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Review

Combating Urban Heat Island Effect—A Review of Reflective Pavements and Tree Shading Strategies

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Abstract: Pavements occupy about 40% of urban land cover, with 75–80% black top roads, playing a critical role in urban connectivity and mobility. Solar energy is absorbed and stored in pavements leading to an increase in surface temperatures. Decreasing green cover is further contributing to rise in regional temperatures. Due to this activity, the city experiences urban heat island (UHI). This study presents a critical review of the literature on mitigation measures to combat UHI using reflective pavements with an emphasis on durability properties and impacts of tree canopy. The strategies with a focus on application of chip seals, white toppings, and coatings were discussed. Role of surface reflectance, including those from asphalt and concrete pavements, albedo improvements, and technological trends, application of waste materials, and industrial by-products are presented. Also, urban tree shading systems' contribution to pavement temperature and microclimate systems is presented. The review shows that the development of mitigation measures using tree shading systems can reduce the pavement temperature during daytime and increase human thermal comfort. The outcomes of this review provide a scope for future studies to develop sustainable and state-of-the-art engineering solutions in the field of reflective coatings and urban forest systems.

Keywords: urban heat island; urban forest; reflective pavements; durability; tree shading

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1. Introduction

Infrastructure development activities are designed to cater to the growing population needs. Pavements are an integral part of infrastructure development in urban areas to provide interconnectivity and transportation. Parking lots, bike lane, and pedestrian paths are developed to facilitate the amenity requirements for a growing city. Overall, pavements occupy 38–40% of the urban land cover, and 75–80% of pavements have black tops with direct exposure to the sun [1]. In the construction process, vegetation is being replaced with heat-absorbing, thermally conductive, and high heat storage materials like bitumen and concrete. Pavements absorb and store solar radiation, leading to a further increase in the surface temperatures [2]. This phenomenon is known as the urban heat island (UHI) effect. Large quantities of solar radiation are absorbed by these materials during the day and released during the night time.

Pavement materials absorb and store solar irradiation, given their dark surface cover and large surface inertia [2]. During summer, heat absorbed by the black asphalt pavements is released into the surrounding environment, leading to pavement rutting and UHI effect [3]. Changes to human thermal comfort, urban microclimates, and the loss of tree cover all contribute to the UHI effect. In urban areas, natural disasters like bush fires and heatwaves exacerbate the heat stress due to interactions between the anthropogenic heat emissions and surfaces (buildings) [4]. Urban and suburban areas are warmer compared to rural areas with the build-up of heat radiation and transference activities from both urban infrastructure and anthropogenic activities like transportation and domestic heating and cooling [5]. The impervious nature of these materials reduces the infiltration rate of water, resulting in dry soil conditions decreasing the evapotranspiration rates and finally affecting urban forestry. Drying atmospheric conditions will further cause imbalances in local terrestrial ecosystems, leading towards a more significant adverse environmental impact.

Elevated temperatures due to UHI effects affect the thermal comfort of humans, potentially leading to heat-strokes, respiratory difficulties, heat cramps, dehydration, and heat related-morality. Children, aged people, and people with health concerns will be increasingly negatively impacted [6]. UHI effects may also further increase the impacts on health during heat waves, bush fires, and elevated temperature days during the summer season. Night-temperatures are also elevated, leading to further heat stress. Electricity demand for cooling also increases with elevated temperatures. The electricity demand increases by 1.5% to 2.0% for every 0.6 °C increase in air temperature. The peak load during the summer afternoons in large buildings increases significantly, further increasing electricity demand, leading to power outages [7].

In urban areas, human thermal comfort is greatly affected by air temperatures. Urban planners and designers have to develop city models to accommodate increasing population pressures with reduced impact on the residential environment and climate change. The development of urban forestry and the application of vegetation to provide better thermal comfort for urban dwelling and pedestrian activity is increasing in interest [8]. Furthermore, the growth of opportunistic weeds will increase under drying climate conditions, which may increase the frequency of bush fires. The loss of trees with large canopy in city suburbs has reduced shading effects and intensified UHI effects. Low rainfall intensity during summer poses a challenge in designing evaporative cooling systems. Urban forests and tree planting strategies to increase the canopy cover is a potential mitigation measure. During the rainy season, permeable pavements allow stormwater drainage, improving the groundwater recharge potential. Permeable pavements can be developed in low pedestrian and car traffic areas and building rooftops [9].

Advancements in reflective pavement focus on application of sealing, resurfacing, coating, and colored pigments to improve the albedo and thermal performance of the pavement surface. However, the scientific literature on the thermal and durability characteristics of the coatings is limited. Research trends in the field of shading and green infrastructure provided solutions to urban planners to develop tailor-made solutions to local needs, however the technical developments in application of vegetative covers and native and exotic trees as shading measures are quite limited. The present study aims to review and assess the approaches and technologies associated with reflective coatings to combat the UHI effect and to assist in the planning and development of cities by equipping with mitigation measures and engineering strategies to combat UHI by integrating reflective coatings and the urban forestry approach. A review on durability properties of reflective coatings and application of tress as protective elements to improve the performance of pavements and reduce daytime surface temperature is presented.

2. Methodology

A systematic review of literature on UHI mitigation measures using reflective pavements and tree shading was performed, with an aim to present and analyze the recent developments on the application of reflective pavements to combat UHI. Scientific reports, articles, and manuals were collected from academic databases that included Web of Science, Science direct, SciFinder, Scopus, and ProQuest, Springer Link, and Wiley online libraries. A combination of terminologies was used to improve the efficiency of the search strategy on a particular topic (e.g., reflective pavements and chip seal). The relevant articles were screened based on the title and abstract. The screening was performed to identify the articles satisfying the following two criteria: First, the application of reflective pavements to mitigate UHI and the implication of the use of by-product and waste materials as pavement material to mitigate UHI were reviewed (Keywords: reflective pavements, pavement materials). Second, the use of vegetative cover to mitigate UHI was reviewed (Keywords:

Green spaces, Urban forest, Tree spaces). The identified articles were reviewed with a prime focus to evaluate the (a) role of surface reflectance, (b) mitigation measures using reflective pavements with a focus on coatings and their characteristics, (c) application of waste and industrial by-products, and (d) application of tree shading to reduce pavement and daytime surface temperature.

3. Role of Surface Reflectance

Globally, asphalt pavements are widely used. Quick construction, smooth surface, and low noise are advantages of asphalt pavements. However, absorption of heat contributes to increase in surface temperatures, leading to pavement damage due to rutting and aging [10,11]. Reduction of absorbed solar energy using reflective pavements is a cost-effective approach to reduce the surface temperature of the pavements. Application of white or light-colored coatings as well as the reduction of the surface roughness are deemed the most efficient approach to reduce absorption of solar radiation through surface reflectance [5].

