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Cool Pavement Technologies for Urban Heat Island Mitigation: A Comprehensive Review with Future Research Directions for Developing Cities

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ABSTRACT

Cool pavement technologies have emerged as an effective solution to mitigate urban heat island (UHI) effects by reducing pavement surface temperatures and enhancing urban thermal comfort. This study reviews three major categories of cool pavements—reflective, evaporative, and thermal energy storage systems—based on their mechanisms, effectiveness, benefits, and limitations. Results show that reflective pavements provide the most immediate cooling performance, with temperature reductions typically ranging from 5 °C to 15 °C, depending on materials and application. In contrast, thermal energy storage systems such as hydronic pavements or thermoelectric technologies may achieve reductions of up to 20 °C. Evaporative pavements offer added value through water retention and stormwater management, although their performance is highly dependent on local climate and water availability. While these technologies offer substantial environmental and societal benefits, challenges remain in terms of long-term durability, cost, and standardization. In the context of Hanoi, Vietnam, ongoing research and pilot implementations are actively exploring light-colored asphalt, porous and water-retentive pavements, microsurfacing, and innovative materials like TiO_2-based asphalt. These initiatives reflect the growing commitment to sustainable and climate-adaptive infrastructure solutions in urban settings.

1 Introduction

In recent decades, the pace of urbanization has accelerated dramatically worldwide. As cities expand to accommodate increasing populations and intensified economic activity, natural landscapes are being replaced by built environments at an unprecedented rate. Green areas and permeable surfaces that once allowed for natural water infiltration and contributed to

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local climate regulation have been largely supplanted by buildings, roads, and other impermeable infrastructure. These transformations have introduced a range of ecological and environmental challenges, with one of the most critical being the Urban Heat Island (UHI) effect.

As indicating in Fig. 1, UHI refers to the phenomenon where urban areas exhibit significantly higher temperatures than their surrounding rural counterparts [1–3]. The observed differences in air temperature between urban, semi-urban, and rural zones can range from 1 °C to 9 °C [4]. This thermal imbalance arises primarily from the extensive modification of land surfaces and the concentration of human activities linked to urbanization [1, 5].

Multiple factors contribute to the formation and intensification of UHIs. One of the primary causes is the replacement of natural surfaces with impervious materials. Urbanization often transforms vegetated areas into built-up zones dominated by buildings and road pavements, which have high solar absorption characteristics [6, 7]. These changes lead to substantial heat accumulation through the reflection and absorption of incident solar radiation [8]. Notably, paved surfaces can account for over 30% of total urban surface coverage [9].

The material properties of urban infrastructure further exacerbate heat retention. Conventional construction materials such as dark asphalt exhibit high heat capacity and thermal conductivity [10], as well as low albedo [6], resulting in intense absorption of solar radiation [9]. This leads to elevated surface temperatures, often reaching up to 70 °C during the daytime [11].

Urban geometry also plays a critical role. The dense configuration of tall buildings and narrow streets can significantly inhibit air circulation, reducing natural ventilation and trapping heat within city canyons [12].

Another contributing factor is the loss of vegetation and evapotranspiration capacity. The scarcity of green areas reduces the natural cooling effects provided by plant transpiration and soil moisture, thereby intensifying local temperatures [7, 8].

Lastly, anthropogenic heat emissions from various sources—including road traffic [4], industrial activities, and energy systems such as air conditioning—further increase urban heat levels [1, 9, 12–15].

In summary, UHI effect results from a combination of surface transformations, material properties, limited ventilation, reduced vegetation, and human-induced heat emissions. Its severity often correlates with urban size and dry climatic conditions [3].

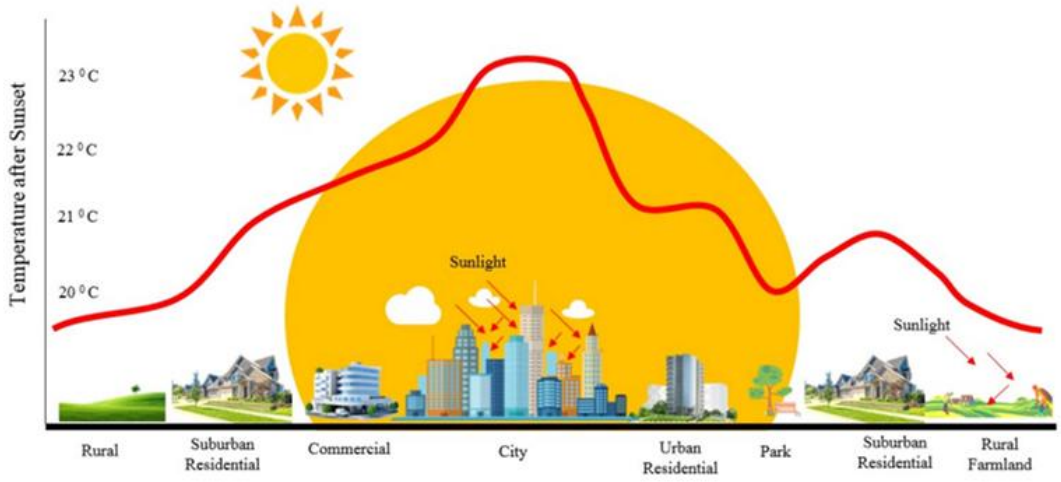


Fig. 1 - The effect of UHI [9]

The impacts of UHI are wide-ranging and affect both environmental sustainability and public well-being. Elevated temperatures due to UHI compromise human thermal comfort [3,16] and increase the prevalence of health conditions such as cardiovascular and respiratory diseases [1,17]. A growing body of evidence also links UHI to adverse mental health outcomes, with studies indicating increased risks of depression, anxiety, and other psychiatric disorders during periods of intense heat exposure [5]. Moreover, UHI raises indoor temperatures, leading to greater reliance on air conditioning, thereby increasing energy consumption and greenhouse gas emissions [1, 3, 8, 13, 17–19]. Air quality deteriorates as a result of

enhanced pollutant formation and reduced atmospheric dispersion [1, 3, 17, 20], and water bodies within cities are also affected by thermally driven changes in quality [8].

Beyond environmental and health implications, UHI exerts significant influence on urban behaviour. Heat stress discourages active transport such as walking and cycling, particularly in areas with higher heat index values, thus impacting daily mobility and lifestyle choices [1]. From a planning perspective, mitigating UHI remains a challenge due to the variability in urban forms, climate conditions, and socio-economic contexts. Data-driven approaches for UHI modelling often lack transferability, underscoring the necessity of locally tailored strategies [21].

2 Research Aim

Given the growing severity of UHI phenomenon—especially under accelerating climate change scenarios—there is an urgent need for innovative, cost-effective, and sustainable mitigation strategies. Among these, cool pavements—which include technologies designed to reflect solar radiation, enhance evaporative cooling, or store and manage thermal energy—have emerged as viable solutions for reducing pavement surface temperatures and improving urban thermal comfort.

This study aims to provide a comprehensive review of cool pavement technologies, encompassing their underlying mechanisms, thermal performance, environmental and operational benefits, and associated limitations. It evaluates three principal categories: reflective pavements, evaporative pavements, and thermal energy storage pavements, with attention to their comparative effectiveness and applicability in different climatic and urban contexts.

In addition to providing a comprehensive review of global research trends, this study also offers synthesized findings on the performance and limitations of cool pavement technologies, which contribute to shaping future research pathways in Vietnam. With a particular focus on Hanoi—a densely built and rapidly urbanizing city experiencing severe UHI effects—this paper underscores the necessity of contextualizing cool pavement solutions to fit local climatic, infrastructural, and policy conditions. The results presented serve not only to inform regional adaptation strategies but also to support the development of sustainable and climate-resilient urban pavement systems across Vietnam.

3 An Overview of UHI Mitigation Strategies and Solutions

Mitigation strategies can be broadly categorized into several approaches, often involving modifications to urban surfaces and the built environment. These include green infrastructure, blue infrastructure, various forms of grey infrastructure (such as cool pavements and shading), and urban planning responses.

