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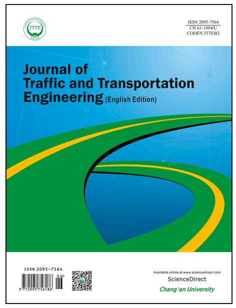

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Review

Thermal performance of cooling strategies for asphalt pavement: a state-of-the-art review

Salam Ridha Oleiwi Aletba[a], Norhidayah Abdul Hassan[a,]*, Ramadhansyah Putra Jaya[b], Eeydzah Aminudin[a], Mohd Zul Hanif Mahmud[a], Azman Mohamed[a], Ahmed Abdulameer Hussein[a]

[a] *School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Johor Bahru 81300, Johor, Malaysia*

[b] *Department of Civil Engineering, College of Engineering, Universiti Malaysia Pahang, Gambang 26300, Pahang, Malaysia*

Highlights

- Physical and thermal properties of pavement influence the heat transfer.
- High emissivity and albedo are preferred for cool pavement design.
- Reflective and permeable pavements are significant for cooling strategies.
- Pavement coating is the most preferred technique for reflective pavement.

Abstract

Asphalt pavements absorb and store more heat than natural surfaces. Thus, high temperatures are emitted from conventional asphalt pavements, subsequently releasing heat into the atmosphere and contributing to the urban heat island (UHI) phenomenon. Several cool pavement strategies, including the provision of additives and materials, surface coating and layer design, have been introduced to reduce the impact of UHI. This article provides a detailed review of the thermal properties of these mitigation measures in the context of cool asphalt pavements. The literature can be divided into three segments. The first segment discusses the impact of pavements on UHI and heat transfer mechanisms in pavements. The second segment focuses on various thermo physical properties that play an important role in mitigation measures; these properties include albedo (α), emissivity (ε), solar reflective index, thermal conductivity (k), specific heat capacity (C_p) and thermal diffusivity. The third segment discusses cool asphalt pavement strategies which specifically cover the ability of the pavement to absorb and reflect solar energy on the basis of the materials and treatments used. The literature reveals that cooling strategies that deal with the pavement surface are important due to its direct incident solar effect, which depends on surface colour, material, shape and roughness. By using high-albedo and high-emissivity surfaces, the pavement can store less heat and lower the surface temperature. These results can also be achieved by designing the materials and pavement layers with low thermal conductivity and high specific heat capacity to reduce thermal diffusivity and pavement temperature and thus combat the heat radiated by the asphalt pavement.

Keywords:

Road engineering; Urban heat island; Cool pavements; Asphalt pavement; Thermal properties.

* Corresponding author. Tel.: +601 1 1613 8284.

E-mail addresses: eng.salam.r@hotmail.com (S.R.O. Aletba), hnorhidayah@utm.my, norhidayah_utm@yahoo.com (N.A. Hassan), ramadhansyah@ump.edu.my (R.P. Jaya), eeydzah@utm.my (E. Aminudin), mzhanif@utm.my (M.Z.H. Mahmud), azmanmohamed.kl@utm.my (A. Mohamed), ahmed.alkaabei@gmail.com (A.A. Hussein).

1 Introduction

Urban construction increases temperatures to above that of the surrounding rural and suburban areas. These differences in temperature are called urban heat islands (UHIs) and are due to the discrepancy in temperature between the construction materials and the natural ground (Arnfield et al., 2003; Qin, 2015a; Rizwan et al., 2008). UHIs are one of the major challenges currently faced by humans as a result of industrial urban development (Rizwan et al., 2008). It is the result of man-made and climatic factors (Maria et al., 2013). Solar radiation increases environmental temperatures, and residual heat passes into surfaces, which has an indirect impact on the environment (Filho et al., 2017; Rizwan et al., 2008). The effect of UHIs is proportional in scale to populations of metropolitan areas, especially in large cities.

According to the US Environmental Protection Agency (EPA), the average air temperature rises 1 ℃ – 3 ℃ annually in cities with populations of one million or more. In a hot season, the temperature of open urban surfaces, such as rooftops and roads, may reach 25 ℃ to 50 ℃ above the ambient temperature. Daytime surface temperatures differ from 10 ℃ to 15 ℃ between urban and rural areas; at night, they vary from 5 ℃ to 10 ℃ (US EPA, 2012). In addition, construction materials, especially those with dark surfaces (e.g., asphalt pavements), are dense and adept at absorbing and storing solar radiation (Benrazavi et al., 2016; Nakayama and Fujita, 2010). Conventional asphalt pavements are the strongest heat collector, following the considerable direct heating of the surface during the daytime. Several factors contribute to the occurrence and intensity of heat islands. These factors include urbanisation, land usage, climate change, air pollution, impervious surfaces and many others (Voogt, 2002).

Studies on the use of cool pavements as a strategy for mitigating the heat island effect, improving outdoor thermal comfort and potentially reducing energy use have been conducted. Cool pavements refer to any new paving material or design technology meant to reduce heat transfer (Phelan et al., 2015; Qin, 2015b; Roesler and Sen, 2015; Santamouris, 2013; Santamouris et al., 2012; Shi et al., 2012). The Lawrence Berkeley National Laboratory, amongst others, has focused its research on cool pavement mechanisms and the effects of UHIs (Gartland, 2008; Ting, 2012; US EPA, 2012). Furthermore, the thermal impacts of cool pavements are being studied and evaluated, particularly during the hot season

(Li, 2012a). Decreasing the surface temperature of pavements may considerably improve the thermal conditions of cities experiencing high temperatures.

Certain thermal properties, such as solar reflectance, thermal emissivity, conductivity and capacity, have been highlighted by previous studies and evaluated for their performance. These thermal parameters were found critical for the evaluation of various pavement strategies for UHI mitigation (Gui et al., 2007). Cool pavements are surfaces with high albedo combined with high thermal emissivity and are achieved by treating the surface through coating or using the latent heat of water evaporation (in the case of water retention pavement) to decrease its surface and ambient temperatures. Both technologies are well developed, and their products have been used in large-scale applications, yielding promising results (Ariffin et al., 2016; Hu and Yu, 2015a, b; Ishiguro and Yamanaka, 2016; Okada et al., 2008; Richard et al., 2015; Santamouris et al., 2011; Stempihar et al., 2012; US EPA, 2012). Furthermore, the increase in the thermal conductivity of paving surfaces contributes to fast heat transfer from the pavement to the ground and vice versa. Specifically, during the daytime, when pavement temperatures are higher than that of the ground, heat is transferred from the pavement to the ground; the opposite is observed at night (Hassn et al., 2016; Sreedhar and Biligiri, 2016a, b).

The influence of temperature on asphalt pavement performance is crucial, especially in tropical regions where the air temperature is usually high, leading to high temperatures on asphalt pavements. At high temperatures, the asphalt pavement mixture can be deformed by loadings caused by vehicles or other loaded transport means (Van Thanh and Feng, 2013). Asphalt is a major type of paving material for roads; thus, a good understanding of its thermal performance is vital for the evaluation and implementation of asphalt pavements; such understanding may effectively mitigate the occurrence of heat islands.

Massive literatures were found to summarise the development of cool pavements to mitigate UHI for various pavement types. However, the thermal characteristics of cool pavement strategies focused on asphalt pavements, are not well documented (Khan, 2002; Kim et al., 2003). Therefore, this systematic review provides discussion on various asphalt pavement cooling strategies particularly on the thermal mechanisms and properties of asphalt and its impact on UHI mitigation. The review was made on the relevant works by framing the significant questions regarding the heat mechanism and thermophysical properties of asphalt pavement and summarising comprehensive evidence on the questions related to the cool asphalt pavement strategies.

2 Impact of pavement characteristics on UHI

Paving materials cover a high percentage of urban areas (Bao et al., 2019). A study conducted in a city in California, USA showed that pavement materials cover nearly 39% of built-up areas, including streets, parking areas, and sidewalks, thus indicating the importance of pavements (Li, 2012a). The pavement developed has had a significant influence on UHI due to changes in the ground caused by an impermeable surface that stores heat and increases thermal mass. Therefore, to determine and investigate the role of roads on the UHI phenomenon, all of their main thermophysical properties must be ascertained (Yavuzturk et al., 2005). Substantial research has been conducted to examine the impact of pavements on UHI (Li, 2012a; Rose et al., 2003; US EPA, 2012; Yang et al., 2008). According Kbari and Ose (2008) pavements could contribute to as much as 44% of the UHI phenomenon in cities, depending on its characteristics. Therefore, the impact of pavements on UHI can be reduced by controlling their physical characteristics and thermal properties (Shi et al., 2012).