Reflectance of pavements was found to increase due to the use of whitish cementitious materials and light-colored aggregate. Resurfacing of conventional roadways with materials having higher albedo (light color) increases solar reflectance and reduces the surface temperature [1,3]. Techniques like chip seals, slurry seal, white topping, ultra-thin white topping, micro-surfacing, and roller compacting with light-colored aggregates and/or emulsified polymer resins could also increase the reflective properties of pavements. Increasing the reflectance of solar radiation mainly mitigates the thermal behavior of the pavement [12]. However, reflectance of ultraviolet (UV), visible, near-infrared, and total reflectance could result in side effects impacting human health. UV radiation has less impact on the thermal environment and the visual perception of humans but could potentially damage human skin. Visible region radiation could cause visual effects on the corona of human eyes [5]. Rosso et al. [13] reported that application of fillers and pigments in the near-infrared region compared to the visible region can enhance reflectance and reduce the glare problem. The solar reflective coating is widely used to improve the reflectance properties of asphalt pavements. The albedo of these coatings (e.g., titanium dioxide) increases the cooling effect of the pavements. However, with these coatings, glare reflectance increases the visibility loss of the drivers [2]. Cool colored coatings were developed to achieve low albedo of visible light and high albedo of near-infrared light. Carbon black, colored organic pigments, or synthetic inorganic metal oxides have been proven to improve the reflectance and cooling properties of asphalt pavements. This carbon black may reduce near-infrared albedo, but they may be either less durable or expensive depending on the type of pigments used. Organic pigments are less durable, while synthetic pigments are expensive and may pollute the environment during its production process [14–16].

Role of Albedo in Pavement

The albedo of asphalt pavement plays a pivotal role in the reduction of pavement temperature [17]. Increasing the albedo of the pavement is the simplest technique that varies the thermal inertia of the pavement [18]. The ratio of solar radiation reflected by surface to total incoming radiation is defined as albedo. The initial albedo value of a reflective coating is in the range of 0.4 to 0.8. Cracking and peeling of coatings over time reduce the albedo. In low-traffic pavements, the life of the reflective coating ranges between 0.5 and 3 years and is comparatively low in high-traffic pavements, leading to increase in maintenance cost. Recoating at periodic intervals improves the pavement reflectance properties and reduces skid-resistance. Precautions to reduce skid-resistance have to be taken to ensure the safety of riders [19]. In addition to heat-reflective coatings, the application of quartz sand and ceramic particles are mitigating measures to further improve pavement friction and skid resistance [20]. However, the addition of quartz sand may reduce the abrasion resistance and durability of the coating [17]. The mechanical properties of the pavement are not altered with the application of these coatings [16].

In concrete pavements, solar reflectance of cement dominates the albedo, which is the ratio of radiosity to the irradiance (flux per unit area) received by a surface (i.e., 0.35–0.40) of hydrated concrete in the primary stages [21]. Production of calcium hydroxide during the hydration process increases the albedo of pavement, and it is stabilized at the end of the hydration process [18]. Application of fly ash as a partial replacement of cement increases the durability due to its reaction with calcium hydroxide. However, the albedo of the pavement reduces slightly because fly ash is darker than cement. The albedo of the pavement increases with the addition of pozzolanic additive slag (0.20 to 0.58) due to its high reflectance property compared to fly ash [22]. Wetting, soiling, and abrasion will influence the solar reflectance properties of concrete pavement with age. In roller-compacted concrete pavements, dry and stiff Portland concrete mixes are compacted in the surface layer using vibratory rollers. The hydrated cementitious mixture has higher albedo and lower surface temperatures than conventional asphalt pavements [23].

The albedo of the pavement also varies with weathering. New concrete pavement is grey in color, and will have an albedo of 0.35–0.40; upon aging, albedo will decrease to 0.20–0.30. The tire wear and accumulation of dirt on the surface of the pavement also reduces the albedo. The albedo of new asphalt pavement is between 0.05 and 0.10 and increases to 0.10–0.15 upon aging. The oxidation of the binder and aggregate wearing due to vehicle activity will also reduce the surface darkness, increasing the albedo [24]. The thermal performance of pavements is affected by the thermal and reflective properties of the paving material (albedo, thermal emittance, specific heat, surface convection, and thermal conductivity), geographic location, ambient conditions (sunlight, wind, and air temperature), and solar conditions (altitude and azimuth) [25]. Albedo is a vital material parameter in determining the thermal behavior of the pavement or surface coating under solar radiation. Recent technological trends in the field of reflective pavements are shown in Table 1. Further research is needed to understand the thermal behavior performance of colored pavements based on differing site locations and solar conditions [26].

Table 1. Technological trends in the field of reflective pavements (extracted from Santamouris et al. [5]).

Technology to Increase the Albedo	Description	Final Albedo Achieved	Thermal Benefits	Ref.
		Asphalt pavements		
Infrared reflective colored paints on the pavement surface	Application of dark infrared reflective paint with hollow ceramic particles on the mass of the pavement	0.46	Daily surface temperature reduced by 5 K compared to a same color concrete	[27]
	Application of dark infrared reflective paint with hollow ceramic particles	0.50	Daily surface temperature reduced by 8–15 K and by 2 K during the night	[28]
	Application of five thin reflective layers of different colors using infrared reflective pigments	0.27–0.55	Daily surface temperature reduced by 16–24 K and by 2 K during the night	[16]
Heat reflecting paint to cover aggregates	Application of reflecting paint to cover all aggregates	0.46–0.57	Reduce of the daily surface temperature of the pavement by 10.2–18.8 K	[22]
	Application of reflecting paint to cover the surface aggregates	0.25–0.6	Reduce of the daily surface temperature of the pavement by 6.8–20 K	[29]

Table 1. *Cont.*

Technology to Increase the Albedo	Description	Final Albedo Achieved	Thermal Benefits	Ref.
		Concrete pavements		
Color changing paints	Application of eleven thermochromic colors	Colored: 0.51–0.78 Colorless: 0.71–0.81	Daily surface temperature reduced by 5.4–10 K	[30]
Reflective colored paints	Application of ten infrared reflective paints of different color	0.27–0.70	Daily surface temperature under hot summer conditions reduced by 2–10 K	[31,32]
	Application of 14 high-reflectivity white paints on surface of concrete tiles	0.80–0.90	Daily surface temperature of a white concrete pavement under hot summer conditions reduced by 4 K and by 2 K during the night	[33]
	Application of white paints based on the use of calcium hydroxide placed on surface of concrete tiles	0.76	Daily surface temperature under hot summer conditions reduced by 1–5 K and by 1 K during the night	[23]
Fly ash and slag as constituents	Replacement of cement with 70% of slag	0.58	Not available	[34]

