INTERNATIONAL JOURNAL OF RESEARCH AND SCIENTIFIC INNOVATION (IJRSI)
ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VI June 2026

Microencapsulated Phase Change Material in Asphalt for Urban Heat Island Mitigation: A Critical Review of Laboratory-Based Experimental Evidence.

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DOI: https://doi.org/10.51244/IJRSI.2026.1306000037

Received: 24 May 2026; Accepted: 29 May 2026; Published: 18 June 2026

ABSTRACT

Urban heat island (UHI) intensification is strongly associated with dark, impervious pavements that absorb, store, and re-radiate solar energy. Among emerging pavement-cooling strategies, phase change materials (PCMs) offer a latent-heat-based mechanism for moderating thermal peaks without relying solely on reflectivity or permeability. In asphalt systems, however, direct PCM incorporation is constrained by leakage, incompatibility with bitumen, and thermo-mechanical instability during mixing and service. Microencapsulation has therefore emerged as a leading strategy because it protects the PCM core, improves dispersion, and enhances thermal durability. By analyzing laboratory-based literature on microencapsulated PCM (MPCM) integrated into asphalt binders and asphalt mixtures, this study evaluates the effectiveness of MPCM in asphalt, its performance in the management of pavement heat, thermal regulation performance, mechanical implications, and research gaps.

Application of MPCM in pavement heat reduction is primarily effective. However, the effectiveness of MPCM is dependent on its application, including phase transition ranges, latent heat, and dosage. The main challenge to the adoption of MPCM includes balancing dosage for health reduction and material strength. There is a research gap in high-strength capsules and thermo-mechanical durability, which future research should focus on.

Keywords: Urban Heat Island (UHI), asphalt pavement, phase change material (PCM), microencapsulation, microencapsulated phase change material (MPCM).

INTRODUCTION

Urban pavements store substantial amounts of heat during the day and have low solar reflectance. These two key characteristics define urban pavements' significant contribution to the Urban Heat Island (UHI) effect. Asphalt surfaces can reach high temperatures of 71°C during hot, sunny days (Refaa et al., 2018; C. Wang et al., 2021). Urban pavements are thus ranked as some of the major contributors to thermal stress. During the transition phase, PCM-based pavements can help reduce UHI by adding temporary thermal energy storage (Pinheiro et al., 2023). Past research on cool pavements shows that the use of heat harvesting approaches is the best approach to maintaining cool pavements. Newer and more advanced methods include the use of PCM-based pavements, which add thermal energy storage in the form of latent heat and thus suppress peak temperature rise while moderating the thermal cycle (Almutairi & Baaj, 2023; Anupam et al., 2020; Fareed et al., 2025).

The adoption of PCM in asphalt is not smooth, and there are complexities around the process. Chemical compatibility with bitumen is a major challenge (Athukorallage et al., 2018; Korniejenko et al., 2024). Microencapsulation has been noted as one of the major breakthroughs in resolving the challenges associated with PCM in asphalt, as it effectively isolates the PCM core, improving survivability (Alva et al., 2017; Gao et al., 2022; Salvo-Ulloa et al., 2025).

This paper reviews laboratory-based evidence on microencapsulated PCM integrated with asphalt material as a method of mitigating UHI.

Methodological Focus

This research uses peer-reviewed literature on the microencapsulation of PCM in asphalt binders. The research prioritizes recent studies but also uses some earlier landmark studies for context purposes. The scope of literature used in this paper is limited to laboratory investigations addressing encapsulation, thermal characterization, morphological characterization, asphalt rheology, mechanical performance, and other closely related topics to microencapsulated PCM in asphalt binders and mixers. In some instances, pavement UHI literature is used where it clarifies the mechanisms or criteria. This focuses the research purely on highly related literature published in the recent past.