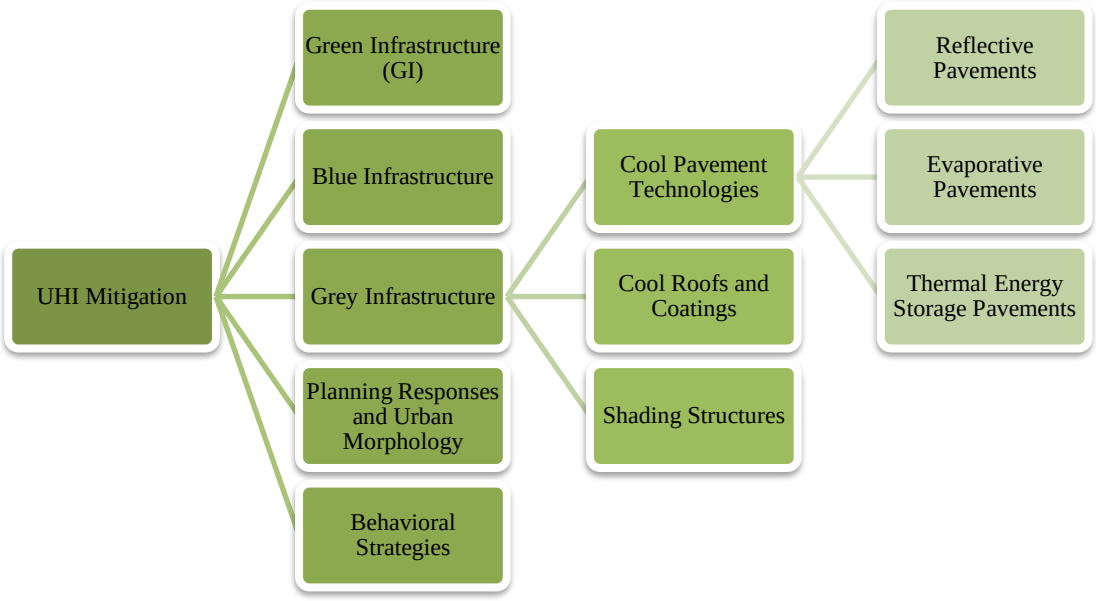


Fig. 2 - UHI mitigation strategies

3.1 Green Infrastructure (GI)

Green Infrastructure (GI) is recognized as one of the most prevalent and effective strategies for mitigating UHI effect, with a strong emphasis on nature-based approaches. Its primary objective is to lower urban temperatures by expanding green areas, enhancing vegetation coverage, and preserving or restoring natural land surfaces [22–24].

3.1.1 Cooling Mechanisms

GI contributes to urban cooling primarily through evapotranspiration, where water evaporates from soil and surfaces and is released from plant leaves, and shading, which limits the absorption of solar radiation. Compared with built materials, vegetation tends to retain less heat, thereby reducing both shortwave and long wave radiation fluxes. Trees, in particular, offer effective natural shade by intercepting and diffusing incoming solar energy [3, 14, 23, 25, 26].

3.1.2 Types and Effectiveness

Different forms of GI deliver varying degrees of thermal regulation. Urban forests, street trees, and green roofs have proven especially effective [14]. For example, green roofs implemented at scale can lower air temperatures by up to 3.0 °C [27]. In tropical urban contexts such as Singapore and Kuala Lumpur, GI applications have achieved air temperature reductions of approximately 2.6 °C and surface temperature decreases up to 11 °C [14]. Evidence also suggests that a 20% increase in tree canopy or the inclusion of 30% water bodies within urban environments can generate substantial cooling, whereas built-up and bare soil areas tend to elevate land surface temperatures (LST) [28].

Street trees have shown particular benefits in enhancing thermal comfort at the pedestrian level by creating localized “cool islands” and alleviating thermal stress. In a case study from Yokohama, Japan, tall deciduous trees were found to be the most efficient single intervention for reducing UHI impacts and energy use [18].

Other green elements such as green walls and grassy courtyards have been identified as viable strategies for improving thermal conditions in high-density residential zones [29].

3.1.3 Co-benefits:

Beyond temperature control, GI delivers a broad range of environmental, social, and economic co-benefits. These include improved stormwater management, enhanced air quality (via carbon uptake and pollutant filtration), support for biodiversity, better public health outcomes, increased climate resilience, and enhanced aesthetic and property value. Furthermore, integrated solutions—such as combining light-colored porous concrete pavement with vegetation like border hedges and trees—have been shown to lower air temperatures by over 3 °C, surface temperatures by over 30 °C, and mean radiant temperatures by more than 20 °C [14, 30].

3.1.4 Challenges

Despite its potential, the performance of GI can be influenced by the specific urban form and spatial configuration of a city. In densely built areas, limited space availability and the need for ongoing maintenance may hinder large-scale implementation when compared to conventional grey infrastructure alternatives [14, 22].

3.2 Blue Infrastructure

Blue infrastructure refers to the strategic use of water elements in urban environments to combat elevated temperatures and mitigate UHI effect [31]. These systems harness the natural cooling properties of water through processes such as evaporation and convection.

3.2.1 Mechanisms:

Water-based cooling relies primarily on the evaporation of water, which absorbs latent heat and reduces surrounding air and surface temperatures [23]. Common implementations include fountains, misting installations, and water-retentive pavements. One notable example is pavement-watering, an age-old practice particularly prominent in Japan since the Edo

period, where water is sprayed onto road surfaces to lower heat accumulation and surface temperatures. This technique reduces heat retention, stimulates convective heat transfer, and enhances evaporative cooling during hot periods [26].

3.2.2 Effectiveness:

The cooling outcomes of blue infrastructure can be substantial. For instance, pavement-watering has been shown to reduce air temperature by approximately 0.7 to 0.9 °C and the Universal Thermal Climate Index (UTCI)-equivalent temperature by 1.5 to 2.2 °C, with the cooling effect sustained for several hours post-application [26]. Proximity to natural or artificial water bodies can result in localized air temperature reductions of up to 3 °C. In addition, water-retentive pavements — which allow water to migrate from subsurface layers to the heated surface — have demonstrated effective thermal moderation by leveraging solar-induced evaporation [14].

3.2.3 Co-benefits:

Beyond temperature regulation, blue infrastructure contributes to broader urban resilience goals. Features such as permeable pavements and water retention systems enhance stormwater management, reduce the risk of urban flooding, and attenuate noise pollution. Moreover, the presence of water in urban design contributes positively to microclimate regulation, human thermal comfort, and overall aesthetic value [32, 33].

3.2.4 Challenges:

Despite its potential, the implementation of blue infrastructure can face limitations. Its efficiency is heavily reliant on a consistent water supply, which may be problematic in arid regions or during drought periods. Furthermore, densely built urban areas with limited open space and complex geometry may hinder airflow and reduce the effectiveness of water-based cooling. Additionally, seasonal variations and monsoonal climates can complicate maintenance and long-term operation [14, 26].

3.3 Grey Infrastructure

Grey infrastructure encompasses engineered and built solutions designed to actively manage and mitigate UHI effect through modification of urban materials and surfaces [34]. Among the strategies identified for UHI adaptation, grey infrastructure ranks second in prevalence, cited in over half of the reviewed studies (52.05%), following green and blue infrastructure (86.30%), and ahead of urban planning interventions (34.25%) and behavioral responses (17.81%) [22].This widespread attention highlights its importance in both short- and long-term heat mitigation planning, particularly in dense, infrastructure-dominated urban environments.

3.3.1 Cool Pavement Technologies

Cool pavements represent a central component of grey infrastructure and are considered among the most scalable and cost-effective strategies to address UHI effect. Since the late 20th century, research has focused on their ability to reduce both surface and air temperatures, thereby enhancing pedestrian thermal comfort and lowering energy demand in adjacent buildings. This is particularly relevant given that paved surfaces account for a substantial portion—approximately 29–45%—of total urban land cover, making their thermal properties a critical driver of urban heat dynamics [2, 12, 35].

Cool pavement systems can be broadly categorized into three principal types based on their underlying cooling mechanisms: Reflective Pavements, Evaporative Pavements, and Thermal Energy Storage (TES) Pavements. Each type contributes differently to mitigating urban heat effects. Their specific material compositions, cooling capacities, and suitability for various climatic zones are discussed in detail in Section 4, where technical performance and application contexts are comprehensively examined.

3.3.2 Cool Roofs and Coatings

Alongside cool pavement systems, cool roofs and high-albedo coatings on building envelopes constitute a critical element of grey infrastructure for UHI mitigation. These technologies function on similar physical principles—primarily by enhancing

the reflectivity (albedo) and emissivity of building surfaces, which helps to limit solar heat gain and minimize heat retention in the built environment [23].

The effectiveness of cool roofs has been supported by empirical studies demonstrating significant reductions in rooftop and adjacent ambient air temperatures. Such temperature reductions enhance thermal comfort for building occupants and contribute to overall microclimatic improvements [36]. When integrated with complementary strategies—such as green roofs and reflective exterior paints—cool roofs further contribute to lowering urban-scale temperatures. This not only reduces the cooling demand of buildings but also helps mitigate greenhouse gas emissions by decreasing energy consumption [33, 37–39].

Beyond their primary thermal control function, cool roofs also deliver important co-benefits. By lowering the reliance on air-conditioning systems, they offer substantial energy savings and help reduce electricity costs and associated carbon footprints [25, 40].

However, these benefits are not without potential trade-offs. The deployment of reflective materials on rooftops and facades may influence indoor thermal conditions, especially during cooler seasons or transitional periods. Improper design or material selection could lead to excessive cooling, thereby causing thermal discomfort for occupants. As such, careful consideration of local climate, building orientation, and seasonal variation is essential when implementing cool roof strategies [36, 41].