4. Reflective Pavements

4.1. Reflective Pavements

4.1.1. Sealing

Sealing the pavements with the light-colored materials increases solar reflectance and reduces the surface temperature. Chip sealing is a resurfacing process in which a thin base of the binder is distributed over the surface of aged pavement and finely graded aggregate is pressed into the base. The albedo of the aggregates exposed to the surface should be between the reflectance of the binder and aggregate results in an increase of heat and light reflection compared to thermal conduction by the pavement [18]. The color of the aggregate and age of the pavement will have an influence on the solar reflectance of the pavement. The albedo of the chip seal reduces over time due to aging. However, it remains higher compared to standard asphalt pavement for about five years [27]. The surface temperature of asphalt roads can be reduced by up to 9 K by the application of this technique [5]. Light-colored slurry seal is a cold mix asphalt containing asphalt emulsion, graded aggregate, additives, and water. It acts as a hard-wearing cover for the pavement surface. The asphalt emulsion acts as a binder to hold the aggregate in the chip sealing and bonding coats. Emulsified asphalt is blended with water; on application, the water separates, developing a black color. This binder is suspended in a surfactant which improves the binding between the old pavement, aggregate, and coating. Emulsifiers used in the binder play a key role in the setting of the binder. The application of these emulsions in wet-freeze climates can reduce water infiltration and increase skid resistance in combination with chip seals and overlays. However, this is not the best solution for wet-freeze climates [35]. The production of whitish slurry seals involves the reformulation of the emulsifier, leading to an increase in project cost [36]. This is mainly suitable for low-volume traffic roads. Partial replacement of the emulsified binders can be achieved with the application of bio-derived binders. Bio-derived binders can be produced from swine waste, waste wood, and vegetable oils. Vegetable oil-based binders are renewable resources, and the products that can be generated include rejuvenators, biopolymers, and resin-like synthetic binders [37–40].

The chip seal lowers pavement surface and subsurface temperature because more of the sun's energy is reflected away, and there is less heat at the surface to absorb into the pavement. They can contribute to lower both surface temperature of pavement and air temperature during day and night [5]. Solar reflectance decreases over time, as soiling from traffic makes chip seals darker. Reflected heat can be absorbed by the sides of surrounding buildings warming the interior of the building and contributing to the UHI effect. Chip seals are most often used to resurface low-volume asphalt roads, although highway applications also exist. This technique may be effective when paving large, exposed areas, such as parking lots.

4.1.2. Resurfacing

Resurfacing is a process to improve the longevity of existing asphalt pavement. White topping is a resurfacing technique in which surface of the asphalt is overlaid with a Portland cement concrete. The high albedo of the cement contributes to an increase in solar reflectance, resulting in a decrease in surface temperature. The albedo of the new concrete varies between 0.35 and 0.4, while the old one varies between 0.2 and 0.3. Based on the thickness of white toppings, they are classified as conventional (>20 cm), thin (10–20 cm), and ultra-thin (5–10 cm). Mixing of asphalt emulsion and aggregates is also used to repair asphalt pavements [5].

4.1.3. Coatings and Color Pigments

Color pigments, fillers, and additives are added to increase the albedo of pavements. Aesthetic and glare problems often increase with the application of paints due to an increase in reflectance. The reflectance of coatings reduces over time due to exposure and weathering actions [30,39,41–44]. Jiang et al. [17] designed a novel reflective coating with functional gradient multilayer structure to alleviate the pavement surface temperature and investigated cooling efficiency, safety, and durability properties. The results showed an internal temperature reduction by 11.5 to 13 °C. The developed reflective coating complied with standards for water, alkali, skid, and abrasive resistance. Xie et al. [44] investigated an application of water-based reflective coatings for reflective pavements. Optical and durability performance of near-infrared TiO_2 reflective coatings including skid-resistance, anti-abrasion, and film hardness were studied. The results showed that the near-infrared reflectance of the coating reached 60% compared with a conventional coating. The summary of studies investigating the cooling effect using coatings and their characteristics of reflective pavements is presented in Table 2.

Table 2. Summary of technology investigations on coatings in the field of reflective pavements.

Binders and Additives	Pigment and Fillers	Skid-Resistance Material	Properties Studied	Key Inferences	Ref.
Silicone modified acrylate emulsion	Near-infrared transmission: Inorganic Y Low near-infrared reflecting: Organic G High near-infrared reflecting: Rutile TiO_2	Silica sand	Thermal Parameter • Cooling performance. Durability Parameter • Water resistance. • Alkali resistance. • Skid resistance. • Abrasion resistance.	• Reduction in temperature up to 8.5–9.5 °C was observed. • Water, alkali, skid, and abrasive resistance of the proposed coatings complied with the requirements of pavement standards.	[16]
Potassium silicate with aluminium phosphate	Titanium oxide	Nil	Optical Parameter • Solar reflectance. Durability Parameter • Adhesive strength. Water resistance	• The material achieved 90% solar reflectance. • Water content had a significantly weak effect on the adhesive strength and on the solar reflectance of the coating. • Water content had no effect on the water resistance. • Adhesive strength of the coating increased with decreasing water content.	[18]
Epoxy glue	Nano-Titanium oxide Micro-Titanium oxide Nano-Zinc oxide	Nil	Optical Parameter • Albedo. Thermal Parameter • Internal temperature transfer. Cooling effect	• Albedos of asphalt mixtures are lower than those of Plain Cement Concrete. • Gradation of asphalt mixture has little impact on the albedo. • Rougher PCC surface reflects less incident solar radiation and produce a higher pavement temperature. • Reflective coating can significantly increase the albedo and decrease the temperature of asphalt mixture. • Micro-TiO_2 has better reflectance than Nano-TiO_2 and Nano-ZnO.	[36]

Table 2. *Cont.*

Binders and Additives	Pigment and Fillers	Skid-Resistance Material	Properties Studied	Key Inferences	Ref.
Silicone acrylic emulsion and epoxy resin	White: Titanium dioxide Black/brown: Nickel oxide Other colors: Ferric oxide and its hydrate in yellow, red, blue, green, and grey	Nil	Optical Parameter • Spectral reflectance. • Lightness. Thermal Parameter Temperature	• Color lightness is the dominant factor for spectral reflectance in the visible radiation region and no influence in near-infrared light region is observed. • Higher lightness means higher visible light reflectance. • The reflectance between 400 and 1100 nm is the main significant factor to influence the thermal performance of reflective coatings.	[44]
Organosilicon-modified acrylate	Red iron oxide and Titanium oxide	Nil	Optical Parameter • Spectral reflectance. • Lightness. Durability Parameter • Skid resistance. • Abrasion resistance.	• Dosage of Near Infra-Red-infrared TiO_2 being limited to 10% to achieve good optical performance and the economic efficiency. • Skid-resistance and anti-abrasion performance of coatings complied with the requirements of pavement standards. • Anti-pollution performance of pavement coatings needs more research.	[45]
Epoxy resin	Full-body Porcelain Monoporosa Porcelain glaze	Nil	Optical Parameter • Surface reflectance. Thermal Parameter • Surface temperature.	• Utilization of waste tiles can improve near-infrared surface reflectance. • Full-body Porcelain showed better results compared other materials and reduced temperature up to 6.5 °C. • Reduction in surface temperature between 4.1 and 9.6 °C was observed. • High reflectivity of the pavement surface will maintain low pavement surface temperature.	[46]