FINDINGS AND DISCUSSION

Importance of Microencapsulation in PCM-Asphalt Systems

PCM using the microencapsulation technique is a potential solution to UHI. The critical challenges of PCM in asphalt are the high mixing temperatures and mechanical shear that the material has to survive. PCM in asphalt is also subjected to repeated thermal cycling and is expected to preserve its latent heat capacity at a useful level (Mohajerani et al., 2017; Yang et al., 2016). Although PCMs in asphalt face these challenges with high mixing temperatures, mechanical shear, and repeated thermal cycling, they still maintain a highly useful heat latency capacity (Chen et al., 2020; Qin, 2015; Rouzmehr & Jamshidi, 2025). Microencapsulation involves coating tiny particles or droplets with a thin layer of polymer to form microcapsules. Microencapsulation in PCM-asphalt systems coats the PCM core with a shell to reduce leakage and improve handling (Cárdenas-Ramírez et al., 2020; Ismael et al., 2024). This technique improves the application of PCM-asphalt systems in pavements. Interfacial polymerization, phase separation, and in situ polymerization are the most common routes used for shell-forming (Y. Du et al., 2019; Wei, Ma, et al., 2019; Wei, Wang, et al., 2019). These methods have proven to be effective in improving the behavior of asphalt systems in the management of pavement heat.

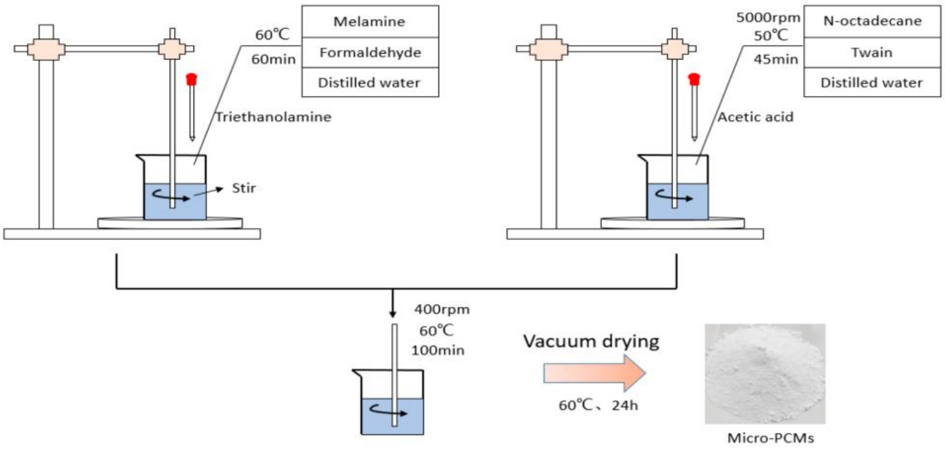


Figure 1: Preparation principle for micro-PCMs with MF resin shells and n-tetradecane cores (Guo et al., 2024)

PCM Cores and Shell Systems

The literature indicates a compromise between strength and storage density in MCP-asphalt systems. When the shell is highly reinforced, the structural integrity is enhanced. However, the PCM fraction is reduced per unit mass, which lowers the latent heat capacity. There are materials used in the PCM core, including paraffins, fatty acids, polyethylene glycols (PEGs), and eutectic organic systems (Dai et al., 2021; X. Liu et al., 2025; Z. Liu et al., 2021; Ma et al., 2026; Ryms et al., 2015). These materials are used because their phase transition temperature can overlap with pavement thermal conditions. Silica, calcium carbonate, polymethyl methacrylate, and acrylic polymers are commonly used shell materials (Guo et al., 2024; Hu et al., 2021; L. Zhang et al., 2025). The composition of the shell in turn determines survivability in asphalt production environments. Shell composition and design should move beyond basic encapsulation to hybrid designs. It is important to balance the shell composition to ensure stability while also ascertaining the ability to store latent heat.