3.3.3 Shading Structures

Shading, whether provided by natural elements like trees or artificial architectural features, is a fundamental and immediately effective strategy for reducing UHI impacts in urban settings. It serves as a direct intervention to control heat exposure in both built and open environments.

The core mechanism of shading lies in its ability to block incoming solar radiation, thereby preventing heat accumulation on surfaces such as pavements, walls, and public spaces [13, 23]. The effectiveness of shading is further influenced by the morphology of the urban environment, including building heights, street widths, orientation, and spatial arrangement. These factors determine how sunlight interacts with the built form and the extent of shade coverage throughout the day [23].

Research has consistently shown that shading can result in considerable surface cooling. For example, pavement surface temperatures can be reduced by 15.0 °C to 21.0 °C, depending on the type of surface material used [42]. When combined with other strategies—such as using light-colored concrete alongside vegetation like perimeter hedges or tall trees—air temperatures can be further decreased by more than 3 °C, and mean radiant temperature can be reduced by up to 50%. Additionally, built shading features such as projecting roofs have demonstrated a potential to reduce air temperatures by approximately 2.07 °C [13].

In addition to thermal regulation, shading structures significantly enhance pedestrian comfort and safety. By mitigating exposure to direct sunlight and high surface temperatures, they reduce the risk of heat stress and promote walkability. This is particularly valuable in densely populated or transit-oriented areas, where urban heat exposure is often most severe.

3.4 Planning Responses and Urban Morphology

Urban planning and morphology have been widely recognized as key determinants in mitigating UHI effect through strategic modification of the physical and functional structure of cities [25, 43, 44].Among various planning dimensions, the configuration of the built environment—including building density, layout, and spatial arrangement—plays a pivotal role in shaping local microclimates.

The characteristics of urban form such as population density, land use diversity, road and building network patterns, and ventilation corridors are significantly correlated with the intensity and distribution of UHI [24, 45].As discussed by An and Dedekorkut-Howes [22], thoughtful architectural and urban design can facilitate natural ventilation and solar access, which in turn influences ambient and indoor thermal conditions. Notably, high-rise buildings may offer enhanced shading but can also intensify nighttime heat retention, especially when building heights exceed street widths. This vertical confinement may restrict long wave radiation dissipation and airflow, exacerbating nocturnal UHI effects.

In addition to form-based interventions, the promotion of sustainable transport systems also contributes to UHI mitigation by reducing vehicle emissions and pavement heat load [10].This includes policies that promote public transit, non-motorized mobility, and compact city development.

Another key planning strategy involves vulnerability and risk mapping, which supports targeted interventions by identifying high-risk zones and population groups most affected by extreme heat [10].Furthermore, integrating climate change projections into urban planning is critical for long-term adaptation. Comprehensive frameworks that combine urban greening, albedo enhancement, water-based cooling, optimized building-street geometry, and well-oriented open spaces offer promising solutions to redistribute and reduce urban heat [43, 44].

3.5 Behavioral Strategies

Although less emphasized compared to structural or planning approaches, behavioral adaptations remain a valuable component of UHI mitigation. These strategies often focus on increasing public awareness, providing timely heat warnings, and implementing health-protective measures—particularly for vulnerable populations such as outdoor workers, the elderly, and those with pre-existing conditions [15, 30, 46]. Workplace policies that encourage hydration, shade use, and adjusted work hours during heatwaves are examples of practical behavioral responses.

3.6 Synergistic Approaches and Implementation Challenges

A growing body of evidence suggests that integrated approaches—which combine multiple mitigation strategies—produce more substantial and sustainable outcomes than any single method alone [13, 15, 40]. For instance, coupling water-retentive pavements with optimized air-conditioning settings and the installation of green roofs has demonstrated enhanced cooling effects and energy savings [18]. Research by Hammoudeh and Sozzer [40] showed that the concurrent implementation of several strategies could lower ambient temperatures by up to 1.14°C while improving energy efficiency by as much as 61%.

However, the effectiveness of mitigation strategies is highly context-dependent. Data-driven UHI models often struggle with cross-regional generalizability, highlighting the need for localized approaches tailored to specific climatic and urban conditions [21]. For example, mitigation outcomes may differ markedly between arid and tropical environments [14].

Despite growing interest, the implementation of UHI mitigation strategies faces several barriers. These include financial constraints, limited availability of urban land, fragmented institutional responsibilities, and the absence of regulatory frameworks that incorporate UHI considerations into land use planning and construction codes. In many Southeast Asian cities, policies related to UHI remain underdeveloped, and research often prioritizes isolated measures over integrated planning [14]. Additionally, long-term monitoring and robust cost–benefit analyses are lacking, limiting the understanding of co-benefits such as public health improvements and energy savings.

Finally, knowledge gaps persist, particularly in translating academic findings into actionable policy and in ensuring effective communication among scientists, practitioners, and local governments [3, 22]. The role of transportation systems in UHI formation and adaptation, though significant, also remains underexplored in the literature [22]. Addressing these gaps is essential for designing comprehensive and equitable heat resilience strategies.

4 Cool Pavements: A comprehensive review

4.1 Effect of pavementin UHI Phenomenon

Road infrastructure plays a vital role in modern transportation systems, facilitating daily mobility and bearing a wide range of vehicle loads across different terrains. Beyond their structural purpose of distributing wheel loads and offering a smooth, safe surface for travel, pavements also possess unique thermal properties that significantly affect the urban microclimate and contribute to broader climate-related challenges.

A comprehensive understanding of pavement thermal behavior is essential. Research conducted in the United States has indicated that asphalt surfaces can reach temperatures exceeding 60 °C during summer months [47–49]. If left unmitigated, such elevated temperatures may negatively impact the surrounding environment, exacerbating heat-related issues in urban areas.

To support efforts in addressing these impacts, Table 1 summarizes key thermal parameters of pavement materials. These parameters provide insights into how pavements influence UHI phenomenon. Broadly, the characteristics can be categorized into two groups: thermodynamic properties and energy transfer attributes [50]. Thermodynamic properties relate to internal heat behavior and storage within pavement layers, while energy transfer characteristics reflect how heat is exchanged between pavement surfaces and their immediate environment [51, 52].

Table 1 - Key Pavement Temperature Parameters and Influencing Factors [9]

Parameter	Definition	Influence on Pavement Temperature	Unit
1. Thermodynamic Properties(Heat storage and material response)			
Thermal inertia	Speed of material's response to temperature change.	Depends on pavement composition; affects thermal conductivity.	$J/m^2 \cdot K \cdot s^{-1/2}$
Albedo	Ratio of solar energy reflected by the surface.	Influences surface and subsurface temperature; affected by color and texture.	Dimensionless
Emissivity	Ability to release stored heat to the environment.	Enhancing emissivity reduces UHI effect.	Dimensionless
Volumetric heat capacity	Heat absorbed and stored per unit volume.	Higher capacity lowers peak and ambient temperatures.	$J/K \cdot m^3$
2. Energy Transfer Attributes (Heat exchange with surroundings)			
Thermal conductivity	Rate of heat transfer through pavement material.	Higher conductivity raises surface temp but may lower overall pavement and ambient temp.	W/m·K
Heat convection	Heat exchange between pavement and air due to temperature difference.	Affected by external factors like wind.	J

Recognizing these distinctions is essential for developing pavement solutions that help regulate surface temperatures. By altering material composition or structural design, engineers can significantly influence thermal responses, thus improving pavement performance under extreme temperatures and reducing their contribution to UHI effects. Over the years, innovative pavement technologies have emerged to address these challenges by optimizing key thermal characteristics.

Building upon this understanding of pavement thermal behavior, cool pavements have emerged as a targeted and forward-looking strategy to counteract UHI effect. These solutions capitalize on the ability to modify surface energy balance by incorporating design and material innovations that reduce heat absorption and enhance heat dissipation [53]. Broadly defined, cool pavements include a suite of engineering interventions that enable pavement surfaces to maintain lower temperatures than conventional materials under the same environmental conditions [47, 54].

Such temperature reduction is primarily achieved through strategies like increasing solar reflectance (albedo), promoting evaporative cooling, or enhancing heat storage and controlled release mechanisms [47]. Recognizing their effectiveness, institutions such as the European Union (EU) and the U.S. Environmental Protection Agency (EPA) have identified cool pavements as integral tools in sustainable urban development, with benefits extending to reduced energy consumption, improved comfort, and enhanced safety for road users [4, 55].

As previously noted, these technologies can generally be categorized into three main types: Reflective Pavements, Evaporative Pavements, and TES Pavements. Each of these categories leverages a distinct cooling mechanism and is examined in detail in the following sections to illustrate their principles, applications, and potential in mitigating UHI impacts.