Table 2. *Cont.*

Binders and Additives	Pigment and Fillers	Skid-Resistance Material	Properties Studied	Key Inferences	Ref.
Epoxy and polyphthalamine resins	Micro-powders of pyrite, spiegeleisen, and titanium dioxide	Nil	Durability Parameter • Anti-compression. • Anti-rolling. • Anti-abrasion. • Anti-corrosion. • Anti-impact.	• The cooling effect increased gradually with an increase in the temperature of the asphalt slab specimen without coating. • The durability properties of the pavement improved with introduction of coatings.	[47]
Polyvinyl alcohol and epoxy resin	Titanium oxide and carbon black	Sand	Thermal Parameter • Cooling performance. Durability Parameter • Skid resistance. • UV radiation aging.	• Reduction in temperature up to 10 ± 2.5 °C. • Addition of sand reduces abrasion resistance performance. • UV absorbent (UV-531) changed the color of coating but improved their UV aging resistance.	[48]
Portland cement and recycled glass aggregates	Titanium oxide	Nil	Optical Parameter • Surface reflectance. Thermal Parameter • Emissivity. • Conductance.	• Cool-colored concrete prototypes were investigated both in lab and in field for characterizing their thermal-optical properties. • No significant variations in thermal conductivity values among the samples, when varying pigment type and percentage. • Additive added is providing the cooling capacity to the material; so, additional manufacturing unit at construction site is not needed. • Results indicated that prototypes with IR pigments have higher solar reflectance, up to +15.8% compared to standard concrete prototypes and +12.5% with respect to same color prototypes without high infrared reflective pigments. • They can maintain surface temperatures that are up to −10.6 °C lower with respect to non-IR samples.	[13]

4.2. Durability Properties of the Reflective Pavements

4.2.1. Skid Resistance

Skid resistance is a significant factor to avoid the loss of control of a vehicle due to wet conditions and pavement coatings. Skid resistance properties are important at crossings, intersections, and on bends to avoid skidding due to application of breaks [49]. Aging of pavement, seasonal variations, debris, and drainage systems influence the skid-resistance of pavements [50,51]. Resurfacing and retexturing are two major options to improve the skid resistance of pavements. The application of cool pavement strategies will provide a dual benefit by improving the life of the pavement and reducing the UHI effect. The retexturing process improves the frictional properties of the pavement. Diamond grooving, shot-blasting, bush hammering, and high-velocity water blasting are also different retexturing approaches for improving the skid resistance. The resurfacing process involves the application of thin surface treatments to improve the texture and wet road skidding. The road surface is sealed, preventing water penetration and reducing the disintegration of the existing road surface. Surface dressing and high-friction surfacing are the methods used in resurfacing of the pavements [52]. Chip sealing, slurry sealing, micro-surfacing, and ultra-micro-surfacing are different methods used in resurfacing. In laboratory investigations, a British Pendulum Tester is used to determine skid resistance. The results are reported in terms of the British Pendulum Number (BPN). The BPN should be more than 45 in conditions at standard temperature (20 °C) for expressways and first-class highways. Xie et al. [45] investigated the skid resistance of a coating containing titanium oxide as a filler, red iron oxide as a colored pigment, and organosilicon-modified acrylate emulsion as a binder. The results showed that skid resistance of the coated pavement decreased by 5% to 10% compared to uncoated in both dry and wet conditions. In dry conditions, the BPN is more than 75, and in wet conditions, it is more than 45. Jiang et al. [17] investigated skid resistance of multilayered coatings. The wearing of the coating due to rubber tires was observed. Chen et al. [47] observed the longitudinal deformation of coatings due to temperature variations. Sha et al. [48] investigated two types of coatings containing sand. The skid resistance performance of the coatings gave the best result with 30% sand content. Zheng et al. [20] reported that particle category and spreading amount are the dominant factors impacting skid resistance, while painting content has less impact.

4.2.2. Ultraviolet Aging

Pavement materials and coatings undergo thermal aging and photo aging. The thermal aging occurs during the construction stages, while photo aging occurs during the pavement service life due to exposure to UV radiation [53,54]. In low-traffic roads, aging of the pavements is due to the oxidation of the bitumen binder, while in high-traffic roads, polishing of aggregate due to wear and tear is the dominant factor for aging [55]. Deterioration of the pavement surface depends on the geographic location, climatic conditions, and traffic load. In coastal zones, salt sprays lead to further corrosion of coatings. Freezing and thawing due to seasonal variations also reduce the service life due to cracking defects and potholing [38,56].

Enrichment, rejuvenation, Polymer-Modified Emastic (PME), and micro-surfacing techniques are methods to protect the bitumen surface from aging. Enrichment is a process of spraying proprietary additives as a protective barrier. The application rate of additives is in the range of 0.3–0.6 l/m^2. This process improves the elastic and viscosity properties and reduces the rate of permeability. The application of this process reduces the road surface friction. PME involves the application of water-based mineral fillers to improve surface texture and prevent aggregate loss. The application rate is in the range of 1.0 l/m^2. Micro-surfacing is a resurfacing process used as an alternative for surface seals. Advantages of this process include oxidation inhabitation, surface friction improvement, and the reduction of rutting [57]. San et al. [52] investigated the aging performance of reflective coating under UV-531 conditions. Variations in the coatings' color due to decomposition was observed. Titanium dioxide and carbon black were stable under the UV radiation. Regular maintenance of pavements also improves the service life. Yu et al. [58] investigated the aging properties of Styrene Butadiene Styrene (SBS)-modified bitumen. Results showed that continuous exposure to UV radiation modified the network structure of the binder and reduced the phase angle (implies improved rutting resistance). However, top-down crack formations may increase due to the development of shrinkage stresses. Cracking at low temperatures may occur due to the pavements' rigid and brittle nature.

4.2.3. Compression Resistance

The compressive property of road coatings changes with environmental conditions. High temperatures, longitudinal compression deformation, and longitudinal static load will result in softening of road cool coating. The anti-compression performance of the coatings has to be evaluated under high and low temperatures and freeze–thaw cycle conditions. Chen et al. [47] investigated the anti-compression performance of six reflective coatings under different environmental conditions. Anti-compressive coefficients of the reflective coating increased by 0.63–4.48% compared to conventional coatings. The anti-compression coefficient is highest under low-temperature conditions and lowest under freeze–thaw conditions. More studies are required to understand the anti-compression coefficients of the coatings based on geographic conditions and traffic loads.