Satellites for infrared and thermal activities have shown that pavements are strong sources of heat radiation (Gorsevski et al., 1998). For example, asphalt pavements subjected to intense solar radiation respond in various ways. Their dark surfaces incessantly absorb the heat, beginning at sunrise until late afternoon (before sunset) (Rizwan et al., 2008). Solar radiation is absorbed in the form of heat through the surface of the pavement, then through the subsurface and finally into the lower pavement layers. After sunset, the heat is then released into the evening air (Li and Harvey, 2011).

Paved areas are affected by several variables, such as albedo (reflectivity of surfaces) and emissivity, which play a vital role in determining a material's contribution to UHI. For example, with every 10% – 25% increase in albedo, surface temperatures could decrease by as much as 0.55 ℃ (Levine, 2011). Researchers have also suggested that albedo and emissivity have the greatest influence on the cooling and heating behaviour of conventional pavements, with albedo having a large impact on maximum surface temperatures and emissivity affecting minimum temperatures (Huang et al., 2005; Li, 2012a). This finding is due to the increase in albedo, which contributes to an increase in the amount of reflected solar radiation, which initially reduces the rise in temperature and heat. By contrast, emissivity contributes to accelerating the release of existing heat, especially when the body begins to cool down after the heat source affecting it has stopped. Pavement temperature is also influenced by the specific heat capacity of pavement materials, particularly when receiving and releasing radiation from the sun. The heat transfer that occurs within the pavement (between the surface and the pavement layers) happens through the process of conduction, as thermal conductivity affects how much surface heat is transferred into the ground. Thermal conductivity is an important parameter for the accurate prediction of field temperature, particularly in the pavement structure, for mechanistic pavement design (Chen et al., 2015).

As previously mentioned, the temperature of asphalt pavements depends on the material's thermal properties. Therefore, the conventional materials used for asphalt pavements can be improved by using cool paving materials to reduce the heat impact. The impacts of cool pavements on UHI mitigation have attracted attention for their application in high-temperature areas (Chen et al., 2009). However, no standard guide, specifications or limitations are available for the design of cool pavements (Haselbach et al., 2011). According to the EPA, "cool pavement" describes any technology that reduces absorption and stores heat energy in pavements, resulting in lower surface temperatures compared with that of conventional pavement (US EPA, 2008b). The use of alternate pavements to provide environmental benefits has become more desirable recently (Wu et al., 2018). Other than material selection, using various colours to coat the pavement surface is another widely used strategy for reducing the impact of heat on pavements (Haselbach et al., 2011). In addition, other factors, such as the permeability and thickness of layers, affect thermal performance (Golden et al., 2007; Ramírez and Muñoz, 2012). Therefore, studies on these factors are crucial, and each one should be assessed independently.

3 Heat transfer in pavements

Heat transfer is an important element that outlines the basic principles behind the effects of UHIs, and it explains the mechanism of how pavement temperature changes. This transfer refers to the movement of thermal energy across the boundary of the system due to temperature difference between the asphalt pavement and its surroundings. The transient energy principle in pavements is based on the balance amongst contiguous materials (Fig. 1). It illustrates the heat transfer phenomenon that occurs in pavements through a few principal mechanisms (i.e., conduction, convection, reflection and radiation emissions) that indicate the thermal behaviour of the materials. In addition, evaporation from rain and surface water influences heat transfer because it helps reduce pavement surface temperatures. On the basis of Fig. 1, these thermal mechanisms can be described as a process that starts with the sun's radiation, which passes through the atmosphere, hits the pavement's surface, and is reflected, absorbed and finally transferred through the pavement. Understanding this process is important for identifying the parameters that should be considered when developing cool pavement strategies.

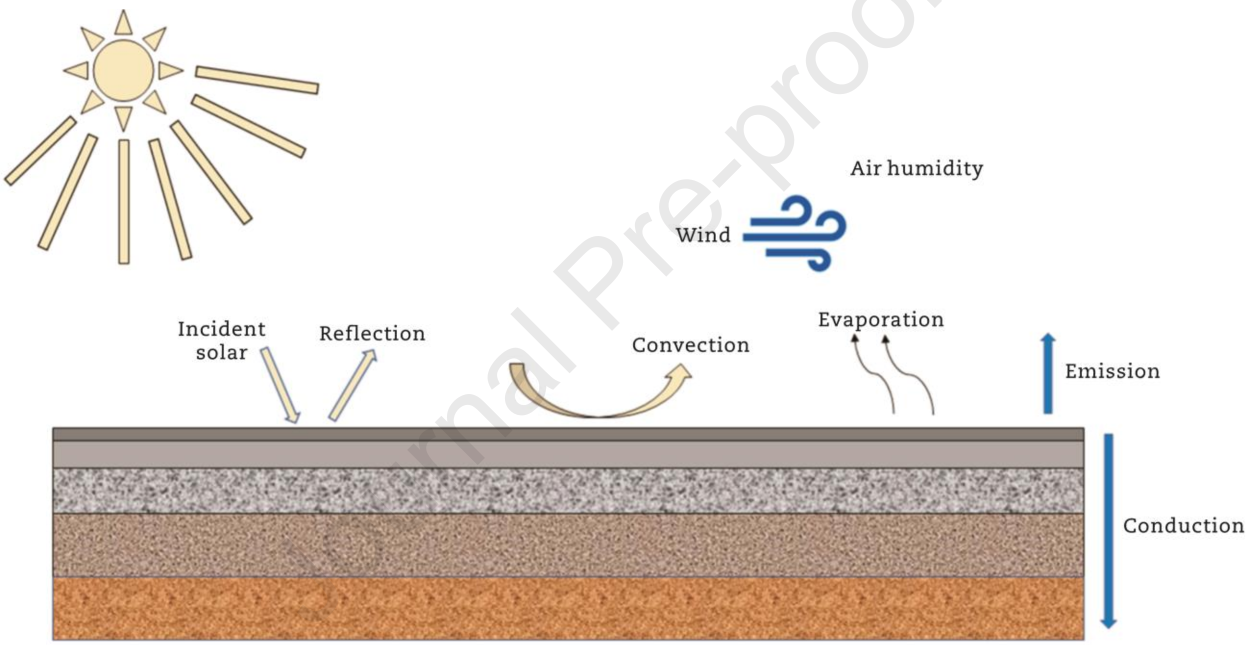

Fig. 1 Heat transfer in pavements.

Radiation from heat transfer is the energy that radiates from the sun and absorbed by pavements. The amount of heat transfer depends on the surface material and colour, as well as the wavelength of the incoming radiation. During this process, the solar radiation reaches the pavement surface, where some is reflected whereas the rest is absorbed and transferred into heat through the pavement. Variations in pavement temperature can be explained by the amount of short-wave radiation (250 – 800 nm) that hits the surface pavement (Solaimanian and Kennedy, 1993). The heat transfer that occurs between two solid bodies in physical contact is called conduction. This process describes the heat transfer energy system that flow from the high-temperature pavement layer to the following layer with a lower temperature until heat equilibrium is achieved. For example, thermal conductivity, heat capacity and density are defined as types of vertical heat conduction (Gui et al., 2007; Herb et al., 2008). In the case of pavements, convection also occurs when heat is transferred from the air to the pavement (Li, 2012a; Nellis, 2009). Newton's law of cooling demonstrates that the convection coefficient is affected exclusively by the geometry, fluid properties, flow condition and roughness of the surface (Nellis, 2009; Roesler and Sen, 2015). Therefore, it is reduced when wind speed and air turbulence above the surface are low, as well as when the variations in air and surface temperature are small (Ting, 2012). For example, permeable pavements have rougher surfaces and higher air void ratios than normal pavements. Open void structures and exposed surfaces allow air currents to flow through the pavement, thus increasing the convection potential between the pavement and air. As a result, the process reduces the heat on the pavement, depending on the airflow conditions (Li, 2012a).