Laboratory Characterization of Microencapsulated Phase Change Materials (MPCM)–Asphalt Systems

Evaluating the thermal characteristics and structural integrity of MPCM-asphalt systems cannot be avoided. Characterization has to be conducted in the laboratory to ascertain if MPCM in asphalt can successfully absorb or release latent heat. At the asphalt level, rotational viscosity, dynamic shear rheometer (DSR) testing, bending beam rheometer (BBR), temperature sweeps, master curve analysis, and creep-recovery measurements are commonly applied to determine how the addition of MPCM affects workability, high-temperature resistance, viscoelasticity, and low-temperature behavior (Al-Khateeb et al., 2024; L. Zhang et al., 2025). A particularly important issue in interpreting thermal tests is incomplete phase transition. If heating or cooling protocols do not fully activate the relevant portion of the PCM transition range, the apparent thermoregulation benefit may be underestimated or misinterpreted.

Laboratory Evidence of Thermal Regulation

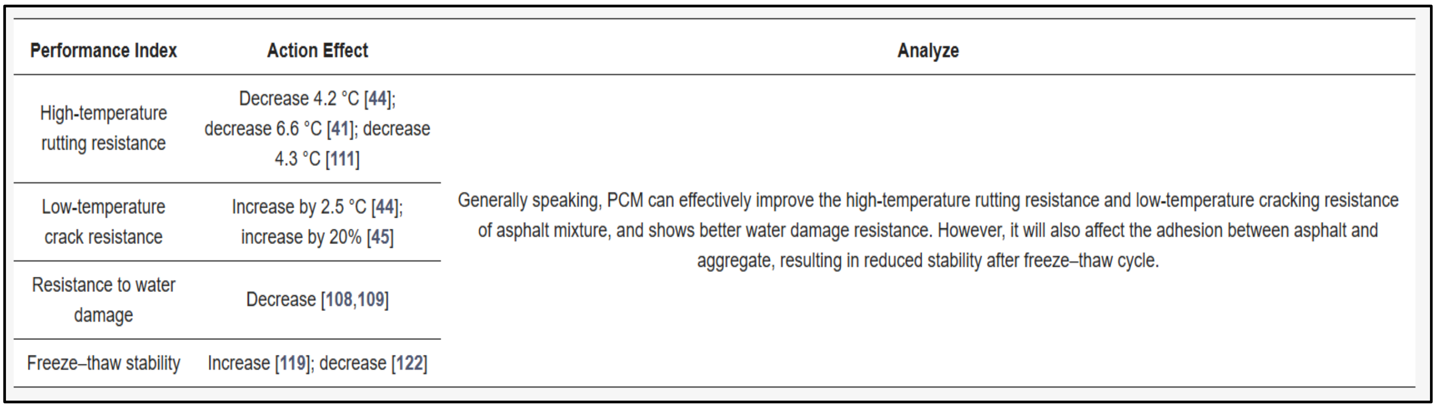
The principal justification for adding MPCM to asphalt is the potential to moderate pavement temperature through latent heat storage. Literature shows that adding MPCM to asphalt enhances the material's ability to absorb heat and delay rise in temperature (Gong et al., 2022; Sha et al., 2022; S. Wang et al., 2022). There are varying results based on how dosage is done and the latent heat capacity of the capsule (Da Rocha Segundo et al., 2023; Wu et al., 2022; Zhu et al., 2020). A PCM that melts outside the critical pavement temperature range contributes little effective thermal buffering.

The thermoregulation potential of MPCM-modified asphalt has been broadly supported. Smooth phase changes in asphalt binders and mixture systems, as well as the temperature-regulation effect of MPCM-modified asphalt, have been demonstrated. This evidence has also been extended into microencapsulated systems, leading to well-designed shell systems and modification of thermal conductivity.