4.2.4. Abrasion Resistance

Abrasion resistance plays a key role in understanding the performance of the coating and its interaction with the wheel surface. The frictional action of the wheel surface changes under different environmental conditions. Chen et al. [47] investigated the anti-abrasion performance of the reflective coatings under low and high temperatures and freeze–thawing conditions. The results show that anti-abrasion resistance of the reflective coatings improved compared to conventional coatings. The abrasion quality loss of the coating decreased by 21–43%. However, further detailed studies are needed to more fully understand the abrasion resistance of the coating materials.

4.2.5. Corrosion Resistance

Reflective coatings undergo corrosion due to their exposure to different environmental conditions. Bubbling and flaking of coatings can be observed due to exposure to different levels of pollutions. Chen et al. [47] investigated the anti-abrasion performance of the reflective coatings under alkali, acid, gasoline, and sand conditions. Compared to conventional coating, the corrosion resistance of the reflective coating increased by 2.65–30.57%. The corrosion of the coating material was relatively high under pollution conditions compared to temperature variations. Structural changes were due to the interaction of the chemicals. Under the sand conditions, coefficient of friction increased, leading to increase in loss of corrosion quality.

4.3. Global Case Studies

Globally, reflective pavements are being applied at the field level to provide thermal comfort to the people. Ashghal public works authority (Qatar) implemented a pilot scale "cool pavement" project with an aim to mitigate the UHI effect. The project was launched in the capital city Doha during the month of August 2019. A road in Sauq Waqif, a popular tourist destination, and pedestrian and bike lanes in Katara cultural village were coated with 1 mm-thick blue-colored cryogenic material. The material is composed of a heat-reflecting pigment with hallow ceramic microspheres. The test sites were opened to traffic to investigate the performance of the material for a period of 18 months. Sensors were installed to record the surface temperatures of the coated and non-coated pavement surface temperatures. As per preliminary studies, the surface temperature of the non-coated pavement was 65 °C, while the coated surface temperature recorded was 58 °C. The temperatures were recorded at an outdoor temperature of 40.3 °C [59,60].

Makkah municipality (Saudi Arabia) implemented a cool pavement project with an aim to reduce by 15–20 °C and provide thermal comfort to the pilgrims. The project was launched in the Haj pilgrimage holy sites during the month of July 2019. The first stage of the project aimed to coat the pedestrian road located near Mina gate leading to Jamarat facility. Heat-blocking coatings were coated over the conventional asphalt pavements. A total area of 3500 m^2 pavement surface was coated in Shaiben. The project is being implemented in collaboration with Japanese corporation Sumitomo. The test sites were opened to pilgrims, and concrete barriers were placed to restrict the entry of vehicles. Sensors were located under the asphalt to record the temperature every 10 s. A survey is planned to collect the feedback from the visitors to enhance the service quality in the future [61,62].

The Bureau of Street Services, Los Angeles, was funded to apply a reflective pavement coating in 15 identified council districts. The goal of this project is to reduce urban-rural temperature differential by at least 1.7 °F by 2025 and 3.0 °F by 2035. A commercial reflective coating "Cool Seal" was applied in one City Street in each council. This project was implemented along with other mitigation approaches such as urban forestry and cool roofs. A total area of 13,000 m^2 was covered in 15 locations by 2018. The preliminary results indicated that the reflective coatings reduced the pavement surface temperature by 5.5 °C, on average. A temperature reduction of 3.3 °C was observed when coated pavements were soiled or eroded. The councils are now extending their research to investigate the longevity of the reflective pavements [63,64].

4.4. Application of Waste/Industrial By-Product Materials in Pavements to Mitigate UHI

The pavements constructed using conventional asphalt and concrete have low reflectance and emissivity due to their low albedo value, reflectivity, emissivity, and high heat absorption. Evapotranspiration and surface albedo are the critical parameters contributing to surface heating [3]. The thermal properties of the construction materials in pavement below the surface also contribute to urban climate variations [18]. Reflectance and durability properties of the raw materials used in pavement play a vital role in contribution to the UHI. Utilization of waste or industrial by-products as replacements to the conventional material provide a scope to mitigate UHI [1,18]. The development of a cool pavement strategy involves a systematic understanding of material properties. Experimental works on reflective pavements are primarily focused on surface layers with less emphasis on under layers and influence on UHI.

Guntor et al. [44] investigated the thermal behavior of asphalt pavement with and without coating material developed from wasted tiles. The results demonstrated that surface temperature of the asphalt pavement with coating reduced the surface temperature by up to 4.4 °C. This study provided a scope for application of waste by-products as coating material for asphalt pavement to combat the UHI effect. Synnefa et al. [16] tested thermal and optical properties of five thin-layered asphalt samples (different colored) prepared using elastomeric asphalt binder (colorless), color pigments, and recycled aggregate on large-scale arrangement of reflective surfaces in Athens, Greece, to mitigate UHI. The results found that all the samples demonstrated high reflectance and low surface temperature compared to conventional black asphalt. The computer fluid dynamics simulations showed a potential reduction of average ambient temperature up to 5 °C on replacing conventional asphalt with developed samples. The application of locally available waste materials to improve the mechanical, geotechnical, and durability properties of the construction material is gaining more attention [65–68]. The material testing includes both mechanical and durability properties studies [69]. Specifically, to evaluate the reflective pavements, solar reflectance and thermal emittance play a key role. The American Society for Testing Materials (ASTM) has developed and validated tests for measurement of solar reflectance, thermal emittance, and solar reflectance index. The laboratory tests are primarily focused to understand the properties of new materials, while field tests assess the performance and durability of the material. "Solar reflectance index" is an approach to determine a single value incorporating both solar reflectance and thermal emittance. The value obtained is used to compare the thermal property of the new material compared to a standard black or white surface.

Application of construction materials with high insulation to radiation and emissivity factor mitigate the UHI effect. The utilization of construction material with lighter color (near to white) or with high reflectance and emittance compared to conventional material increases the albedo of the pavement. Asphaltic material exhibits more reflectivity compared to the black top and is a preferred option in pavement structures. Development of the asphaltic material using chip seals increase the albedo that can reduce the surface temperature by up to 15 °C compared to conventional asphalt. Recycled asphalt pavement (RAP) and recycled concrete aggregate (RCA) are used widely in the USA for different sections of pavements. The utilization of 15–20% RAP in a wearing course is acceptable across the USA [70]. The Virginia and Texas transportation departments permit up to 30% and 20% application of RAP in base or sub-base applications [71]. The State of Nebraska approved the utilization of 50% RAP as a pavement construction material [72]. European countries are also utilizing industrial by-products in pavement construction.