4.2 Reflective Pavements

4.2.1 Mechanisms and Principles of Operation

Among cool pavement technologies, reflective pavements are one of the most widely adopted and effective solutions for mitigating UHI effects. These pavements reduce surface temperatures by utilizing materials or coatings with high solar

reflectivity (albedo), often achieved through light-colored aggregates or specialized reflective treatments [56, 57]. In addition to their thermal benefits, reflective pavements have also shown improved durability under various environmental conditions [58, 59].

The cooling performance of reflective pavements primarily depends on enhancing albedo, emissivity, and limiting heat transfer within the pavement structure. By increasing solar reflectance—typically from ~0.10 in conventional asphalt to 0.30–0.35 or higher—these pavements absorb less heat and maintain lower surface temperatures [4, 11, 20, 60, 61]. High-emissivity materials further aid in releasing stored heat into the atmosphere, especially during nighttime. Additionally, surface characteristics such as light color and smooth texture significantly contribute to improved thermal performance.

4.2.2 Types and Technologies of Reflective Pavements

A wide range of engineering approaches has been developed to enhance pavement reflectivity and mitigate surface heat accumulation.

Reflective Coatings and Paints are among the most commonly used methods [12, 56, 57]. These formulations typically consist of a resin matrix combined with pigments, fillers, and functional additives and are designed for application on existing pavement surfaces [62]. Highly reflective white paints can achieve solar reflectance values exceeding 0.9 [63]. According to Santamouris et al. [64], when reflective coatings were applied to both the surface and the bulk of concrete tile pavements, albedo values ranging between 0.8 and 0.9 were observed under summer conditions. Similarly, another study examining 14 types of high-reflectance white surfaces reported that most coatings demonstrated albedo levels within the same range. Aluminum-free coatings displayed thermal emittance above 0.8, whereas those containing aluminum ranged from 0.3 to 0.4 [65]. The application of these coatings lowered daytime surface temperatures by 4 °C and night-time temperatures by 2 °C, with the tiles staying close to ambient air temperature during the day and substantially cooler at night. Coatings containing aluminum tended to yield higher surface temperatures compared to other reflective materials.

Near-infrared (NIR) reflective coatings and pigments are specifically engineered to reflect the near-infrared portion of the solar spectrum (700–2500 nm), which accounts for approximately 50% of incoming solar energy [12, 17]. These materials offer the dual benefit of thermal regulation and visual versatility, allowing even darker-colored pavements to function effectively as reflective surfaces. Titanium dioxide (TiO_2) and iron oxide yellow are among the commonly used pigments due to their favorable NIR reflectance characteristics [66].The mechanism of these coatings, which reflects both visible and infrared radiation, is illustrated in Fig. 3 [67].

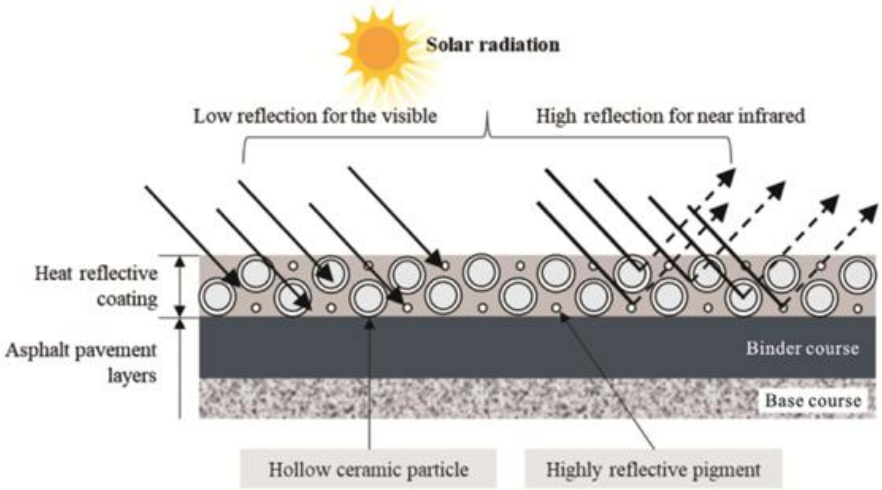


Fig. 3 - Operating principles of solar-reflective coatings [67]

In addition to treating the entire surface, a more targeted approach involves applying reflective coatings directly to aggregates instead of the full pavement layer. This method allows for thermal performance improvements without altering the overall appearance of the pavement [4].

Thermochromic materials offer a dynamic solution by changing color in response to ambient temperature. As temperatures rise, these coatings become lighter and more reflective, while cooler conditions trigger a return to darker shades. This reversible behavior supports adaptive thermal control and may contribute to reduced pavement deterioration due to thermal cycling [4, 6, 9, 12, 17, 68].

Retro-reflective coatings present another strategy, redirecting incident solar radiation back toward its source. This can help reduce heat accumulation in areas with dense urban geometry, such as narrow streets and canyons [9, 17].

Beyond surface treatments, structural modifications to pavement composition can significantly improve solar reflectance. Whitetopping (WT) and ultra-thin whitetopping (UTW) involve overlaying asphalt pavements with Portland cement concrete, which naturally possesses higher albedo values than typical asphalt surfaces [4, 69]. Similarly, using light-colored aggregates, specialized binders, or pigments in asphalt and concrete mixtures enhances the surface's reflectivity [4].

Chip seals, consisting of high-albedo aggregates embedded in asphalt emulsions, provide a cost-effective option for low-traffic applications. These treatments can incorporate recycled light-colored materials—such as crushed brick or concrete—to increase reflectivity and sustainability [4, 20, 70].

Microsurfacing applies a thin reflective layer, typically 1/8 to 1/4 inch thick, composed of cement, sand, and polymeric emulsions. These coatings maintain skid resistance under wet conditions and offer reflectivity levels comparable to new concrete. Commercial products such as E-Krete and Street Bond exemplify this technology [4, 63].

Another reflective strategy involves pigment integration. Colored asphalt surfaces are produced by mixing transparent binders with pigmented aggregates or synthetic particles. These overlays are generally categorized as light-colored or pigmented pavements and are often used in visually or culturally sensitive areas where aesthetic value is critical [71, 72].

Incorporating recycled materials also provides dual benefits of sustainability and improved reflectivity. Materials such as fly ash, slag, ceramic waste, and tiles can be used in concrete mixes or coatings. For example, replacing 70% of cement with slag increased albedo by 71% to 0.582 [4]. Research by Huang et al. [73] found that ceramic waste aggregates not only enhanced thermal insulation, reducing pavement temperature by up to 8.8 °C, but also improved rutting resistance by 45.36%.

Finally, polymer-based systems combining methyl methacrylate (MMA) with fillers like aluminum silicate (AS), glass bubbles (GBs), or microencapsulated phase change materials (PCM) offer advanced heat mitigation. Among these, aluminum silicate was the most effective, reducing surface temperatures by up to 10 °C [7].

Collectively, these technologies reflect a diverse and evolving set of strategies for improving solar reflectivity in pavement surfaces. By leveraging both material innovations and targeted surface treatments, they offer viable options to reduce urban heat buildup and enhance thermal comfort in cities.

4.2.3 Cooling Performance and Effectiveness

Reflective pavements have shown significant potential for temperature reduction, as can be seen in Table 2. The data highlights a wide range of cooling performances depending on the type of reflective material and application method. In general, surface-applied reflective coatings and pigments demonstrate substantial temperature reduction capabilities, ranging from 4.4 °C up to more than 13 °C in some cases.

For example, white high-reflective and infrared paints applied on surface or aggregates were reported to reduce daytime temperatures by up to 24 °C and nighttime temperatures by 2 °C [47]. Similarly, high-performance materials such as multilayer coatings incorporating TiO_2, SiO_2, and glass beads achieved temperature drops as high as 13.25 °C [74]. Other technologies, including thermochromic powders, near-infrared (NIR) reflective coatings, and epoxy resins with functional fillers, also showed effective cooling, typically between 6 °C and 12 °C [75–77].

In addition, some innovative solutions like TR-HRC composite pavement and cooling asphalt modifiers such as Tourmaline Anion Powder (TAP) achieved reductions between 6.6 °C and 13.2 °C [78, 79]. The use of recycled or modified materials—such as ceramic waste in stone mastic asphalt or floating beads mixed with TiO_2 also showed promising results with surface temperature reductions of up to 9.7 °C [73, 80].

Overall, these findings emphasize the importance of material selection and surface treatment in enhancing pavement albedo and thermal performance. They also confirm the viability of reflective pavement technologies as effective UHI mitigation strategies under various environmental and operational contexts.

4.2.4 Benefits Beyond Cooling

In addition to mitigating UHI effect, reflective pavements provide a range of additional benefits. One major advantage is their ability to enhance pavement durability and extend service life by reducing thermal-induced stresses, particularly during peak daytime temperatures [11, 12, 58, 61]. This improvement in thermal performance also contributes to energy efficiency. By lowering ambient urban temperatures, reflective pavements help decrease air conditioning demand in nearby buildings, which can lead to notable energy savings and reductions in greenhouse gas emissions [11, 81]. For instance, translucent binders used in colored pavements can reduce lighting needs at night, further cutting electricity costs [71].