By contrast, evaporation can also decrease the pavement temperature by absorbed latent heat during the transformation of water into steam, especially with a porous pavement that allows water to permeate through the pavement. Permeable pavements can provide these benefits by inducing latent heat stored water (Roesler and Sen, 2015). The cooling effect of evaporation depends highly on the evaporation rate. Therefore, when investigating cool pavement strategies, the evaporation rate for different pavement materials must also be considered (Ting, 2012). Through a good understanding of the heat transfer mechanism and its association with the necessary parameters, temperature in pavements can be controlled. Table 1 summarises the heat transfer mechanism and the cooling strategies used for asphalt pavements.

Table 1 Cooling strategies in asphalt pavements.

Heat transfer mechanism	Description	Cooling strategy
Conduction	Affected by materials used and thicknesses of layers Measured by thermal conductivity (k) for each layer	i. Increase albedo and emissivity through surface treatment (results in high SRI).
Convection	Affected by wind, pavement surface area and air temperature	ii. Reduce thermal conductivity and increase specific heat capacity through material selection (results in less thermal diffusivity)
Emission	Affected by materials used Measured by emissivity	
Evaporation	Affected by air voids and permeability of pavement design criteria	iii. Control permeability through pavement design criteria and increase air voids (results in high evaporation)
Reflection	Affected by materials used Measured by emissivity	

4 Thermophysical properties

The amount of solar energy that can be absorbed or reflected by a material depends on the material's physical properties, especially those related to the material's surface. The amount of absorbed solar energy that is transferred as heat inside a material's body depends on the material's conductivity. Later, this heat is released to the surrounding area as infrared waves through emission. Thermophysical properties are usually related with a material's ability to transfer and store heat without undergoing a chemical reaction or chemical change, which varies with temperature, pressure and composition. These properties include albedo, emissivity, solar reflectance index, thermal conductivity, heat capacity, thermal diffusivity, density and permeability. By using these properties, pavements can be evaluated and monitored in terms of UHI mitigation.

4. 1 Surface reflectance: albedo

Albedo can be described as the percentage of solar energy reflected by a surface. Most research on cool pavements has focused on this property as it is the main determinant of a material's maximum surface temperature (Li, 2012a). Albedo only comes into effect when the sun is out and shining. Thus, high albedo is important in reducing a material's temperature during the daytime. It can also be presented as a reduced amount of energy absorption, which decreases the temperature at night (Shi et al., 2012). In other words, albedo is the rate of reflected solar energy, and materials with substantial albedo can reduce pavement temperatures. By contrast, radiation that is not reflected permeates the material by absorption (rate of energy absorbed per unit surface area). The absorption rate depends on the material's surface and absorption capability (Pomerantz et al., 2003). The albedo can be calculated using Eq. (1).

$$\alpha = 1 - \alpha_{abs} \tag{1}$$

where α_{abs} is absorptivity of the surface, α is albedo.

The term "solar reflectance" is used to measure the degree of energy reflected from each different wavelength of solar radiation as it hits surfaces. Meanwhile, albedo is the portion reflected to incident solar. According to Richard et al. (2015) pavement surfaces obtain their peak albedo in the early morning and in the late afternoon. It then decreases in the middle of the day. The surface temperature of new asphalt pavements with an albedo of 0.05 reflects 5% and absorbs 95% of the solar radiation. Such pavement can become 50 ℃ hotter than the air temperature (Richard et al., 2015). Fig. 2 shows the decreases in pavement surface temperature resulting from the increase in albedo, as reported in previous studies (Li et al., 2013a, b; Maria et al., 2013; Sreedhar and Biligiri, 2016a, b). A field measurement of albedo was conducted on various materials with different reflecting responses to incident solar radiation. According to the National Asphalt Paving Association (NAPA), increasing albedo could affect people's comfort levels by increasing upward light scatter and night-time light pollution (NAPA, 2015); thus, albedo should be limited to a certain level. The albedo value is a number from 0 to 1.0. According to ASTM C 1549-09, a value of 0 indicates that the material absorbs all solar energy, and a value of 1.0 indicates total reflectance. Reflectance can be measured in accordance with ASTM E903, ASTM E1918 or ASTM C1549 (ASTM, 2009a, 2012, 2016), whereas pavement albedo can be accurately measured in accordance with ASTM E1918-06. This procedure is conducted with an apparatus called a pyranometer, which enables the solar reflectance to be determined based on the alternate readings of incoming and reflected solar radiation, as the albedo is the ratio of the reflected solar to the incident.

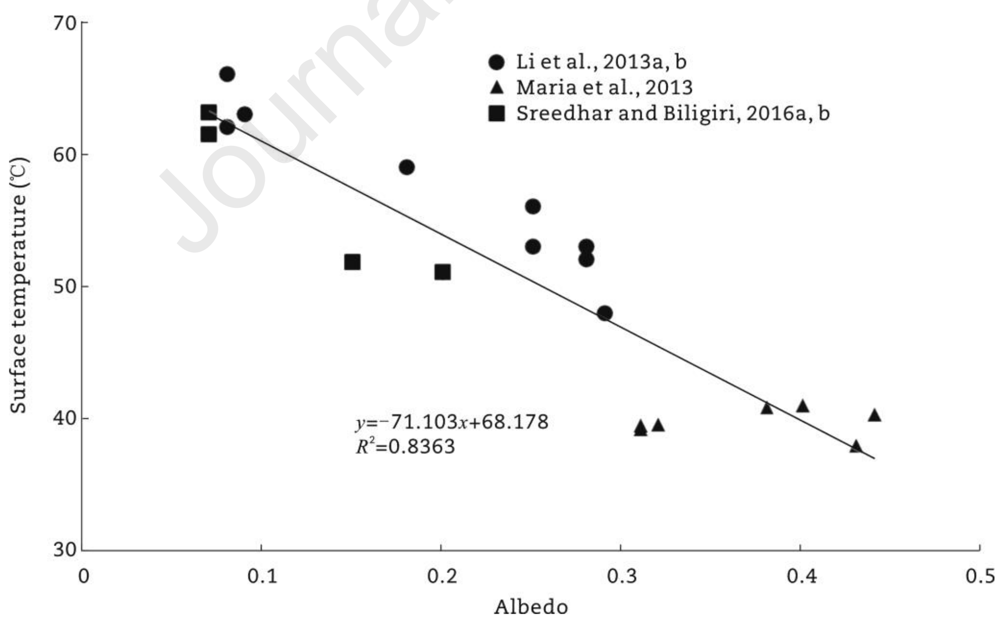

Fig. 2 Relationship between albedo and pavement surface temperature.

4.2 Emissivity

Emissivity (ε) is a measure of the radiated surface of the material or level of heat (scaled from 0 to 1) that is released into the surroundings (Maria et al., 2013). It is the electromagnetic radiation of energy emitted from any material when the temperature increases to above 0 K (−273 ℃ or 0 °F) (Young, 2002). It is a proportion of energy emitted from a material's surface to a black body under similar conditions. Emission power is measured by the ratio of emitted energy to the area's unit, E ($W \cdot m^{-2}$), on the basis of the Stefan–Boltzmann law (Shi et al., 2012). Generally, the material's surface reflects some of the radiation; therefore, the radiated energy normally becomes a lesser amount than a black surface or lower than 1 (Shi et al., 2012). The maximum emission of a material can be less than 0.1, and minimum emissions can be more than 0.9 (Marceau and Vangeem, 2007). Emission also depends on materials, surface texture and finishing (Pourshams-Manzouri, 2015).

Heating materials cause a rise in infrared energy, and the intensity from infrared energy can be used to measure a material's temperature. Fig. 3 shows that the materials with the highest emissivity can have low surface temperatures (Gui et al., 2007). Thermal emissivity is considered one of the important factors that contribute to albedo, which has a direct impact on pavements. Emittance can be measured in accordance with ASTM E408 or ASTM C1371 (ASTM, 2013, 2015). An IR camera facilitates the measurement of emissivity. In this case, the procedure involved heating the samples to a specific temperature that can be established with precision based on a contact thermocouple in settings with known air temperature and humidity. The sample temperature was displayed by the IR camera, with the emissivity percentage being adjusted until both the IR camera and thermocouple indicated the same temperature (Adesanya, 2015; ASTM, 2013; Rakrueangdet et al., 2016).