Effects of MPCM on Mechanical Performance

There is a central question regarding the effects of MPCM on the mechanical versatility of pavements. Balancing the thermal benefits of MPCM without losing the performance of the pavements has been reported in some literature as a major setback to its adoption. MPCM reduces the viscosity of binders as well as their stiffness by acting as a softening or lubricating additive (Deng et al., 2022; Fu et al., 2024; Özdemir et al., 2025; Wong et al., 2024; D. Zhang et al., 2021). This makes the mixture level more dosage-sensitive. When MPCM content is added beyond its optimum threshold, the running resistance is weakened, thus losing the stability of the pavement (Dai et al., 2024; Jin et al., 2024).

The dosage trade-off between thermal benefit and pavement performance can be complicated to solve. Injecting higher quantities of MPCM material enhances thermal regulation. However, some literature indicates that low-to-moderate dosages are more feasible, while dosages above 10% often begin to noticeably degrade performance (Cheng et al., 2021; X. Du et al., 2025; D. Zhang et al., 2021; J. Zhang & Xu, 2024). The effects of MPCM are thus only meaningful when the core material, shell chemistry, dosage, and host asphalt are specified together.



Performance Index	Action Effect	Analyze
High-temperature rutting resistance	Decrease 4.2 °C [44]; decrease 6.6 °C [41]; decrease 4.3 °C [111]	Generally speaking, PCM can effectively improve the high-temperature rutting resistance and low-temperature cracking resistance of asphalt mixture, and shows better water damage resistance. However, it will also affect the adhesion between asphalt and aggregate, resulting in reduced stability after freeze–thaw cycle.
Low-temperature crack resistance	Increase by 2.5 °C [44]; increase by 20% [45]	
Resistance to water damage	Decrease [108,109]	
Freeze–thaw stability	Increase [119]; decrease [122]	

Figure 2: Effect of PCMs on performance of asphalt mixture pavement (Guo et al., 2024)

Durability and Survivability

Durability and survivability of capsules remain one of the barriers to adoption of MPCCM. There is limited evidence on the success of measures to address the survivability of capsules during incorporation, although recent research has begun to address the issue (Li et al., 2025; Rashid et al., 2025; Y. Wang et al., 2025). As a result, it is hard to declare a breakthrough in this process at this point. There is also no standard protocol on testing the impacts of mechanical interaction with the shell during mixing or how mechanical mixing can fracture capsules or create defects. These issues need to be addressed before finding a lasting conclusion on how MPCM can be effectively used in pavement heat management.

Research Gaps

The main gaps include a weak standardization of studies, the tense state of latent heat capacity and mechanical robustness, and a more profound need for studies on the interaction of PCM with modified binders. There is a clear need to have a standardized laboratory protocol for testing PCM against modified binders within different studies. This will increase the amount of comparable literature, making decision-making easier, and more data-informed decisions can be made.

There are limitations in cross-study comparison caused by diversity of research, including specimen geometry and dosage metrics. This weakens analysis and meta-analytical synthesis. This weakness makes current literature inadequate. There is a need for further investigation into the interaction between MPCM and polymer-modified binders. These findings will avail more comparative literature on binder types.

The multifunctional designs are likely to define the next phase of this research area. Another important direction is the development of shell materials that do not merely contain PCM but actively improve heat transfer and compatibility with bitumen. Such transfer will improve thermal conductivity or improve the temperature regulation efficiency of composite PCM-modified asphalt.

CONCLUSION

Microencapsulated phase change materials represent one of the most technically credible strategies for integrating latent heat storage into asphalt materials for UHI mitigation. Laboratory evidence consistently demonstrates that properly designed MPCM systems can flatten thermal peaks, delay heat accumulation, and improve the temperature-regulation capacity of binders and mixtures. The most successful systems are those in which the PCM transition window matches pavement operating temperatures, and the shell remains sufficiently stable during asphalt processing and thermal cycling.

Despite this promise, the field has not yet solved the central optimization problem of maximizing thermal benefit without sacrificing workability, rutting resistance, storage stability, and long-term durability. The literature makes clear that capsule design matters as much as PCM selection and that dosage optimization, shell robustness, and compatibility with the asphalt matrix must all be treated as co-equal design variables.

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