Table 2 - Summary of Temperature Reduction Achieved by Reflective Pavement Technologies

No.	Reflective Material	Technology/Method	Max. Temperature Reduction	Reference
1	White high-reflective & infrared paints	Painted on surface/aggregates	16–24 ℃ (day), 2 ℃ (night)	[47]
2	Crushed tile & epoxy resin	Coating layer on asphalt	4.4 ℃	[75]
3	Thermochromic powders	Mixed with asphalt binder	6–8 ℃	[82]
4	High near-infrared reflective paint	Applied to pavement surfaces	8–20 ℃	[55]
5	Full-body porcelain tile	Epoxy-bound aggregates	6.4 ℃	[83]
6	Fluorinated acrylate with TiO_2	Heat-reflective coating	13 ℃	[62]
7	SHRCL with TiO_2 pigment	Surface coating	10 ± 2.5 ℃ (top), 10 ± 3 ℃ (bottom)	[84]
8	Retro-reflective coatings	Passive cool surface	Up to 8.5 ℃ (surface), 7 ℃ (air)	[76]
9	Light yellow asphalt layer	Slurry surfacing	Max 11.5 ℃ (surface), 1.5 ℃ (ambient)	[85]
10	TiO_2 & iron oxide coatings	NIR heat-reflective coating	9 ℃	[77]
11	Epoxy resin with pigment/filler	Super RHRC coating	11.7 ℃	[86]
12	CuO nanoparticles (flake)	NIR-reflective black coating	12.62 ℃ (summer), 10.04 ℃ (autumn)	[74]
13	Multilayer coating (TiO_2, SiO_2, glass beads)	Reflective + emissive + insulation layers	13.25 ℃	[87]
14	TR-HRC (heat reflective + thermal resistant coating)	Composite reflective pavement coating	13.2 ℃	[78]
15	Tourmaline Anion Powder (TAP)	Cooling asphalt modifier	6.6 ℃ (indoor), 7.2 ℃ (outdoor)	[79]
16	Solar reflective coating	Field-tested by mobile thermal platform	6.0 ℃ (midday), 4.0 ℃ (evening)	[88]
17	Ceramic waste in SMA	Insulation from recycled ceramic aggregate	4.5–5.0 ℃ (bottom vs. surface diff.)	[73]
18	TiO_2 + floating beads coating	Composite reflective coating	9.7 ℃ (surface), 8.3 ℃ (2 cm depth)	[80]

Reflective pavements also support roadway safety by improving visibility, especially when used as colored surfaces for crosswalks, bike lanes, and traffic-calming zones, helping to alert road users and potentially reduce accident risks [11]. Some solutions, such as micro-surfacing, are specifically engineered to maintain high skid resistance under wet conditions, while the addition of materials like manufactured sand or ceramic particles can further enhance surface friction [4, 66].

From a financial perspective, reflective pavements offer long-term cost-effectiveness. While the initial investment in light-colored or modified materials may be comparable to conventional options, their improved resistance to heat and weathering often translates to lower maintenance and repair costs over time [12, 76]. Furthermore, cooler pavement surfaces are less susceptible to rutting and plastic deformation, contributing to improved structural integrity and reduced need for early

rehabilitation [11, 12]. Finally, certain polymer-based reflective systems also help limit environmental impact by exhibiting low emissions of volatile organic compounds (VOCs) [7].

4.2.5 Drawbacks and Challenges

Although reflective pavements offer various environmental and functional benefits, they also face several limitations and implementation challenges. One of the most frequently cited concerns is glare and visual discomfort caused by highly reflective surfaces, especially those with white or light-colored coatings. These can result in excessive brightness, posing potential risks to both drivers and pedestrians, while also raising concerns about ultraviolet (UV) radiation exposure. In addition, the radiation reflected from pavement surfaces may inadvertently increase the heat load on adjacent buildings and walking areas, potentially leading to higher cooling energy demands. To counteract this, the inclusion of vegetated buffer zones has been proposed as a mitigating measure.

Durability and performance over time also remain critical issues. Pavement albedo tends to decrease due to material aging, dirt accumulation, weathering, and traffic abrasion, particularly during the initial period following installation. This degradation necessitates regular maintenance to preserve the cooling performance. Furthermore, the disparity in material stiffness between resin-based coatings and asphalt binders can lead to early surface damage such as cracking or spalling. In colder climates, reflective pavements can exacerbate winter hazards by reducing the absorption of solar energy that typically aids in snow and ice melting, thereby increasing the risk of slippery conditions and freeze-related cracking.

Another challenge relates to pavement texture and safety. Thin reflective layers can diminish surface macrotexture, potentially compromising skid resistance and traction, especially under wet conditions. Financially, while some reflective technologies are cost-effective in the long run, the initial cost of premium materials—such as titanium dioxide—can be substantial. Additionally, progress in developing new reflective technologies has been relatively slow, with many studies relying on similar approaches and materials. This highlights the pressing need for continued innovation. Lastly, more in-depth research is required to better understand the long-term durability, maintenance requirements, and life cycle cost implications of reflective pavement systems.

4.2.6 Future Research Directions

To support the broader adoption and optimized performance of reflective pavements, several key research directions warrant further exploration. First, there is a critical need to assess the long-term durability of heat-reflective asphalt systems, particularly regarding the degradation of optical properties due to environmental exposure, traffic loads, and material aging. Investigating how repeated solar exposure impacts coating performance is essential for predicting service life. In parallel, life cycle cost analyses that encompass the full spectrum of construction, operation, and maintenance costs are needed to evaluate the overall economic viability of reflective technologies. Innovation in materials—especially through the incorporation of industrial byproducts or recycled content—should also be prioritized to improve performance and sustainability while mitigating current limitations.

Safety concerns, such as glare, require more rigorous investigation through real-world driver assessments and human-factor studies. Establishing clear thresholds for visible reflectance and developing indices to quantify specular reflection can inform safer pavement design. Furthermore, achieving an optimal balance between thermal regulation and traditional pavement functions—such as skid resistance and fatigue performance—is a significant technical challenge. Future studies should adopt a holistic thermal evaluation approach that accounts for the entire pavement structure, rather than isolated surface layers. Material-specific properties, including the relationship between aggregate porosity and asphalt mixture mechanics, as well as chemical compatibility for adequate adhesion, must also be better understood. Lastly, research should consider contextual factors such as daily and seasonal temperature fluctuations, urban morphology, and regional climate characteristics to ensure reflective pavement technologies are appropriately tailored to their intended environments.

4.3 Evaporative Pavements

4.3.1 Mechanisms and Principles of Operation

In addition to reflective pavements, evaporative pavements represent another category of cool pavement technologies aimed at alleviating UHI effect by lowering surface temperatures. These pavements function primarily through water

retention and the evaporative cooling process, wherein latent heat is absorbed during the transition of water from liquid to vapour [9, 24, 66]. As pavement surfaces heat up, the moisture held within or on the surface evaporates, resulting in a cooling effect that benefits both the pavement and the adjacent microclimate [4, 8, 53, 66].

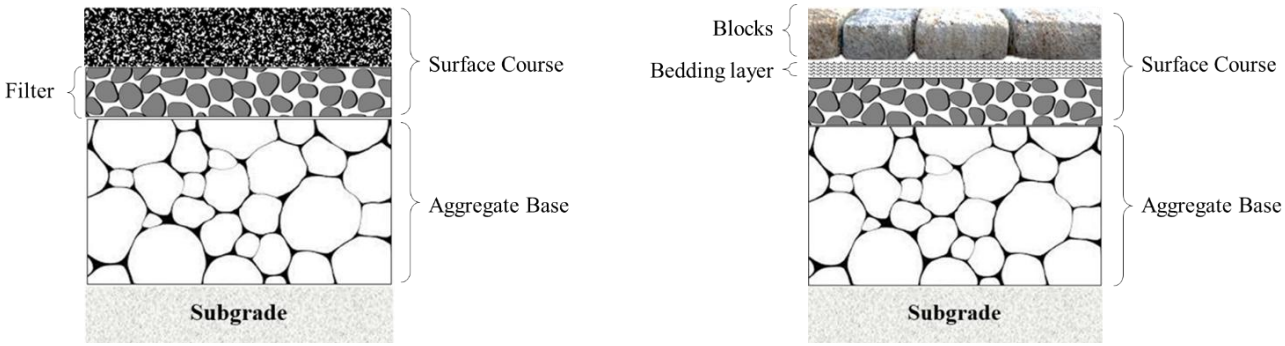
The efficiency of this cooling mechanism, however, is contingent upon the availability of a consistent water supply [12, 17]. The evaporation rate is governed by the material's moisture content and environmental factors, and is especially sensitive to surface temperature fluctuations [4, 24]. Enhancing this cooling effect requires optimizing several physical attributes of the pavement material, including porosity, permeability, water retention, and capillary action, as well as the texture and particle size distribution [24]. Additionally, the porous structure of evaporative pavements contributes to reduced thermal conductivity and slower heat diffusion, further supporting their cooling potential [66].