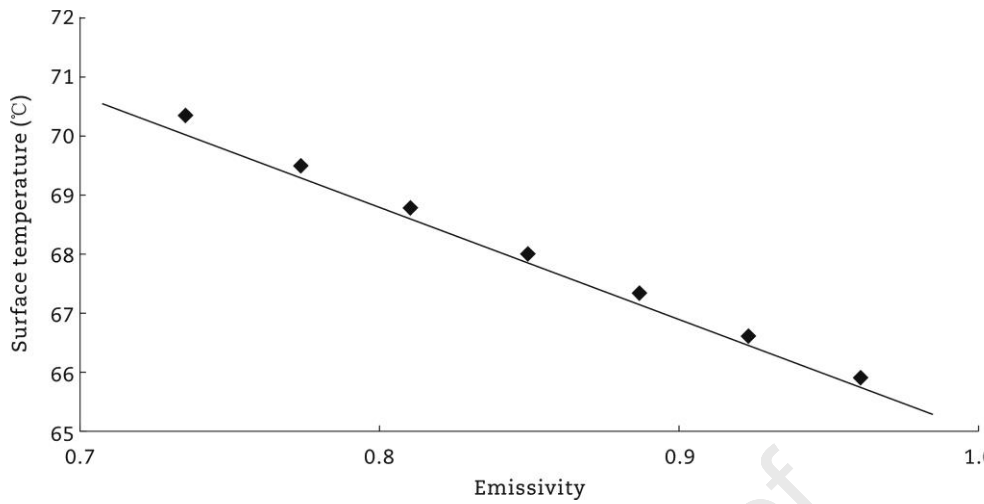

Fig. 3 Effect of emissivity on pavement surface temperature (Gui et al., 2007).

4.3 Solar reflectance index

Solar reflectance and thermal emissivity are principal factors that affect thermal properties. The effect of both parameters can be measured using the solar reflectance index (SRI). The SRI is an aptitude to reflect and reduce solar heat from material surfaces by which a black surface is equal to 0 (albedo 0.05, emissivity 0.90) and a white surface is equal to 100 (reflectance 0.80, emittance 0.90) (US Green Building Council, 2016). The SRI can be calculated in accordance with ASTM E1980-11 (ASTM, 2001) by using Eqs. (2) and (3).

$$\mathrm{SRI} = 123.97 - 141.35X + 9.655X^2 \quad (2)$$

$$X = (\alpha_{\mathrm{abs}} - 0.029\varepsilon)\,(8.797 + h_c) / (9.5205\varepsilon + h_c) \quad (3)$$

where SRI is the solar reflectance index, α_{abs} is solar absorptance, ε is thermal emissivity, h_c is convective coefficients of one of three values corresponding with low, medium, and high wind conditions at 5, 12, and 30 W/(m^2·K), respectively.

4.4 Thermal conductivity

Thermal conductivity (symbolised as k) is used to explain and measure the heat transfer through a body; such transfer occurs when the heat from the surface is transferred to the cold section of the body through microscale interactions (Nellis, 2009). It is an important material parameter that determines the thermal conditions of a pavement, and it influences the pavement cracking and rutting (Geng and Heizman, 2016). Fourier's law describes the relationship amongst the heat-transfer process, heat flux and thermal conductivity whilst showing how temperature increases on the surface of the material (Nellis, 2009).

Kaloush and Carlson (2008) reduced thermal conductivity in pavements to reduce the heat flow rate through pavements by incident solar and high air temperatures, thus reducing the pavement's temperature. This is important as a concern to the initial heat absorption capability of the material to minimise the heat transfer within the pavement structure. Therefore, a low thermal conductivity of materials is preferable because it tends to conduct less heat throughout the pavement structure and prevent it from heating up the surrounding. The thicker the pavement layers, the higher the thermal resistance or the greater its resistance to heat transfer. This is ideal for the asphalt pavement itself as materials with less temperature susceptibility are preferred for improved performance. Reducing the heat transfer capability could reduce any potential changes in the mechanical behaviour due to temperature changes. Many factors play a role in the thermal conductivity of a material. For example, the thermal conductivity of a pavement can be changed by using different mix designs and aggregate types and proportions. The thermal conductivity of aggregate base materials and subgrade materials depends on the nature of the material, mineral content, moisture content, gradation size and specific gravity. Thus, thermal conductivity can be difficult to control in various kinds of asphalt pavements (Andersland, 2004; Chen et al., 2017). The thermal conductivity of an asphalt mixture can be determined using a standard method of ASTM C177-04 (ASTM, 2004). In general, there are instruments that can be used to measure thermal conductivity directly (Kuvandykova, 2010).

4.5 Specific heat capacity

Specific heat capacity (C_p) is the amount of heat required to increase the temperature of one-unit weight by 1 ℃ without changing the material phase. The unit of measure is J/(kg·℃) or J/(kg·K) for pavements; it describes the volumetric heat capacity used to express the amount of energy that is absorbed and stored in the pavement at a certain temperature (Sreedhar and Biligiri, 2016a, b). Energy storage developed by the increased heat and the thermal body decelerates the temperature increase throughout the day. When the body of a material begins to store heat, the maximum temperature during the day is reduced because increasing the specific heat capacity requires additional heat energy to rise the body temperature, thus heating up the surroundings. However, temperatures at night increase because of this phenomenon's effect on thermal mass, that is, the ability of a material to absorb and store heat energy and the impact it has on the amount of heat released at night (Gui et al., 2007). Therefore, as the material used for the pavement has high specific heat capacity, the more the energy can be absorbed from the surface prior to 1 ℃ temperature increment, hence reducing the surrounding temperature.

A few methods, such as thermochemical and latent energy storage, can be used to store energy. Such methods have demonstrated low heat losses in the storage period and have high heat storage capacity (Tatsidjodoung et al., 2013). Thermochemical energy storage implements an energy source for triggering a reversible chemical reaction, which tends to include a gas and a solid that can react (e.g., using water vapor to develop applications). In latent energy storage, the heat that is absorbed is released after a material's physical state changes. Therefore, the increased specific heat capacity of a pavement could influence the heat impact by preventing temperatures from rising during the day and by increasing temperatures during the night. Specific heat capacity can be measured in accordance with ASTM C351-92b (ASTM, 2008). Differential scanning calorimetry (DSC) is a potential tool in evaluating heat capacity (Roesler and Sen, 2015), where the heat capacity can be calculated using Eq. (4).

$$Q = cm\,\Delta T \tag{4}$$

where Q is the amount of energy transferred (J), m is the mass of the object receiving the energy (kg), c is the specific heat of the object, ΔT is the temperature difference.

4.6 Thermal diffusivity

Thermal diffusivity is a parameter that describes how heat spreads through a material's body (Pourshams-Manzouri, 2015). It is important for understanding the behaviour of elements and systems for different engineering specialties during modelling (Luca and Mrawira, 2005; Tatsidjodoung et al., 2013; Xu and Solaimanian, 2010). A high thermal diffusivity value increases internal temperatures on a surface, whereas a low thermal diffusivity increases heat storage and decreases conductivity (Ng et al., 2011). Eq. (5) mathematically explains the property of this energy.

$$a_{\mathrm{Diff}} = k/\rho C_{\mathrm{p}} \tag{5}$$

where a_{Diff} is thermal diffusivity, k is thermal conductivity, ρ is density, and C_{p} is specific heat.

Diffusivity is an indication of the extent of heat spread on the pavement surface, as it is clear from the measuring method that it depends directly on the conductivity and inversely with the heat capacity and density.

4.7 Density

Density is not a thermal property, but it influences thermal behaviour. Fig. 4 shows the linear relationship between density and surface temperature. The temperature increases as density increases because the transfer of heat within the material becomes more effective through conduction. Thus, an increase in the air void ratio or using low density materials in pavement leads to a decrease in density and surface temperature (Chen et al., 2018; Sreedhar and Biligiri, 2016a, b). Density can be measured according to ASTM D2726 (ASTM, 2009b).