Mitigating the UHI can be achieved by increasing the permeability of the concrete to achieve a cooling effect. The reflectance of the pavement can be increased to reduce the heat storage in the pavement. The application of slag, recycled aggregate, and epoxy resins in pavement construction can enhance the surface reflectance and reduce the storage of heat. Unitization of slag material with dynamic optical and thermal properties that are durable and withstand wear and tear contribute to reduce UHI effect. In Germany, pavements are constructed with the complete replacement of traditional materials with blast furnace slag. Ferrochrome slag with a particle size between 10 and 100 mm is permitted to be used as a pavement material by the Swedish national road and transportation research institute [73]. The performance of the pavement depends on both good mix design and the load-bearing capacity of the subgrade. Lime and cement are conventionally used materials to improve the strength, durability, and swelling properties of the soil [74].

Fly ash, a waste product from coal combustion, has also been used to improve the mechanical strength, shrinkage, and durability properties of the sub-soil [75]. A rapid hydration process with the addition of lime and fly ash simulates the cation exchange to flocculate the soil particles. This phenomenon improves the strength of the sub-soil and reduces shrinkage effects. A combination of fly ash with other industrial by-products has also shown improvements in soil properties. Application of fly ash as a replacement for cement increases the albedo due to dark color compared to cement. The utilization of fly ash as binder material up to 10% in pervious concrete developed with recycled aggregate helps in reducing the clogging. Development of binary concrete mix by including slag will reduce the albedo due to high surface reflectance. The application of fly ash and stone dust to control swelling properties in expansive soils have also been investigated. The results reported an improvement in the mechanical properties, maximum dry density, and soil index properties [76,77].

In Table 3, a summary of industrial by-products and waste materials commonly used in road pavement application is presented. The performance inferences presented in this review provide an overview of the structural and mechanical properties considered. The use of different pavement materials to mitigate UHI needs further research in order to provide an understanding of associated thermal, optical, and durability properties. These investigations need to be performed under both laboratory and field conditions in order to understand the efficiency of pavements in potentially mitigating UHI effects across a range of variables, including pavement material, reflectivity properties, geographic location, and solar conditions. Understanding these properties gives research and construction companies further information in successfully developing cool pavements that assist urban designers and local council authorities in the design and implementation of cool pavement strategies.

Table 3. Summary of application of industrial by-product waste materials in pavements.

<table>
<tr><th>Cement Substituent</th><th>Additional Substituents</th><th>Inference</th><th>Application in UHI</th><th>Ref.</th></tr>
<tr><td>Fly ash</td><td>-</td><td>• Replacement with 50% fly ash resulted in lower compressive strength up to 3% than 25% fly ash up to the age of 28 days.
• At a 90-day period, 50% fly ash samples showed higher compressive strength.
• Rate of water absorption decreased on replacement of fly ash with cement up to 41%.</td><td rowspan="2">• Addition of fly ash increases the albedo of the concrete. This is due to the dark color of fly ash compared to cement.
• The development of binary blends in combination with slag will increase the albedo and will provide a scope for mitigating UHI.
• The utilization of fly ash as a replacement for binding material in pervious concrete needs future investigations to understand reflectance, permeability, porosity, and clogging parameters.</td><td>[78]</td></tr>
<tr><td>Fly ash</td><td>Electric arc furnace Slag</td><td>• Increase in compressive strength up to 4% at 91-day age was observed.
• Replacement of fly ash up to 20% is recommend.</td><td>[79]</td></tr>
<tr><td>Recycled Concrete Aggregate (RCA)</td><td>Fly ash</td><td>• Virgin aggregates were replaced with RCA at different percentages up to 100% along with 18.5% to 20% cement replacement by class C fly ash.
• Air content of 6.5% was easily achieved.
• At 50% of RCA replacement, an increase in flexural strength up to 4%, good durability, and moderate 56-day chloride ion penetration was observed.</td><td rowspan="2">• Application of RCA in permeable pavements mitigate UHI. The research on field level application of permeable pavements with RCA has huge scope.
• Utilization of fly ash and 25% RCA showed lower clogging compared to the conventional concrete.
• The albedo of pervious Portland concrete is low compared to the conventional cement concrete.
• Application of pervious concrete to mitigate UHI is recommended only if evaporation of pervious concrete is promoted. The additional solar absorption due to lower albedo is compensated by the evaporation process.</td><td>[80]</td></tr>
<tr><td>RCA</td><td>-</td><td>• Concrete samples with 15% RCA had strength, permeability, and void content similar to those of the control mix.
• Concrete samples with 30% RCA or greater had a significant loss in strength and increase in permeability and void content.</td><td>[81]</td></tr>
</table>

Table 3. *Cont.*

Cement Substituent	Additional Substituents	Inference	Application in UHI	Ref.
Copper slag	-	• Inclusion of copper slag as fine aggregate showed no variation on 7- and 28-day strength. • Drying shrinkage decreased with the increase in slag and the decrease in stone dust content.	• Addition of slag increases the albedo of the concrete due to its high reflectance compared to fly ash. • Application of slag up to 70% of cement replacement improved the albedo by 71% (0.582) compared to conventional mix (0.341). • The studies on application of these materials at field level are limited, providing scope for research in this field. • The application of slag using micro-surfacing techniques can improve the skid resistance of the pavement.	[82]
Ground Granulated Blast Furnace Slag (GGBS)	-	• 40% replacement of cement by slag led to reduced porosity, water absorption, and permeability. • Addition of slag increased the moisture content required for maximum compaction.		[83]
Ferrochromium slag	Flash	• Improved compressed strength was observed at 28-day compressive strength of the concretes made with original slag and with standard limestone as aggregates (water/cement = 0.64 and 350 kg/m^3). • Utilization of slag improved volume stability, high-volume mass, good abrasion resistance to wear, and crushability compared to normal aggregate.		[84]

5. Tree Shading as a Mitigation Measure to Combat UHI

5.1. Pavement Temperature

The tree species, the geometric characteristics of trees, their leaf density, leaf area, and evapotranspiration all play a role in UHI mitigation [85]. Urban landscaping and the development of green spaces play a key role in controlling the variations of land surface and ambient temperatures in cities [86]. Increases in the percentage of vegetative cover with a high canopy index reduces solar energy absorption during summer [87]. However, the percentage of canopy cover required to counteract the elevated temperatures from pavements needs more research [88]. Impervious cover, low soil moisture, nutrient deficiencies, lack of rooting volume, water/air pollutants, and transport-related toxicities create hostile environments for trees in urban areas [89]. Low-temperature pressures, anthropogenic heat sources, air turbulence, and high wind speed due to urban canyons also influence tree population survival in cities. Evapotranspiration and the heat and drought tolerance of tree species depend on their morphological and physiological features, water availability, and wind strength in the geographic locations [90]. Direct solar radiation increases pavement surface temperatures, but tree canopy cover will provide shading and reduce these surface temperatures. Several studies on urban air and pavement temperature have reported that the pavement temperatures are high compared to air temperatures. Pavement temperature reduction between 5 and 25 °C was observed under the tree shading compared to the non-shaded areas [91].