4.3.2 Types and Technologies of Evaporative Pavements

Two primary classifications of evaporative pavements exist: vegetative and non-vegetative types [9, 52, 83]. Vegetative pavements are designed to facilitate plant growth by allowing water to seep through joints or seams, whereas non-vegetative pavements are generally applied in pedestrian pathways or urban spaces where vegetation is not desired [9].

Within these broader categories, several specific technologies and materials have been developed. Porous pavements typically consist of interlocking units filled with gravel, sand, or vegetation. These systems retain water within the interconnected voids or through gaps between the blocks, with void coverage typically ranging from 20% to 50% of the surface area [89, 90]. In porous asphalt pavements, air void contents are generally around 18%, with European and Asian mixtures often exceeding 20%, while those used in the United States tend to have less than 20% void content [91]. A schematic representation is provided in Fig. 4 a).

Permeable pavements, while similar in concept, are distinguished by their ability to allow water to pass directly through the pavement material itself. Materials such as pervious concrete and open-graded friction courses (OGFCs) are designed with interconnected pores that enable vertical water movement into sublayers. This not only facilitates evaporative cooling but also supports urban water management through improved groundwater recharge and reduced surface runoff [4, 17, 55, 89]. Fig. 4 b) shows an example layout of permeable pavement.



a) Porous pavement ***b) Permeable pavements***

Fig. 4 - Schematic layer arrangement of a porous pavement (a) and permeable pavement (b) [9]

A further subcategory, high-void porous pavements, is characterized by even greater void content, often achieved through specially designed asphalt or concrete mixtures. These designs offer enhanced water retention capacity and increased cooling potential compared to conventional porous pavements [92].

Water-retaining pavements, also referred to as water-holding, water-retentive, or watered pavements, are specifically engineered to retain moisture near the pavement surface for extended periods [94]. These systems can be constructed from concrete, asphalt, or hybrid materials, and may include insulating layers and fine pores that facilitate capillary movement of water toward the surface. The use of light-colored materials in these pavements can further enhance reflectivity and cooling performance. Examples include porous asphalt treated with water-holding fillers derived from industrial by-products or slurry coatings designed to retain moisture [4, 66]. A typical structural diagram is shown in Fig. 5.

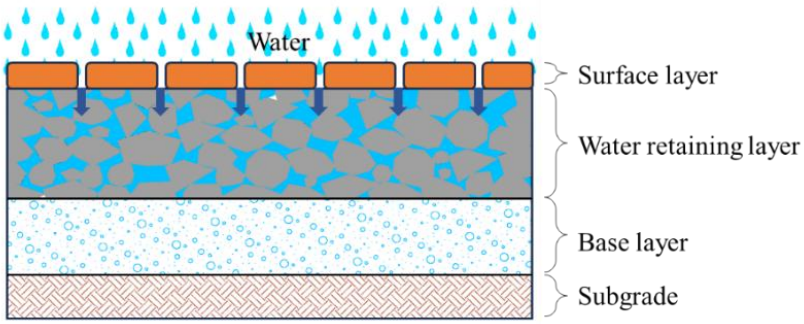


Fig. 5 - Schematic layer arrangement of a water-retaining pavement [93]

In some implementations, these pavements may include structural gaps to direct water toward the substrate or underlying soil layers [4]. Additionally, modular systems using paving blocks or plastic grid components have also been explored as part of this technology group [95, 96].

4.3.3 Cooling Performance and Effectiveness

Evaporative pavements have demonstrated considerable potential in reducing pavement surface temperatures, as summarized in Table 3. The temperature reduction achieved by these pavements varies depending on their structure, materials, and water retention capabilities. Reported surface temperature reductions range from approximately 4 °C to over 35 °C, with additional reductions in air temperature observed above some pavement types.

Table 3 – Summary of Temperature Reduction Achieved by Evaporative Pavement Technologies

No.	Evaporative Pavement Type	Technology/Method Description	Max. Temperature Reduction	Reference
1	Porous pavement	Water infiltrates and evaporates through voids in the pavement	Reduced surface temperature by 5 °C (from 54 °C to 49 °C)	[98]
2	Porous pavement	Modified concrete and asphalt mix with improved water retention	6.6 °C lower on concrete, 3.9 °C lower on asphalt vs conventional types	[99]
3	Permeable pavement	Water-permeable layers enabling subsurface cooling	15–35 °C surface temperature reduction in summer afternoons	[81]
4	Evaporation-enhancing permeable pavement	Capillary columns in aggregate and a liner at the bottom	Evaporation-enhancing permeable pavement was cooler than a conventional permeable pavement by as much as 9.4 °C during the experimental period.	[97]
5	Porous pavement (high void ratio)	Increased void content allows greater water retention and cooling	Surface temperature decreased by 4.1 °C	[100]
6	Water-retaining pavement	Designed to hold moisture near the surface	Reduced surface temperature from 16.6 °C to 7.2 °C	[101]
7	Water-retaining pavement	Post-rain cooling through surface water retention	5–20 °C lower above-surface temperature than conventional pavement	[102]
8	Water-retaining porous asphalt with insulation layer	Combines water-holding capacity with thermal insulation	10 °C lower temperature compared to basic porous pavement	[103]

9	Porous/water-retentive pavement	Compare conventional and Porous/water-retentive pavements	Air temperature reduction performance of 4.6 °C50 cm above the blocks	[104]

For instance, permeable pavements incorporating water-permeable layers have shown notable performance, with surface temperature reductions reaching 15–35 °C during summer afternoons [81]. Similarly, evaporation-enhancing permeable pavements, designed with capillary columns and bottom liners, demonstrated cooling effects of up to 9.4 °C compared to conventional permeable types [97].

In the case of porous pavements, water infiltration and evaporation through high-void structures have led to significant cooling outcomes. Reductions include 5 °C drops in surface temperature [98] and 4.1 °C in high-void configurations [100]. Moreover, hybrid porous-asphalt systems incorporating thermal insulation layers further improved performance, achieving 10 °C lower temperatures than basic porous alternatives [103].

Water-retaining pavements, engineered to hold moisture near the surface, have also proven effective. One study reported reductions from 16.6 °C to 7.2 °C after rain events [101], while another noted 5–20 °C lower temperatures above the surface compared to conventional pavement [102]. Even in scenarios without direct contact, porous/water-retentive systems demonstrated an air temperature reduction of 4.6 °C at a height of 50 cm above the surface [104].

Overall, these findings highlight the role of moisture-retaining capacity, surface porosity, and structural enhancements in improving pavement cooling performance. They reinforce the promise of evaporative pavements as a viable solution for mitigating UHI effect under conditions where water availability is sufficient and retention mechanisms are effectively integrated.

4.3.4 Benefits Beyond Cooling

Beyond their well-documented capacity to alleviate urban heat, evaporative pavements offer a range of additional environmental and functional advantages. One of the most notable benefits is their ability to support stormwater management. Due to their high permeability, these pavements facilitate water infiltration and retention within their structure, thereby reducing surface runoff and mitigating flood risks during heavy rainfall events. Moreover, they contribute to groundwater recharge by allowing rainwater to seep through, minimizing the volume of water conveyed through underground drainage networks and increasing the share of permeable land surfaces in urban areas [4, 17].

In addition to controlling runoff, evaporative pavements can improve water quality. As water infiltrates through permeable surfaces such as sidewalks, particulate matter and pollutants are filtered out, resulting in cleaner water entering subsurface systems [4, 17]. This passive filtration function is a key feature in integrated urban water management strategies.

Road safety is another area where evaporative pavements provide measurable benefits. By facilitating rapid drainage of surface water, they reduce the accumulation of thin water films that often compromise tire traction, thereby improving vehicular grip under wet conditions [8, 105]. Furthermore, these pavements can lower vehicle tire noise levels by approximately 2 to 8 dB, contributing to a quieter and more comfortable urban soundscape [105].

From a lighting and energy efficiency perspective, the reflective characteristics of some permeable pavement materials improve visibility during nighttime. This enhanced reflectivity can reduce the demand for artificial lighting in urban environments, leading to energy savings and improved pedestrian and driver safety [4].

Moreover, evaporative pavements are increasingly regarded as a critical component of green infrastructure. In line with the principles of Nature-Based Solutions (NBS), these pavements utilize natural processes—particularly water evaporation and infiltration—to deliver ecosystem services that address urban sustainability challenges. This aligns with broader environmental goals, such as those outlined in the European Union's Water Framework Directive. Vegetated pavement variants further support this function by creating environments conducive to plant growth, enhancing biodiversity and microclimate regulation [9, 106].

