PCM, part of the incident thermal energy is absorbed as latent heat during the transition from solid to liquid. Consequently, the increase in pavement temperature can be moderated during the phase-change period. The results also indicate that increasing PCM content generally improved the thermal performance of the pavement specimens. However, the additional benefit obtained between 6% and 9% PCM was relatively small. Increasing the PCM content from 6% to 9% resulted in an additional peak-temperature reduction of approximately 0.5 °C. This observation suggests that increasing PCM content beyond 6% did not produce a proportional improvement in the measured peak surface temperature under the experimental conditions.

The observed temperature reductions are broadly consistent with the range reported for PCM-based pavement systems in previous studies [appropriate references]. However, differences in PCM type, encapsulation method, pavement composition, climate, monitoring period, and test configuration should be considered when comparing temperature reductions across studies.

A. Compressive strength Performance

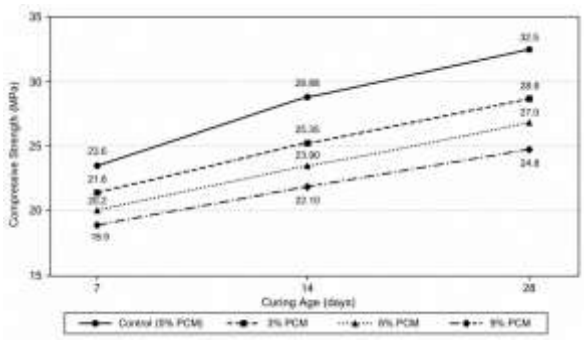


Figure 3. Compressive Strength Performance

Figure 3 presents the compressive strength of the control and PCM-enhanced mixtures at 7, 14, and 28 days. The control mixture recorded the highest compressive strength, while the incorporation of PCM-integrated ECA resulted in a reduction in compressive strength compared with the control mixture. Nevertheless, all mixtures showed an increase in compressive strength with increasing curing age from 7 to 28 days. The reduction in strength observed in the PCM-containing mixtures may be associated with the replacement of conventional coarse aggregate with the more porous and comparatively lower-stiffness expanded clay aggregate. However, the present study did not directly investigate cement hydration; therefore, no specific conclusion regarding the effect of PCM incorporation on cement hydration can be made from the available experimental results. The 6% PCM mixture recorded a 28-day compressive strength of approximately 27 MPa, compared with the corresponding control mixture. The percentage reduction relative to the control should be reported quantitatively using the measured control value.

B. Flexural strength performance

Figure 4 presents the 28-day flexural strength of the control and PCM-enhanced concrete specimens. Similar to the compressive strength results, the control mixture exhibited the highest flexural strength, while the PCM-containing mixtures showed lower values.

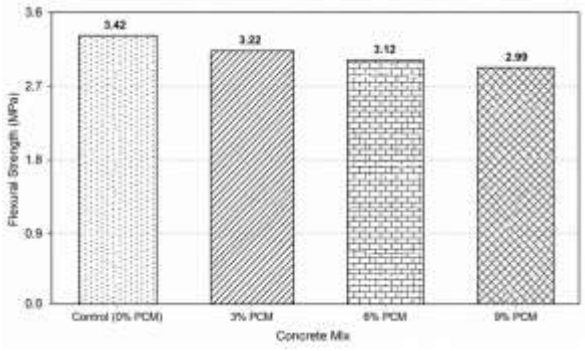


Figure 4. Flexural strength performance

The reduction in flexural strength may be associated with the incorporation of porous ECA and the resulting changes in the internal aggregate–cement matrix. Since the PCM was concentrated within the upper pavement layer, the effect of the modified material on the overall structural behaviour should be considered together with the pavement-layer configuration. The 6% PCM mixture recorded a 28-day flexural strength of approximately 3.12 MPa. The percentage difference between the control and PCM-containing mixtures should be reported to provide a clearer quantitative comparison.

IV. Conclusion

This study investigated the thermal and mechanical performance of a PCM-enhanced concrete pavement incorporating paraffin-wax-impregnated expanded clay aggregate within the upper pavement layer. The experimental results demonstrated that PCM incorporation reduced the peak surface temperature of the pavement specimens under outdoor tropical conditions. The control specimen reached a peak surface temperature of approximately 42.0 °C, while the 3%, 6%, and 9% PCM mixtures recorded peak temperatures of approximately 38.5 °C, 36.0 °C, and 35.5 °C, respectively. These results correspond to reductions of approximately 3.5 °C, 6.0 °C, and 6.5 °C compared with the control specimen. Although thermal performance improved with increasing PCM content, the additional temperature reduction between 6% and 9% PCM was relatively small.

PCM incorporation also resulted in lower compressive and flexural strengths compared with the control mixture. The 6% PCM mixture recorded a 28-day compressive strength of approximately 27 MPa and a flexural strength of approximately 3.12 MPa. Considering the observed thermal and mechanical performance, the 6% PCM mixture provided a practical balance within the investigated mixtures. The results demonstrate the potential of PCM-enhanced concrete pavement for pavement-level thermal regulation under tropical outdoor conditions. However, the present study does not directly quantify urban-scale UHI intensity. Further research is therefore required to evaluate long-term thermal cycling, PCM leakage, durability, environmental impacts, field-scale performance, and the potential contribution of PCM-enhanced pavements to broader urban heat mitigation.

V. Recommendations

Based on the findings of this study, the following areas are recommended for further investigation:

Long-term outdoor monitoring should be conducted to evaluate the thermal performance of PCM-enhanced pavement under repeated heating and cooling cycles.
PCM leakage and containment performance should be experimentally evaluated over repeated phase-change cycles.
Additional pavement durability properties, including abrasion resistance, water absorption, permeability, and freeze–thaw resistance where relevant, should be investigated.
The environmental implications of paraffin-based PCM should be assessed through a life-cycle perspective, considering material production, service life, potential leakage, and end-of-life management.
Numerical modelling should be developed to investigate heat transfer and PCM phase-change behaviour under different climatic conditions.
Field-scale studies should be conducted to determine whether pavement-level temperature reductions can contribute to measurable changes in local outdoor thermal conditions.

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