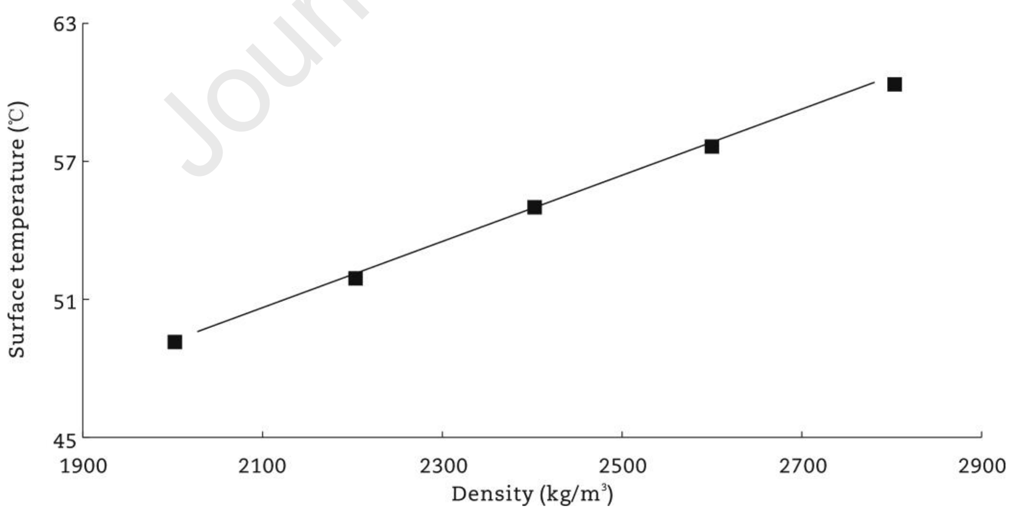

Fig. 4 Effect of density on pavement temperature.

4.8 Permeability

Permeability influences the evaporative cooling effect of pavement. Therefore, the evaporative cooling effect of pavements is to maintain wet conditions, thus reducing the pavement temperature (US EPA, 2008a). Permeable pavements allow water to pass through into the ground layer and evaporate when temperatures rise. The degree of evaporation depends on the moisture content and temperature of the material and the atmosphere; an increase in moisture content reduces pavement temperatures (Santamouris, 2014). Therefore, pavement designs with an open aggregate structure allow water to drain through the asphalt layer and cool the pavement layer. In accordance with NAPA, a porous mixture can be classified as a mixture with air voids greater than 16% (NAPA, 2003). Even with these features, permeable pavements tend to be hotter than conventional pavements during dry seasons (Buyung and Ghani, 2017). Permeability is also beneficial for reducing the run-off of urban rainwater (Tang et al., 2018). The permeability of pavements can be determined on the basis of ASTM C1781 / C1781M (ASTM, 2018).

4.9 Discussion on thermophysical properties

The thermal performance of materials can be evaluated by considering their thermophysical properties. Controlling the material properties affects the pavement surface and body absorption, storage and the amount of radiated heat (Chen et al., 2009). A material's thermophysical properties (i.e., thermal conductivity, emissivity, albedo, heat capacity and thermal diffusivity) have a considerable impact on the distribution and variation of temperatures in a pavement's layers (Kuvandykova, 2010). Internal thermophysical properties, including thermal conductivity, heat capacity and density, are also crucial to the overall thermal behaviour of paving materials (Bai, 2013). A pavement's density can increase mid-depth temperatures and affect heating and cooling responses, along with storage capacity (Nordcbeck et al., 2011). Table 2 shows the impact of each thermophysical property on asphalt pavement based on previous studies.

Table 2 Effect of thermophysical properties on pavements.

Property	Value	Impact	Reference

Albedo	High	Mitigates UHI effect	Yang et al., 2015
		Cools pavement layers	Richard et al., 2015
		Reflects more solar into adjacent constructions	Li et al., 2013a, b; Wang et al., 2014
		Increases upward light scatter, adding to night-time light pollution.	Wilson, 2013
Emissivity	High	Mitigates UHI effect	Li, 2012a
		Negative reflective in the urban canopy	Sreedhar and Biligiri, 2016a, b
		Reduces night-time temperature	Santamouris et al., 2011
Thermal conductivity	Low	Mitigates UHI effect (surface)	Chen et al., 2017
		Reduces heating into lower layer	Bai, 2013; U.E. Environmental Protection Agency, 2008
		Increases surface temperatures	Solaimanian and Kennedy, 1993
	High	Absorbs more heat, enhance heat capture.	Mallick et al., 2008
Heat capacity	High	Mitigates the UHI effect	Li, 2012a; Mohajerani et al., 2017
		Increases heat storage	
		Contributes to heat islands at night	
Permeability	High	Mitigates UHI effect (wet condition)	Bai, 2013
Density	Low	Reduces thermal conductivity	Roesler and Sen, 2015
	High	Increases pavement temperatures and store energy	Nordcbeck et al., 2011

In summary, asphalt pavements have a lower albedo than other pavement types. Most of the aforementioned studies focused on the aged asphalt pavement, pavement layer depths, type of aggregate used, or structural factors related to broad design types of asphalt pavements. These features have been found to influence the quantity of reflected and absorbed solar radiation, the total amount of heat released and the level of heat obliterated during the night (Li, 2012a). Therefore, many techniques, including the use of different methods or materials during the construction of new asphalt pavements, can be used to decrease the impact of its temperature on the surrounding area.

5 Analysis of cool asphalt pavement strategies

Previous studies have mentioned that asphalt pavements can influence the UHI effect in cities (Ikechukwu, 2015; Santamouris, 2013). Investigations have revealed that the cool pavement strategies can be classified into two major concepts: reflective and permeable pavements (water cooling mechanism). Reflective pavements increase the solar energy reflected from their surfaces (Anting et al., 2018; U.S. Green Building Council, 2016). These reflective pavements have been studied widely, with consideration given to their cost efficiency and their ability to combat the UHI effect by decreasing the pavement and surrounding temperatures and sustaining the environment (Synnefa et al., 2011; Pomerantz et al., 2003; Yang et al., 2015). Many notable implementations of reflective pavements are used worldwide with high mitigation reactions (Huynh and Eckert, 2012; O'Malley et al., 2015). Overall, colour, flatness and surface permeability affect albedo and lead to the improved reflectance of solar radiation (Santamouris, 2013). By contrast, permeable pavements, such as evaporative and water-retentive pavements, are designed with high air void ratios, whereas conventional porous asphalt pavements are designed with open-graded asphalt surfaces applied over base layers (NAPA, 2003). This design permits water to flow into the sublayers to cool the pavement; in certain design criteria, the stormwater is kept within the pavement. Early mix designs were conducted following the Hveem mix design procedure (Moore et al., 2001). According to Takahashi and Yabuta (2009), water-retentive pavements have three principles: (1) their surface temperatures can be lower than temperatures under normal weather conditions; (2) they need to reduce temperature increases continuously, following rain; and (3) they need to be of a high durability and show low reductions in performance as they age.

The following sections discuss in detail the cool pavement strategies implemented on the basis of the aforementioned concepts.

5.1 Surface Coating and Treatment

Coating a pavement surface increases its reflectance (albedo) and reduces solar absorption and thermal conductivity due to decreased pavement temperature. Table 3 summarises the various techniques of surface treatment used in asphalt pavements. Conventional colours, especially in new asphalt pavements, strongly absorb energy from daylight. Light colours enable an increase in surface reflectivity (Santamouris, 2013). According to previous studies, increasing the albedo by using a light-coloured surface is an efficient method for mitigating UHI (O'Malley et al., 2015; Pomerantz et al., 2003; Santamouris, 2013). For example, the albedo value of a chip seal could be increased by using a light-coloured material depending on the aggregate used (e.g., light-coloured aggregate). However, this value reduces over time (Pomerantz et al., 1997). A white seal is considered uncommon because it requires the reproduction of an emulsifier, which is expensive (Bretz et al., 1992). The idea of using light-coloured aggregate was also studied by Guntor et al. (2014) using waste materials, such as wasted tiles, to increase albedo and emissivity at 0.52 and 0.93, respectively.