Ziter et al. [92] investigated the interaction between tree cover and impervious cover surfaces during summer. An average of 3.5 °C difference in air temperature was observed between the coolest and hottest locations during the daytime in Madison, USA. The maximum cooling was achieved when the canopy cover was 40%. A nonlinear trend was observed for temperature with the increase in canopy cover. By comparison, the City of Canning only has a canopy cover of 7.6%. Planting more trees by integrating urban geometry can yield better outcomes. During the night-time, an average of 2.1 °C difference was observed between the coolest and hottest locations. The temperature during the night increased with the increase in impervious surface area. The reduction of impervious surfaces provides better mitigation in reducing the urban warming during the night. During heat waves, the time required to reduce the urban heat load increases, resulting in more use of energy in air-conditioning systems. Optimization of canopy cover and impervious surfaces is therefore a key mitigation strategy. The transmission of light through the canopy cover plays a key role in maintaining the temperature of the pavement [93]. Development of a database on native tree species, vegetative cover, and tree volume will help improve decision support systems for urban planning and landscaping to mitigate UHI [94]. Globally, government agencies and local communities are planning to develop mechanisms to mitigate urban heat by increasing urban vegetation.

Reflective pavements are applicable to the regions with hot summers and long hours of sunlight [1]. In hot and humid climatic conditions, during summer, surface temperature varies between 35 and 45 °C during the day and 10–15 °C during the night. During the daytime, due to absorption of heat, the inside pavement temperature rises up to 65–80 °C. The release of heat and reduction in the temperature during the night leads to development of a freezing and thawing effect in pavement. The repetitive cycles of freezing and thawing leads to development of cracks in the pavement. This rate of deterioration of pavement increases, leading to a decrease in service life of the pavement. Provision of tree shading provides a reduction of day temperature, leading to a decrease of variations in pavement temperature gradient. This improves the service life of the pavement. The present review is focused on reduction of the pavement surface temperature during the daytime. Research study needs to be performed to understand the relationship of pavement longevity and temperature based on the geographic location, and climatic and solar conditions.

5.2. Urban Microclimate

The shading, plant species, and orientation of trees contribute to temperature variations at the regional level. Urban shading reduces the local temperature, contributing to lower heat transfer from the surfaces countering the UHI. Urban shading is quantified through tree geometry, structure, leaf size, canopy cover density, and orientation. The determination of leaf size, type, angle, density, depth, and continuity of the actual solar radiation intercepted by a tree species can be quantified [95,96]. Thermal comfort in the ambient atmosphere is assessed by computing the air temperature and radiation exchange. Human thermal comfort can be enhanced through the development of tree shading zones. Trees with large canopy cover intercept direct solar radiation, reflected radiation from buildings, pavements, glass, and other infrastructure surfaces. Canopy leaf area, size, density, projection, and transmissivity are the contributing factors in improving the quality of shading. Heat exchange, surface temperature, and heat gain by infrastructural elements can all be reduced with the provision of shading. Reflection, absorption, and transmission are the mechanisms for intercepting and dissipating solar radiation. Reflectance is influenced by leaf structure, epidermal characteristics, and angle. Absorption is influenced by foliar canopy, which is primarily measured through the determination of leaf-area index, chlorophyll, and water content. Transmissivity is a dimensionless ratio used to assess the amount of solar radiation passing through the canopy cover and is influenced by canopy architecture [97].

Trees and vegetation dissipate solar radiation through reflection, adsorption, and transmittance. A component of absorbed solar radiation is utilized for photosynthesis activities and a component is converted into heat. The absorption of heat leads to the increase in leaf temperatures. The leaf cooling mechanisms include conduction, convection, and transpiration. The process of converting water from liquid to vapor is known as evaporation. The process of absorbing water through roots and releasing through the tree leaves is known as transpiration. The combination of both of these processes is called evapotranspiration. Evapotranspiration combines transpiration from leaves and evaporation from soil, vegetation, and evaporation from humans and infrastructure elements. In the transpiration process, water within the leaf is converted to water vapor and it is released into atmosphere through leaf stomata. During the conversion mechanism, loss of latent heat leads to conversion of water vapor and the cooling of the leaf. The uptake of carbon dioxide for photosynthesis and the transpiration process enables the cooling of the surrounding atmosphere. This process in combination with shading leads to a reduction in surrounding temperatures during summer. Peak air temperatures in open terrains are warmer than in tree groves by 5 °C. The suburbs without trees are warmer by 2 to 3 °C than the suburbs with mature trees. Barren lands are warmer by 3 °C than irrigated fields. The sports fields without grass are 1 to 2 °C warmer compared to fields with grass [92].

Leaf Area Index (LAI) is used as an indicator for urban surface temperatures and tree cooling [98]. This provides a relationship between vegetative cover density and evapotranspiration rates in urban areas. LAI quantifies the leaf surface area that can exchange heat, water, and carbon dioxide with the atmosphere. Tree species, age, hydraulic status, vapor pressure deficit, soil nutrient availability, seasonal variations, ground water conditions, and wind speed play a key role in the determination of LAI. This is also an indirect indicator for potential evapotranspirative cooling. Vegetative cover in an urban landscape varies based on leaf structure, longevity, orientation, senescence, root systems, dormancy, stomatal control, and osmotic adjustment. The LAI provides an understanding of the process mechanisms in maintaining the hydraulic conditions and transpiration process during high heat loads, Vapor Pressure Deficit (VPD), and low soil water [99,100].

Mirzaei et al. [98] assessed various types of models developed to evaluate the effectiveness of strategies to mitigate and predict UHI for different objectives and scales. It was observed that elevated air temperatures in a city increased the heat and pollution, thereby reducing human comfort. The peak energy demand of buildings also increases. The development of a model for an entire city area involves extensive computational cost and complexity of many important parameters. The accuracy to predict large-scale effects of UHI given urban canopy layer-based meso-scale model investigations is low. Computationally efficient and spatial models have to be developed to understand the effect of UHI at the city level. Jamei et al. [8] investigated the urban greening and geometry to mitigate heat island effects and to improve thermal comfort. Preliminary studies focused on urban planning to improve microclimate in cities. The outcomes of this help urban planners to design guidelines to enhance outdoor thermal comfort. Rafiee et al. [93] quantified the local impacts of tree density on nocturnal heat island intensities. The study involved the modelling of the tree volume using geospatial technology and multi-linear regression analysis. Air temperature, urbanization degree, and sky view factors for the identified locations were also included to assess the impact of vegetative cover. Aggregated tree to uncover area was modelled to study the UHI effect with varying radius. The model results predicted that the tree volume has the highest impact on UHI within a radius of 40 m. Demuzere et al. [99] developed an urban climate model to understand evapotranspiration rates in urban areas. A Community Land Model was developed to model a typical urban street system in Melbourne, Australia. In the model, the ground was covered with a biofiltration system with a capability to take runoff from the roadside. In addition, rainwater tanks were included to understand the evapotranspiration rates. The results showed that evapotranspiration rates increased by 35% with the introduction of biofilter systems. The addition of open rainwater tanks further increased the evapotranspiration. Studies on mitigation strategies using different trees to reduce surface temperatures are presented in Table 4.