Finally, in the context of urban sustainability, evaporative pavements contribute to reducing surface heat accumulation and subsequent heat exchange with the atmosphere. This moderation of urban temperatures plays a vital role in creating more livable, climate-resilient cities [4, 106]. As such, these multifunctional systems support both environmental performance and long-term adaptation strategies in the face of growing urban heat stress.

4.3.5 Drawbacks and Challenges

Despite their numerous advantages, evaporative pavements also pose several limitations and operational challenges that can hinder their effectiveness and broader implementation. One of the primary concerns is their strong dependence on water availability, which restricts their performance to regions with adequate rainfall or high ambient humidity. In arid or dry conditions, these pavements may paradoxically exhibit higher surface temperatures—ranging from 5 °C to 10 °C more than conventional pavements—due to low reflectivity, insufficient water content, and increased solar absorption. Their relatively low thermal inertia and conductivity can further exacerbate surface heating under such conditions. Structural concerns also arise, as their porous design, while enhancing infiltration, compromises durability and makes them vulnerable to deformation and clogging. This degradation not only reduces cooling performance but may also inhibit long-term functionality.

Additional environmental and health concerns include the potential migration of pollutants from surface runoff into groundwater systems and the formation of localized humidity near the pavement surface, which may interfere with the natural cooling mechanisms of pedestrians. Moreover, the typically rough and dark surface textures of permeable pavements contribute to a lower albedo, reducing their ability to reflect solar radiation—particularly problematic in dry spells. Temperature variability is another issue, as the heterogeneous pore structure complicates convective heat transfer and moisture retention, leading to unpredictable surface temperatures. From an implementation perspective, the adoption of evaporative pavements remains limited, primarily due to gaps in technical knowledge, lack of design standards, and low stakeholder interest. Some systems also require external energy inputs for maintaining water circulation, which can offset the environmental benefits. These challenges highlight the need for site-specific evaluations and technological improvements to enhance the feasibility of evaporative cooling pavements.

4.3.6 Future Research Directions

Future research and development efforts related to evaporative pavements should focus on addressing current limitations and enhancing their overall performance and applicability. A key area involves improving the universality of these systems by collecting empirical data under varied climatic conditions—such as different levels of solar radiation, sunshine duration, and wind speed—to better understand the relationship between environmental factors and cooling effectiveness. Further studies should investigate the inherent thermal behavior of pavement materials, particularly under dry conditions, to evaluate their standalone performance. Optimizing water usage is also essential; analyzing in-situ temperature profiles and heat fluxes can help identify appropriate water volumes required for pavement watering, providing valuable insights for urban planners. Given the challenges in measuring outdoor evaporation rates—such as disruptions in capillary water flow—a relative measurement approach, using bare water as a benchmark, could enhance accuracy.

Additionally, mechanical durability and skid resistance under varying vehicle loads must be assessed through accelerated wear testing and field trials to ensure safety and longevity. Research should also target the development of novel materials and construction methods that enhance evaporative performance, for instance, by improving capillarity to increase water retention and evaporation. Integrated solutions tailored to seasonal and daily thermal cycles, and adapted to local urban design, will improve system efficiency. The lack of standardized monitoring protocols presents another gap; establishing robust evaluation frameworks—including the strategic placement of temperature and heat flux sensors—will facilitate more consistent assessments across studies.

Understanding the broader-scale impacts on air temperature, particularly in densely built environments, remains a significant challenge but is crucial for quantifying the benefits of cool pavements in urban climate regulation. Moreover, comprehensive life cycle assessments are needed to ensure economic and environmental sustainability. Finally, overcoming institutional hesitation and encouraging greater adoption by public authorities will be vital for scaling up the deployment of evaporative pavements in real-world applications.

TES pavements represent an innovative category of cool pavement technologies designed to mitigate UHI effect by managing heat absorption and release. This comprehensive review delves into their mechanisms, types, performance, benefits, drawbacks, and future research directions.

4.4 Thermal Energy Storage Pavements

4.4.1 Mechanisms and Principles of Operation

TES pavements represent the third major category of cool pavement technologies, functioning through the regulation of heat flow within the pavement structure to minimize surface temperature fluctuations. Their fundamental goal is to moderate urban heat accumulation by preventing sharp and excessive temperature shifts in pavement systems [53].

One of the core mechanisms in TES pavements involves the integration of Phase Change Materials (PCMs). These materials are capable of absorbing and releasing considerable amounts of latent heat during phase transitions—typically from solid to liquid or to an amorphous state—without significant changes in their own temperature. When embedded within pavement layers, PCMs can effectively buffer temperature peaks by storing thermal energy within a targeted temperature range, thus reducing heat accumulation at the surface [53, 66].

Another common strategy includes the use of embedded heat exchange systems, where fluid-filled pipes are installed beneath the pavement surface. These systems work by transferring heat away from the pavement via convection, as circulating fluids (such as water or air) absorb excess thermal energy. The removed heat can be repurposed or dissipated elsewhere, reducing the thermal load retained in the pavement and, by extension, in the surrounding urban microclimate [17].

Thermoelectric pavements offer distinct approach by leveraging natural temperature gradients within the pavement structure or between the pavement and ambient air. These systems employ thermoelectric generators (TEGs) that convert the temperature differential into electrical energy through the Seebeck effect, a thermoelectric phenomenon in which an electric voltage is generated when a temperature gradient exists across two dissimilar conductive materials. This mechanism contributes to both pavement surface cooling and energy harvesting [66].

Photovoltaic-integrated pavements, although primarily designed for solar power generation, also demonstrate UHI mitigation benefits. Their surface temperatures are significantly lower than those of traditional asphalt pavements, partly due to the reflective and energy-absorbing characteristics of the solar panels embedded in the pavement structure [9].

Collectively, these technologies aim to improve the thermal regulation capabilities of pavement systems. This is accomplished either through passive means—such as storing latent heat within PCMs—or via active mechanisms that remove or convert excess thermal energy. Together, they offer a promising avenue for both UHI reduction and enhanced pavement performance in urban settings.

4.4.2 Types and Technologies of Thermal Energy Storage Pavements

TES pavements encompass a diverse set of technologies aimed at moderating pavement surface temperatures by storing or redistributing heat. These technologies are generally classified based on their heat regulation strategies, including PCMs, embedded heat exchange systems, thermoelectric devices, and photovoltaic integration.

PCM Pavements utilize substances capable of absorbing and releasing latent heat during phase transitions to regulate thermal fluctuations in the pavement. Among the commonly studied PCMs are polyethylene glycols (PEGs), particularly PEG2000 and PEG4000, due to their favorable phase transition ranges and high latent heat storage capacities [53]. Other materials investigated for PCM pavements include ceresin [107], binary fatty acid blends combined with diatomite [108], polyurethane-based solid–solid PCMs [109], and organic mixtures such as OM 35 and OM 42 [110].

Integration of PCMs into pavement structures can be accomplished through several techniques. These include the dry method, where PCMs replace part of the aggregate before compaction, and the wet method, in which PCMs are blended with asphalt binder prior to mixing with aggregates [53]. Alternative approaches involve applying PCM-based acrylic coatings on the pavement surface [53], embedding PCMs in prefabricated tiles [111], or utilizing encapsulated forms—either within a carrier medium or as microcapsules. Examples of encapsulated systems include n-docosane PCM combined with methyl methacrylate (MMA) resin [7] and expanded clay aggregates coated in cement paste [110].

Hydronic Pavements, or Heat Exchange System Pavements, feature embedded piping systems beneath the surface that circulate cooling fluids to extract and redistribute heat. Common materials for the piping network include cross-linked polyethylene (PEX) [19] and galvanized steel [17]. One prominent application is the Road Energy System developed by Ooms Avenhorn Holding, which effectively captures and reuses thermal energy from roadways [66].

Thermoelectric Pavements incorporate thermoelectric generators (TEGs) to convert temperature differences within the pavement into electrical energy using the Seebeck effect [17]. To enhance thermal gradients, design modifications may include the addition of vapor chambers, water tanks, and aluminum heat-conducting plates [66]. Microencapsulated PCM powders have also been used to augment the temperature differential within the pavement layers and improve TEG performance [17].

Photovoltaic Pavements integrate solar energy harvesting into pavement infrastructure. These systems typically feature embedded photovoltaic panels within the pavement surface [9]. Some innovative approaches employ photovoltaic coatings in combination with ceramic substrates, providing both energy generation and pedestrian compatibility [4].

Each of these TES pavement technologies demonstrates unique mechanisms for managing thermal loads and holds promise for integration into urban heat mitigation strategies. Further research into their long-term performance, durability, and cost-effectiveness remains essential to support broader adoption.

4.4.3 Cooling Performance and Effectiveness

TES pavements demonstrate considerable potential in reducing surface temperatures by actively regulating heat within pavement structures. As shown in Table 4, the effectiveness of these systems varies across different technologies. In general, TES pavements can achieve surface temperature reductions between 4 °C and 14 °C under warm weather conditions [17].