Carnielo and Zinzi, (2013) compared different colours used as coatings, and the results showed that the maximum temperature differences between green, blue and grey samples relative to the control ranged between 8 ℃ and 10 ℃. Low values were obtained for the red coating, whereas the difference approached 20 ℃ for the off-white sample. Synnefa et al. (2011) also used various colours as coating of asphalt pavement. The results of field measurements showed that an off-white asphalt sample has the highest solar reflectance, 55% and the greatest difference, 11.9 ℃ in temperature compared to the conventional asphalt. The study also found that the red coating produces the least difference in temperature. Kyriakodis and Santamourisa (2017) focused on a thin layer of light-yellow asphalt and compared it with conventional asphalt. The finding showed that the light colour can increase the albedo and obtain a temperature reduction of 7.5 ℃. Other researchers also agreed that the white paint coating has a high solar reflectance, mostly greater than 90% (Bretz et al., 1992).

In addition to research that focused on colour, many previous studies also used coatings made of different materials. For example, Kinouchi (2004) developed a thin paint coating using a dimmer dye with high solar reflectance in near-infrared light with less brightness to decrease negative glare. Others developed heat-reflective coating on the asphalt surface and decreased the pavement temperature to nearly 9 ℃ and 17 ℃, as found by Wan et al. (2012) and Cao et al. (2011), respectively. The use of dark infrared reflective paint on the surface of the asphalt along with hollow ceramic particles reduced the thermal conductivity and increased reflectance to 81%. Sha et al. (2017) used a special pigment in coating layers made of titanium dioxide as a solar heating reflective coating layer in asphalt pavements.

They found that the pigment reduces the pavement temperature and prevents energy transfer to the layers underneath, with a temperature reduction of 10 ℃. Zheng et al. (2014) used a special coating by spreading a 1.18 mm fine aggregate of 160 g/m^2 and tested for skid resistance. The coating was found to improve skid resistance with high drops in pavement temperature, indicating that the method promotes UHI mitigation and improves pavement performance.

Table 3 Various types of coating for cooling pavement.

Reference	Material	Strategy	Thermal property			Finding
Bretz et al., 1992; Pomerantz et al., 1997	Conventional asphalt	-	Albedo New 0.05 – 0.1 Weathered 0.15 – 0.2			Albedo of chip seal depends on aggregate used/ageing increased albedo
	Chip seal	Hot asphalt, various aggregates mixed before spreading	Albedo New 0.1 Weathered 0.2			
Guntor et al., 2014	Light-coloured aggregate	Wasted tiles, sand and epoxy resin	Albedo 0.52 Emissivity 0.93			Reduction of surface temperature by coated materials achieves 4.4 ℃
Kyriakodis and Santamourisa, 2018	Conventional asphalt	With a thin layer of light-yellow asphalt	Albedo 0.35			Reflective asphalt reduces temperature 7.5 ℃ lower than the surface of conventional asphalt
		Normal	Albedo 0.04			
Carnielo and Zinzi, 2013	Coloured coating	Type	ΔT_{max} (℃)	ΔT_{mean} (℃)		Increased colour brightness reduces the surface temperature
		Control	0.0	0.0		
		Off white	19.3	8.2		
		Grey	10.0	3.8		
		Green	7.8	3.5		
		Blue	7.9	2.7		
		Red	6.2	1.8		
Carnielo and Zinzi, 2013; Synnefa et al., 2011	Coloured coating	Type	Solar ref. %	ΔT_{max} (℃)	ΔT_{mean} (℃)	Increased colour brightness reduces the surface temperature
		Control	4	0.0	0.0	
		Off white	55	11.9	7.7	
		Beige	45	7.9	6.2	
		Green	27	4.8	3.2	
		Red	27	4.1	3.1	
Cao et al., 2011	Dense-graded asphalt pavement	Heat reflective coating	Reflectance 60%			Reduces by 9 ℃, good waterproofing, resistance to abrasion and ageing
		No coating	Reflectance 10%			
Wan et al., 2012	Dark-coloured pavement coating with high albedo	Coating (perfect cool)	Reflectance up to 81% Low thermal conductivity to 0.252 W/(m·K) Emissivity up to 0.83			Temperature reduction up to 17 ℃
Sha et al., 2017	Pigment in coating layers	Titanium dioxide (TiO_2)	Increase solar reflectance			Reduced by (10 ± 2.5) ℃ on top (10 ± 3) ℃on bottom
Higashiyama et al., 2016	Coating (different material combination)	Ultra-rapid hardening cement, ceramic waste powder and fly ash	ΔT = 12.8 ℃			Reduces the surface temperature of the porous asphalt
		Ultra-rapid hardening cement, ceramic waste powder and Natural zeolite	ΔT = 20.6 ℃			

5.2 Design methods

Pavement design depends on the proportion of constituents used, and the air void ratio must be appropriate for its purpose. The basic mix component or structure of an asphalt pavement is shown in Fig. 5. The asphalt pavement structure comprises asphalt surface layers on top of a base and then a subbase, which sits upon the subgrade (Mohajerani et al., 2017). The surface layer has the primary role in the heat effect, whereas the lower layers depend on the ratio of heat absorbed by the surface and conductivity between the pavement layers. The proportions of the materials in the asphalt mixture determine the thermal and mechanical properties of the asphalt pavement. Table 4 summarises previous studies on the effects of mix design on temperature mitigation.

(a) (b)

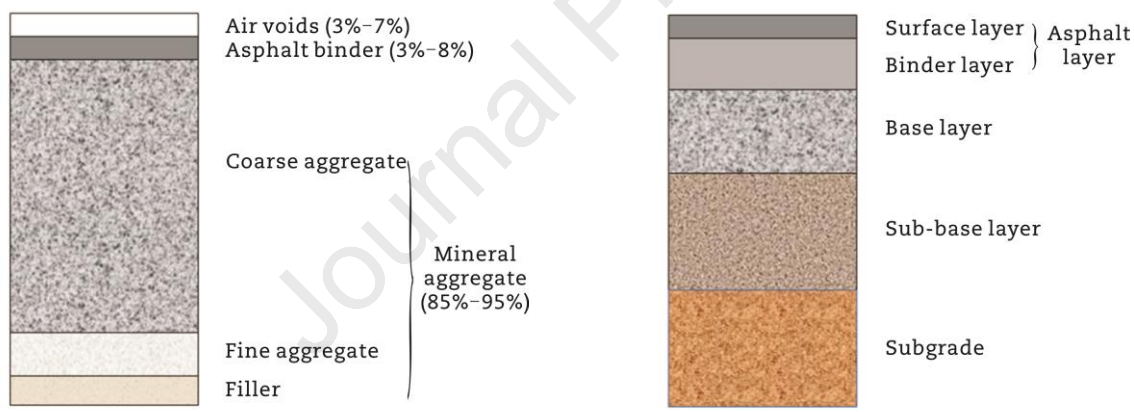

Fig. 5 Typical structure and components for several types of asphalt pavements. (a) Components of asphalt layers. (b) Structure of asphalt pavements.

Table 4 Impacts of mix design on pavement temperature.

Reference	Mix design	Strategy	Thermal property	Finding
Sreedhar et al., 2016a, b	Asphalt-rubber open graded	18% AV 9% BC	C_p 664 k 0.51	Albedo 0.7 for all samples, reduction in heat energy stored, cooling of the adjacent area.
	Asphalt-rubber gap graded	8% AV 7% BC	C_p 863 k 0.77	
	Conventional dense graded	4% AV 4.5%BC	C_p 933 k 0.88	
	Conventional	7% AV	C_p 1,039	

	dense graded	4.5% BC	k 0.96	
Takebayashi and Moriyama, 2012	Conventional asphalt	Normal	Reflectance 0.082, k 1.03	Emissivity of surface ranges from 0.97 to 1.0.
	Porous	Porosity: 13.6%	Reflectance 0.074 k 0.90	Reduction in the sensible heat flux by all samples compared to conventional.
	Water-retaining material	Porosity: 13.6%, inject by white agent	Reflectance 0.172–0.267 k 1.03 – 1.43	
Hassn et al., 2016	Asphalt slabs with various air void contents	5.0% AV	k 1.16, C_p 963.7	Temperature increase rate under dry conditions continuously decreases until the steady state.
		13.2% AV	k 0.96, C_p 957.77	
		17.4% AV	k 0.92, C_p 953.03	
		21.5% AV	k 0.90, C_p 947.11	
		25.3% AV	k 0.82, C_p 945.92	
Wang, 2015	Concrete pavement	Normal/no tining	Mean albedo 0.354	Tining of the pavement creates small shadows in the tiny grooves in the pavement surface.
	Tining concrete pavement	Direction of tining from east to west	Mean albedo 0.374	
	Tining concrete pavement	Direction of tining from north to south	Mean albedo 0.383	

Note: AV is air voids. BC is bitumen content. C_p is specific heat capacity (J/(kg·K)). k is thermal conductivity (W/(m·K)).