Table 4. Summary of global studies investigating the cooling effect of trees.

Location	Maximum Temperature (°C)	Temperature Reduction (°C)	Key Inferences	Ref.
Italy	NA	13.8–22.8	Tree species, leaf area index, and soil water content play a key role in reduction of surface temperatures	[100]
Australia	54	0–6.5	Tree cover, geometry, and prevailing meteorological conditions influence the canyon air temperature. Cooling benefit of street tree canopies increases as street canyon geometry shallows and broadens.	[101]
Germany	49.4	5.5–15.2	Trees species with high leaf area density and high rate of transpiration are effective in cooling surface temperature	[102]
England	53	7–16	Trees species with high leaf area density are effective in reduction of surface temperatures	[103]
Brazil	52	9–10	Pavement shaded by vegetation with high canopy cover is a sustainable strategy for reduction of surface temperatures	[104]

5.3. Recommendations

Growing urbanization sprawl is making urban spaces more like concrete jungles, that under climate change pressures, will increasingly become unnecessarily warm with the heat absorbed during the day by urban infrastructure then radiating this heat back into the urban environment into the evening long after the sun has set. Pavements are primarily infrastructure components that enable connectivity and mobility between places. The creation of multiple lane highways in modern cities with significant surface area for heat absorption is increasingly noted as a major contributor to the UHI effect. The design and development of urban forestry systems to assist urban micro-climate management provides scope to reduce the thermal stress from pavements during the day. Trees and vegetation provide direct shading to pavements, which also decreases pavement maintenance costs by reducing the rate of pavement deterioration. This also reduces the impacts associated with greenhouse gas emission, air pollution, noise pollution, and thermal stress from pavement production. The successful implementation of urban forestry in UHI mitigation, however, also requires an understanding of climatic conditions, native tree species selection, tree planting density, and urban geometry based on the required geographic location. The following recommendations are made based on the aforementioned review to combat UHI effects:

(a) The application of reflective coatings to counter UHI effects needs to consider regional climatic conditions, seasonal variations, and the urban microclimate in incorporating this form of UHI mitigation in urban planning strategies.
(b) Further research on the thermal properties and durability of reflective coatings also need to be conducted to further understand the pavement performance at both laboratory and field scale.
(c) Further effort should be made to incorporate waste material and industrial by-products in pavement materials, including investigating their impact on pavement mechanical, durability, and thermal properties to assist with reducing pavement impacts on UHI and reducing the environmental impacts associated with pavement production.
(d) In urban planning, city councils need to further understand how UHI mitigation by trees and vegetation cover in an urban microclimate will vary with building density and seasonal variations. This research is essential in the development of green vegetation guidelines to help mitigate UHI impacts.
(e) Urban geometry (distribution of buildings, pavement structures, and vegetative cover) also plays a key role in the urban microclimate. Designing green spaces and tree planting areas in residential zones provides scope for the absorption of solar radiation and shading effects and increases air flows that then improve energy performance (up to 30%) by resident urban structures.
(f) Planting native trees to provide shade canopy's helps to extend pavement lifecycle and reduce both the associated thermal stress loads and maintenance costs.
(g) Increased city level UHI planning policy development around green spaces, vertical gardens, and urban vegetation cover will also help to deliver better climate change adaptation and UHI mitigation strategies.
(h) Development of increased public communication outreach and education strategies on UHI impact management through local communities, local government/council authorities, construction companies, and other stakeholders will also assist the development of more effective UHI management outcomes.
(i) Further ecological research on the shade and cooling benefits of native and exotic tree species based on irrigation rates, vegetation cover, and tree survival rates is also necessary to encourage further investment in the vegetation management of UHI.

6. Conclusions

Conventional pavements absorb and store solar radiation due to their dark surface and large thermal inertia. During summer, temperatures in urban areas increase due to this process. Reflective pavements are a mitigation strategy gaining in interest to combat UHI effects. Reflective pavements and evaporative pavements are being explored to help improve thermal comfort in urban areas. Surface reflectance plays a key role in the development of reflective pavements. The albedo of the pavement can increase with the application of resurfacing techniques or the utilization of white toppings or colored coatings on conventional pavement materials. Global case studies have shown that cool pavement strategies can mitigate UHI effects at the micro-level to increase thermal comfort. However, studies are yet to be performed that integrate reflective pavements with other mitigation strategies like tree shading to more fully understand their potential impacts on city and urban area temperatures.

Durability of the pavement plays a key role in the performance of the pavement. The application of cool pavement strategies is primarily focused on the reduction of urban temperatures and reducing the impacts of climate change. Research is limited in terms of the longevity of cool pavement materials. Skid resistance, abrasion resistance, and UV aging have been studied to assess durability parameters. However, studies related to the impact of pollution (corrosion resistance), impact resistance, acid, and alkali resistance on cool pavement materials is yet to be investigated. At the regional level, laboratory and field scale investigations need to be devised to evaluate the optical, thermal, and durability properties of reflective coatings based on geographic location and climatic and solar conditions by developing a combination matrix using pigments (titanium dioxide, zinc oxide, aluminum dioxide, etc.), binders (water-based solvents), and additives (anti foaming agent, anti-settling agent, fortifier, solvent, and disperser). Application of waste materials and industrial by-products as a pavement material can counteract UHI effects by improving the albedo of the pavement, and this provides a scope to achieve energy savings of up to 20–70%.

Urban development activities should integrate more urban forestry and green infrastructure to reduce the thermal stress load on pavements and urban environments. The international research reviewed shows that urban plantations can decrease surface temperatures of pavements and increase their service life. However, there is a need for further research to determine street geometry influences and the magnitude of cooling that can be achieved for pavements. Based on this research, it can be understood that an increase in tree planting is a solution with multiple benefits, including a reduction in UHI impacts in a warming climate, increased biodiversity habitat, and increased aesthetic value in new suburbs. A combination of strategies integrating local conditions needs to be considered. The percentage of tree canopy and type of tree species required to mitigate the increase in urban temperature over a decade also needs more research. Urban planning and development activities should integrate more urban forestry and green infrastructure strategies to reduce the thermal stress on both humans and pavements, particularly under climate change conditions.

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