Table 4 – Summary of Temperature Reduction Achieved by Thermal Energy Storage Technologies

No.	Type of Pavement Technology	Maximum Surface Temperature Reduction	References
1	General TES Pavement	Decrease in surface temperature ranging from 4 °C to 14 °C	[17]
2	PCM Pavement (e.g., Ceresin)	Temperature drop observed up to 5 °C	[107]
3	PCM Pavement (OM 35 and OM 42)	OM 35: 1.85 °C reduction; OM 42: 2.76 °C reduction (vs. standard asphalt)	[110]
4	Heat Exchange System Pavements	Reduction of 15–20 °C in peak summer conditions	[66]
5		Temperature drop of ~15 °C achieved	[19]
6		3.62 °C reduction per 100 W/m² heat removal	[66]
7	Thermoelectric Pavement (TEG-based)	Surface temperature decreases up to 9 °C during summer	[115]
8		Novel TEG design led to 14.1 °C reduction compared to concrete specimens	[112]
9	Photovoltaic Pavement	Surface temperature lower by 3–5 °C compared to asphalt/concrete pavements	[4, 9, 114]
10		Approx. 5 K surface temperature reduction and nearly 1 K ambient cooling	[113]

Among TES approaches, hydronic systems (embedded heat exchange pipes) offer the most substantial peak reductions, with several studies reporting temperature drops of 15 °C to 20 °C during summer periods [19, 66]. These systems function by circulating a cooler fluid beneath the pavement surface, efficiently absorbing and dissipating heat, although their complexity and cost may limit practical application.

PCMs also show promising results, with temperature reductions depending on the type and method of integration. For instance, ceresin-based asphalt achieved a surface temperature decrease of up to 5 °C [107], while other organic PCMs such as OM 35 and OM 42 led to reductions of 1.85 °C and 2.76 °C, respectively, in outdoor experiments compared to conventional asphalt [110].

Thermoelectric pavements, though still at a relatively early development stage, have demonstrated cooling capabilities as well. One innovative configuration achieved up to 14.1 °C lower surface temperatures than standard concrete mosaics [112], highlighting the potential of thermoelectric generators (TEGs) to both harvest energy and moderate thermal buildup.

Photovoltaic pavements also contribute to temperature reduction while generating renewable electricity. These surfaces were found to be 3 °C to 5 °C cooler than typical concrete or asphalt pavements, and in some cases, they yielded an additional ambient air temperature drop of approximately 1 K [4, 9, 113, 114]**.**

In summary, TES pavements provide both passive and active cooling benefits, with varying degrees of effectiveness depending on material properties and system configurations. While some systems offer exceptional performance, particularly under high solar radiation, practical implementation must consider associated costs, durability, and integration complexity.

4.4.4 Benefits Beyond Cooling

In addition to their effectiveness in mitigating UHI effect, TES pavements offer a variety of broader functional and environmental benefits.

From an energy perspective, these systems can serve as renewable energy platforms by utilizing the solar heat absorbed at the pavement surface. Photovoltaic pavements directly generate electricity, while underground heat exchange networks can collect and repurpose low-grade thermal energy for applications such as ejector cooling and double-effect absorption cooling systems [9]. Moreover, thermoelectric pavements provide the added benefit of converting ambient heat into electrical power. For instance, a TES pavement system implemented in Switzerland was reported to collect approximately 140 MW·h of energy annually [66, 116].

TES pavements also contribute to enhanced pavement performance and durability. By stabilizing surface temperatures, these systems help minimize thermal deformation, shrinkage, and cracking—thereby extending service life and reducing maintenance demands [12, 17, 53]. The integration of PCMs within the pavement structure reduces temperature fluctuations and mitigates thermal stresses, leading to better fatigue resistance and overall structural performance. In particular, incorporating thermochromic materials has shown to improve rutting resistance, with a study indicating a 6.73% reduction in rutting depth under every 5000 vehicle loads when using 8% thermochromic powder [68].

From an environmental and societal perspective, TES pavements support sustainable urban development by lowering surface and ambient temperatures, thereby reducing reliance on energy-intensive cooling systems in nearby buildings [11, 68]. This contributes to the reduction of greenhouse gas emissions and promotes thermal comfort in densely built environments [11, 15]. Furthermore, pavement-integrated heating and cooling technologies can help preserve the roadway infrastructure and reduce environmental degradation caused by frequent repairs [19]. In these ways, TES pavements represent a multifunctional solution that aligns with broader climate resilience and sustainability goals.

4.4.5 Drawbacks and Challenges

Despite their promising potential, thermal energy storage pavements face several limitations that hinder their large-scale implementation. One of the primary concerns lies in the complexity and high initial cost of these systems. Pavements that rely on embedded piping or thermoelectric systems often require intricate construction and maintenance techniques, which can be both expensive and technically demanding. The use of advanced materials—such as titanium dioxide, diatomite, or hollow glass beads—further contributes to elevated costs, posing a barrier for widespread adoption. Additionally, the incorporation of thermoelectric components may compromise pavement strength, particularly under heavy traffic loads, due to structural voids or reduced material density around embedded elements.

In terms of performance, thermal energy storage technologies are still in the early stages of development compared to more established reflective and evaporative pavement systems. Thermoelectric solutions, for instance, suffer from low power conversion efficiency, with the highest documented rates not exceeding 7.4%. Moreover, the operation of such systems may require supplemental energy, especially to maintain fluid circulation under sloped road conditions, thus reducing net energy gains. The use of PCMs introduces another layer of complexity, as excessive PCM content can degrade the mechanical integrity of asphalt mixtures. The degradation of thermochromic microcapsules during mixing and paving processes, as well as the lack of clarity surrounding the optimal fusion enthalpy for UHI mitigation, also pose technical obstacles. Lastly, the long-term durability and aging behavior of thermally active materials remain critical issues, calling for continued research and refinement to ensure sustained performance under real-world conditions.

4.4.6 Future Research Directions

To fully unlock the potential of thermal energy storage pavements, future research must address several critical areas. First, achieving an optimal balance between thermal regulation and mechanical stability is essential. This includes identifying effective strategies for incorporating PCMs into pavement structures to ensure both durability and performance over time. In particular, more systematic investigations are needed to evaluate the long-term behavior of these pavements, especially under field conditions. Further, a comprehensive understanding of the pavement temperature field influenced by different regulation techniques would improve design accuracy and implementation.

On the material side, future work should delve into refining PCM properties such as particle size, melting point, and latent heat capacity. Effective methods for integrating PCMs into asphalt and preventing leakage remain key technical challenges. Detailed assessments of both thermal and mechanical responses of PCM-modified mixtures are required to validate their suitability for practical applications. Similarly, thermochromic materials need to be studied further—especially regarding their effect on pavement friction and the persistence of their thermal responsiveness after wear. New immobilization techniques for thermochromic coatings and evaluation of their performance over time could lead to improved safety and efficiency.

In addition to material-focused research, broader contextual factors also demand attention. Many existing studies lack testing under realistic environmental conditions, limiting their applicability. Thus, standardized evaluation protocols should be established, particularly for quantifying air temperature reductions at the neighborhood or city scale. Furthermore, life cycle assessments that consider economic, environmental, and performance metrics across diverse climates and urban settings are crucial for guiding the sustainable adoption of heat-mitigating pavement technologies.

5 Conclusion

This study has provided a comprehensive review of the development, classification, mechanisms, and thermal performance of cool pavements, focusing on three primary categories: reflective, evaporative, and thermal energy storage systems. Findings highlight that cool pavements can significantly reduce surface temperatures—up to 20 °C in certain conditions—depending on the technology and materials used. Among these, reflective pavements generally deliver the most immediate temperature reduction, while evaporative and thermal storage approaches offer extended performance benefits through water retention and heat modulation. In addition to their cooling effect, cool pavements also provide various co-benefits such as improved road safety, enhanced stormwater management, energy savings, and increased material durability.

However, several limitations and challenges remain, including high initial costs, material aging, durability issues, potential glare or safety concerns, and limited field validation under real-world conditions. Moreover, further research is needed to improve material formulations, quantify long-term performance, develop cost-effective solutions, and establish standardized evaluation protocols.

The UHI phenomenon poses growing challenges for rapidly urbanizing cities in developing countries, where climate vulnerability is compounded by high-density construction, limited green infrastructure, and strained urban services. In this context, Hanoi, Vietnam is experiencing intensifying UHI effects driven by fast-paced urbanization, increased impervious surface coverage, and rising energy demand. Recognizing these challenges, this study not only synthesizes global advancements but also helps shape research directions tailored to local conditions. Future studies in Hanoi should focus on testing and adapting cool pavement technologies under regional climate patterns, traffic conditions, and policy frameworks. These efforts will be crucial for building climate-resilient, livable, and sustainable urban environments in Vietnam and other developing nations.

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