Asphalt mix designs, including elements, such as stone mastic and porous asphalt, can be categorised as dense graded, open graded or gap graded. Most asphalt pavements are dense graded with a reflectance value ranging from 0.04 to 0.45. As a result, the surface temperatures of conventional asphalt pavements can reach up to 48 ℃ – 67 ℃ with peak solar intensity (Beddu et al., 2014). Many studies have explored the extent to which permeable asphalt pavements influence pavement temperature (Buyung and Ghani, 2017; Wang et al., 2018). Researchers have investigated the impact of UHIs by considering the diurnal temperature cycle (Pourshams-Manzouri, 2015). Some researchers refer to porous pavements as possible cool pavements due to their high permeability, which allows water to pass through the pavement and evaporate (Li, 2012b; US EPA, 2012). Porous asphalt gains more heat on its surface during the daytime particularly under dry conditions; at night, it releases heat faster and thus is cooler than other asphalt pavement surfaces (Stempihar et al., 2012; Toraldo et al., 2015). Takebayashi and Moriyama compared the asphalt surfaces of conventional pavements, porous asphalt and water-retaining asphalt with a white liquid water-retention agent injected into the voids (Takebayashi and Moriyama, 2012). The results showed that the reduction in sensible heat flux for a water-retaining asphalt surface is approximately 140 W/m^2 during the day and almost 0 for a porous asphalt surface. Accordingly, only the porous asphalt does not solve the problem of high temperatures, unless it is included or injected with materials that contribute to heat reduction, as mentioned in Table 4.

By contrast, the dried and saturated asphalt samples with various air void percentages were tested under infrared light. The results revealed that under dry conditions, the air voids influence the specific heat capacity and thermal conductivity of the asphalt mixtures, whereas under wet conditions, the evaporation process reduces the temperature of the asphalt mixture (Hassn et al., 2016). To show the effect of air voids, different air void ratios were compared by gradually increasing the voids for different mixtures. The results indicated that air voids influence the heat response of asphalt pavements. For example, the result for conventional dense-graded pavements with different air void content showed that at 4% and 7%, the mixtures have the highest heat capacity and conductivity, whereas the asphalt-rubber open-graded mixture has the lowest specific heat capacity and conductivity. However, the issue under observation for this study was that the binder content and air voids varied amongst the mixtures and thus might have affected the comparison (Sreedhar and Biligiri, 2016a, b). Another study was also conducted on the conventional porous friction course, and its effect on the median pavement sample temperature was monitored. Based on the analysis, the pavement cannot be classified as a “cool pavement” during dry season (Nordcbeck et al., 2011). Another method called “tinning” creates small shadow areas which affect the pavements’ surfaces and solar radiation due to increments in the albedo value (Wang, 2015).

The above findings reveal that the various mix designs show no remarkable improvement when using the same materials, air void ratio and porosity. For example, the use of reclaimed asphalt pavement and warm mix asphalt have reached reductions of 12% for CO_2, 15% for energy consumption and 9% for greenhouse gas emissions (Giani et al., 2015) but had no impact on UHI mitigation. Only the porous asphalt had an impact on UHI mitigation, especially under wet conditions. This outcome can be achieved with the design method, such as the proportion of constituents, design mechanism, and equipment. A positive impact of this factor on heat islands can be observed, especially in tropical areas, because these areas experience high levels of rainfall and permeable pavements can reduce the pavement temperature through evaporation, as well as by decreasing stormwater and lessening noise (García and Partl, 2014). However, this strategy is not preferable in dry areas.

5.3 Materials used

Aggregate, filler and bitumen are the basic components of a conventional asphalt pavement. Therefore, any modification of the materials used results in an altered pavement which responds differently against solar radiation. Therefore, these materials can be classified in accordance with their thermal performance and physical properties (Doulos et al., 2004). For example, Toraldo et al. (2015) tested five open- and dense-graded mixtures (i.e., control samples); two open- and dense-graded mixtures containing cement mortar (resulting in a light colour); and one open-graded mixture with cement mortar and TiO_2. Compared with the conventional dense-graded asphalt, the open-graded asphalt mixture containing cement mortar demonstrated temperatures that were lowered by approximately 14 ℃. Table 5 shows the roles of different materials used in a sphalt mixtures to produce cool pavements.

Table 5 Different materials used for cooling pavements.

Reference	Mix design	Materials used	Thermal property	Finding
Toraldo et al., 2015	Dense-graded asphalt	-	Temperature at 1 cm depth: 59.3 ℃	Open graded highly influenced by air temperature; Photocatalytic coating is effective for dense graded surface (decrease in temperature) but not for porous pavements.
	Open-graded asphalt	-	59.6 ℃	
	Dense-graded sprayed with a photocatalytic coating	Emulsion with TiO_2	57.6 ℃	
	Open-graded sprayed with a photocatalytic coating	Emulsion with TiO_2	59.5 ℃	
	Open-graded asphalt	Filled with a cement mortar and TiO_2	45.5 ℃	
Xie et al., 2015	SMA with synthetic modified ceramic powder (infrared powder)	Infrared powder contents from 3% to12 %	Temperature difference is 8 ℃	Increase in powder content reduces temperature.
Hu and Yu, 2015b	Superpave asphalt mixture	Thermochromic (black, blue and red) powder as additive to bitumen PG 64-22	Reflectance and C_p increase, k decreased	Reduces temperature and improves performance.
Du et al., 2014	Superpave asphalt mixture with 3 layers 1st layer 15% floating bead	Without coating	Heat absorption less by 12.7%	Temperature differences, 2.4 ℃ (without coating) and 7.7 ℃ (with coating).
	2nd layer 5% graphite 3rd layer 10% graphite	Coating by heat reflective layer	Heat absorption less by 35%	
Chen et al., 2016	Dense-graded asphalt four different pavement layer combinations	Material asphalt Mineral aggregate Graphite Ceramic	k 0.8 k 2.86 k 50 k 0.23	Changes the thermal behaviour of the surface and subbase.
Wang et al., 2014	Conventional asphalt	-	More than 466 W/m^2 of heat was transferred into the soil, and less than 462 W/m^2 of heat was transferred out of the samples.	Reduces surface temperature, 3.4 ℃ field measurement.
	Multilayer modified asphalt	For top layer – 10% of aluminium oxide powder, for middle layer – 10% of graphite powder and for bottom layer – 15% of graphite powder		

Note: SMA is stone mastic asphalt. PG is performance grade. C_p is specific heat capacity (J/(kg·K)). k is thermal conductivity (W/(m·K)).

Xie et al. (2015) used infrared powder in bitumen. The sample’s temperatures under the same conditions were obtained at 66.59 ℃, 63.71 ℃, 61.34 ℃, 59.49 ℃ and 58.57 ℃ for infrared powder contents of 0, 3%, 6%, 9% and 12%, respectively. The modified bitumen increased the specific heat capacity and decreased thermal conductivity and thus reduced the potential of heat transfer through the pavement. Other studies evaluated the use of thermochromic powder, i.e., red, blue and black mixed with bitumen. They found that asphalt with black powder showed the lowest temperature, followed by the red and blue, and the difference in surface temperature was 6.6 ℃, 2.7 ℃ and 4.9 ℃ lower than that of the conventional asphalt, respectively (Hu and Yu, 2015a, b).

Another study tested two bidirectional heat-induced structures. The first gradient consisted of a top layer mixed with 15% floating beads followed by middle 5% graphite and bottom 10% graphite. The second used the same combination of gradient thermal conductivity coated by a heat reflective layer (with a reflectivity of 0.4), which resulted in the contrast of 12.73% reduction in heat absorption. In consideration of the impact of the powder on the mixture’s volume indexes and performance and the combination of the three technologies, the heat was kept outside the pavement with less heat absorption by 35% for the one with coating (Du et al., 2014, 2015).

Chen et al. (2016) designed four combinations of pavement layers, where 40% coarse mineral aggregates were replaced by light-weight ceramic particles to generate low conductivity (LC), and 20% volume fraction graphite powder was added to the base binder to produce high conductivity (HC). The result of the multilayer LC top layer with LC base layer and LC top layer with HC base layer could reduce the maximum average temperature in the asphalt pavement. The combination of LC top layer with LC base layer achieved the highest reduction of the UHI effect.

Wang et al. (2014) compared the conventional dense-graded asphalt with modified asphalt samples mixed with high-conductivity powder, namely, aluminium oxide and graphite. Samples comprised three layers: the surface course, which was mixed with 10% aluminium oxide powder; the in-between layer, which contained 10% graphite powder; and the lower mix, which had 15% graphite powder. The asphalt mixture was designed with SMA-13 as the surface course with a binder content of 6.1%, AC-20

(OBC 4.6%) for the mid and AC-25 (OBC 5.0%) for the lower course. The temperature of the modified samples was 6.2 ℃ lower than that of the control set during the heating process and 1.3 ℃ lower during the heat release. Another study mentioned that phase change material (PCM) can also improve the heat exchange between a pavement's surface and its surroundings, resulting in a reduction of the UHI impact (Guan et al., 2011). PCM is defined as an energy needed for phase transition to provide effective heating and cooling on the basis of the principle of high latent heat of fusion; it can store a substantial amount of thermal energy before transferring to another phase (Anupam et al., 2020).

5.4 Energy harvesting method

Photovoltaic materials in pavements were also investigated, with the results showing that recent technologies for photovoltaic pavements may provide electricity (Golden and Kaloush, 2005). Photovoltaic pavements can reduce the solar heat flux, thus decreasing surface pavement temperatures during daytime and night-time (Golden et al., 2007). The concept of a hydronic asphalt pavement is an emerging renewable energy technology that provides an interesting method for solar energy utilisation. Fluid circulating through a pipe network embedded in asphalt pavements can capture solar energy and store it for later use (Pan et al., 2015). The method of rotating water in pipes placed within the asphalt pavement has also been studied by various researchers to evaluate its cooling potential (García and Partl, 2014; Jiang et al., 2017; Mallick et al., 2009; Roshani et al., 2016; Symeoni, 2012). Another study was conducted on pavement by having a single row of pipes installed under the wearing course layer where air could flow through the designed system via natural convection. From the study, the surface temperature was reduced by up to 5.5 ℃ (Chiarelli et al., 2017).

6 Conclusions

This review discusses the basic concepts of thermal properties and previous research on asphalt pavement strategies for UHI mitigation. Such strategies include the use of materials and techniques for asphalt cooling. By achieving greatest surface emissivity and albedo was shown to be effective in reflecting the solar energy for the design of cool pavement. Other properties, such as low thermal conductivity and high specific heat capacity, of materials or designed layers are preferred to reduce the heat transfer capability within the pavement; these properties are considerably affected by air void content. In addition, some materials can be used to achieve varying degrees of conductivity. Existing strategies, such as material modification (including material types and proportion), can produce cool pavements by using high-reflectance materials depending on colour, density and thermal diffusivity. Thus, achieving a proper combination reduces conductivity, thereby delaying the emergence of extremely high temperatures contributed by the asphalt. Even though the use of thin-layer coatings with light colours or high-reflectance materials, such as off-white coating, can reduce the surface temperature and improve visibility, but the application of coatings also must consider the cost efficiency, ageing and skid resistance of the pavement. Therefore, by understanding the thermal performance of the different cooling strategies proposed for asphalt pavement, proper materials and design selectioncan be made to potentially reduce UHI phenomenon. From the literature it is suggested that, the materials strategy should be further studied and highly prioritized to improve the thermal properties of asphalt pavement.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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Dr. Salam Ridha Oleiwi Aletba graduated from Baghdad University in 2009 with bachelor’s in civil engineering before he completed his master’s in Civil Engineering-Transportation Department from Jawaharlal Nehru Technological University Hyderabad (JNTUH), India in 2013. He pursued his study on PhD level at the Universiti Teknologi Malaysia (UTM) in August 2016 and successfully completed in February 2021. He is interested in pavement and materials engineering and thrive into traffic and transportation.

Dr. Norhidayah Abdul Hassan is a senior lecturer of pavement engineering materials. She completed her PhD in civil engineering at Nottingham Transportation Engineering Centre (NTEC), University of Nottingham, United Kingdom specializing in pavement materials (rubberized asphalt). Currently she is responsible for teaching highway engineering and advanced road material courses. She also being appointed as the head of Pavement and Transportation Research Group (PTRG) at the School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Malaysia.

Dr. Ramadhansyah Putra Jaya is an associate professor in Universiti Malayia Pahang. Dr. Ramadhansyah Putra Jaya's research interest is in highway engineering, concrete technology, advanced materials and nano technology. He is a registered member and a fellow at Institution of Engineers Indonesia, American Society of Civil Engineers (USA), Institution of Civil Engineers (UK), International Association of Engineers (Hong Kong), World Association for Scientific Research and Technical Innovation (India) and Institute of Highway Engineers (UK). He is also a visiting research fellow for the Center of Excellence Geopolymer & Green Technology, School of Materials Engineering, University of Malaysia Perlis and Earth Resources and Sustainability Center, University of Malaysia Pahang. In 2019 he received Global Top Reviewers in Materials Science award from the Web of Science, United States. The most prestigious award in 2020 "Howard Medal" from The Institution of Civil Engineers, United Kingdom was awarded for one of his publication on Nano Technology. He has published more than 310 articles/proceedings/book chapters including 233 articles indexed on Scopus and Web of Science with H-index is 19.

Dr. Eeydzah Aminudin is a senior lecturer in Department of Structure and Materials, Universiti Teknologi Malaysia (UTM). Her enthusiasm in research and education has brings her up to date more than 80 publications published while involving herself in multidisciplinary research projects, which part of it is the government initiatives projects with different fields since 2010. She has developed numbers of award-winning research product and services that have been patented trademarked in Malaysian construction industry. Her associated professional membership includes: Concrete Society Malaysia (CSM)) and currently trainer for Building Information Modelling (BIM) under MyBIM Center, CIDB. She's also Certified Energy Manager (CEM) under Suruhanjaya Tenaga. Her research focuses on mitigating the urban heat island issues mainly on construction materials, environmental technology and sustainability waste materials, sustainable energy consumption, construction management and cost benefit analysis.

Dr. Mohd Zul Hanif Mahmud joined Universiti Teknologi Malaysia (UTM) as a senior lecturer in the Faculty of Engineering since February 2020. He graduated from Universiti Malaysia Sarawak (UNIMAS) in 2011 with bachelor's in civil engineering before he completed his master in highway and transportation engineering from the Universiti Teknologi Malaysia (UTM) in 2013. He pursued his study on PhD level at the Universiti Teknologi Malaysia on February 2013 and successfully completed on October 2019. Since then, he has prolonged his interest in pavement engineering and thrive into traffic and transportation. He has published 23 articles indexed on Scopus and Web of Science. His current H-index by Scopus is 7. His research area is mainly focused on transportation and pavement engineering mainly on bus transportation issues and traffic noise. The research area covers the experimental work, questionnaires, interviews, traffic noise characterisations, and microstructure study.

Ts. Dr. Azman Mohamed has a PhD in civil engineering and master of engineering (traffic and highway). He is the recipient of SLAI and SLAB scholarships from Ministry of Higher Education, Malaysia (MOHE) for the research studies and he also registered as professional technologist. In Universiti Teknologi Malaysia (UTM) he is a member of the Pavement and Transportation Research Group and an affiliate member of Construction Materials Research Group in Construction Research Alliance. His research interests are in underside shaped of concrete block, paver block, filler materials between blocks, pavement engineering, advanced concrete materials, concrete engineering and concrete block pavement application.

Dr. Ahmed Abdulameer Hussein completed his master in highway and transportation engineering from the Universiti Teknologi Malaysia (UTM) in 2014. He pursued his study on PhD level at the Universiti Teknologi Malaysia and completed on January 2019.