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Review

The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete

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A R T I C L E I N F O

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A B S T R A C T

The Urban Heat Island (UHI) is a phenomenon that affects many millions of people worldwide. The higher temperatures experienced in urban areas compared to the surrounding countryside has enormous consequences for the health and wellbeing of people living in cities. The increased use of manmade materials and increased anthropogenic heat production are the main causes of the UHI. This has led to the understanding that increased urbanisation is the primary cause of the urban heat island. The UHI effect also leads to increased energy needs that further contribute to the heating of our urban landscape, and the associated environmental and public health consequences. Pavements and roofs dominate the urban surface exposed to solar irradiation. This review article outlines the contribution that pavements make to the UHI effect and analyses localized and citywide mitigation strategies against the UHI. Asphalt Concrete (AC) is one of the most common pavement surfacing materials and is a significant contributor to the UHI. Densely graded AC has low albedo and high volumetric heat capacity, which results in surface temperatures reaching upwards of 60 °C on hot summer days. Cooling the surface of a pavement by utilizing cool pavements has been a consistent theme in recent literature. Cool pavements can be reflective or evaporative. However, the urban geometry and local atmospheric conditions should dictate whether or not these mitigation strategies should be used. Otherwise both of these pavements can actually increase the UHI effect. Increasing the prevalence of green spaces through the installation of street trees, city parks and rooftop gardens has consistently demonstrated a reduction in the UHI effect. Green spaces also increase the cooling effect derived from water and wind sources. This literature review demonstrates that UHI mitigation techniques are best used in combination with each other. As a result of the study, it was concluded that the current mitigation measures need development to make them relevant to various climates and throughout the year. There are also many possible sources of future study, and alternative measures for mitigation have been described, thereby providing scope for future research and development following this review.

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1. Introduction

The aim of this literature review is to present and define the various developments and studies that have occurred with regard to the thermal properties of asphalt concrete (AC), and their associated effect on the environment. This study summarises the surface temperature, albedo and other limiting factors of AC, and links these closely to the urban heat island (UHI) effect. The UHI effect is defined and analysed, and the mitigating methods for this phenomenon ailing urban environments, as described in the literature, is discussed. This review also identifies areas in which there has been minimal study, and provides scope for future research and development accordingly.

2. Background to the urban heat island

The UHI is a global issue that threatens the operation and habitability of our cities and urban environments. According to Oke (1982), the concept of the UHI has been well researched and documented; however, the understanding of the topic is quite limited. This has changed in recent years as a result of a greater focus on global warming and climate effects, the greater prevalence of hotter cities, and due to changes in technology for measurement and analysis. The heat island effect is characterised by the development of noticeably higher temperatures in our cities compared with the countryside that directly surrounds them (Nakayama and Fujita, 2010; Synnefa et al., 2011; Santamouris, 2013b, 2015a). Initial studies conducted by the World Meteorological Organisation (1984) and Oke (1982), cited in Gorsevski et al. (1998), revealed that the UHI effect can increase air temperature in an urban city by between 2 and 8°C. Recent studies illustrate that a more accurate range is between 5 and 15°C (Santamouris, 2013a). The heat island effect arises due to the changing nature of our cities, and is the result of a reduction in vegetation and evapotranspiration, a higher prevalence of dark surfaces with low albedo, and increased anthropogenic heat production (Stone et al., 2010). Therefore, the existing surface conditions of an urban area will directly impact on the chosen UHI mitigation strategies. Akbari and Rose (2008) found that the average urban surface of four different metropolitan areas in the USA were characterised by 29–41% vegetation, 19–25% roofs and 29–39% paved surfaces. This demonstrates that over 60% of an urban surface can be covered by hard, man-made, heat-absorbent surfaces. The authors concluded that knowledge of the urban fabric and surface conditions of a city is important in order to explore the effects of possible UHI mitigation measures.

The UHI can be illustrated by drawing a curve from one side of a city to the other, mapping graphically the temperature change from the rural to the urban environment and back to the rural environment. The 'island' would be represented by the large spike in the centre of the graph, which generally mimics the outline of the structures within the urban area, and is bound by the cliffs either side that mark the urban and rural boundary (Oke, 1982). By illustrating the UHI in this way, it is easy to recognise the profound increased temperature difference to which our cities are exposed. Yang et al. (2015), in their studies on UHI, illustrate the temperature intensities of UHI for various cities around the world. This effect is only getting greater, and, hence, it is important that strategies are developed for adapting to, and mitigating the adverse environmental effects of UHIs (Yang et al., 2015). In most research to date, the primary solution to the UHI has been replacing dark materials with high albedo light-coloured materials for greater solar reflectivity. This, however, is not the only solution (Stempihar et al., 2012), and further methodologies are illustrated in this review.

2.1. Regional atmospheric and geographic conditions

The regional atmospheric and geographic conditions are a key determinant of the UHI effect and its intensity in cities. The UHI effect is significantly affected by the geographic features, climatic conditions, and seasonal variations of a city's particular location. Even the time of day will dramatically affect the intensity of the UHI. Take for example night-time, during which the emissivity of a pavement and the heat radiated into the atmosphere are the most critical contributors to the temperature of the surface and lower atmosphere within an urban canyon (Santamouris, 2013b). Debbage and Shepherd (2015) conducted a study of the fifty most populous cities in the USA using PRISM data (a climate data collection network that incorporates various monitoring methods and stringent quality control measures). The authors found that geography and climate heavily affected the manifestation of the UHI across the US. For example, Salt Lake City exhibited the highest UHI effect due to the high prevalence of calm, clear and stable conditions that are ideal for UHI formation. This localised atmospheric condition resulted in the UHI being most intense during the winter months. In addition, the authors identified mitigation techniques that worked during summer but increased the UHI in winter. This research demonstrates the importance of tailoring mitigation techniques to regional conditions.

The UHI intensity is also affected by the built environment of an urban area. The configuration of urban zones is a topic of some ambiguity in UHI research. The UHI effect has often been linked to urban sprawl, and, therefore, urban densification has been espoused as a potential mitigation method (Stone et al., 2010 as cited in Debbage and Shepherd, 2015). However, Debbage and Shepherd (2015) suggest that UHI intensity is more strongly linked to other urbanisation factors, such as urban contiguity, and that both sprawled and dense cities exhibit the UHI effect. This again demonstrates the irregularity of the UHI effect and that it is an issue best tackled with localised research and mitigation efforts.

As cited in Oke (1982), and in accordance with Taesler (1981) and Oke (1976), the atmosphere in our cities can be categorised into two interrelated layers; the urban canopy layer (UCL) and the urban boundary layer (UBL). The urban canopy layer, quite similar to a vegetation layer, extends only up to the roof level of the buildings, whilst the urban boundary layer extends from the mean roof level to a few kilometres above this. Each layer has a significant effect on the other, with the UCL contributing heating, cooling and evaporation to the UBL, and the UBL contributing greater mesoscale weather conditions (Oke, 1982). Yavuzturk et al. (2005) conducted an assessment of the temperature fluctuations in asphalt pavements due to the environmental conditions. In this assessment, they deduced that a city's orientation to the wind significantly affects airflow, and the associated cooling that this brings for a pavement structure. Whilst the critical effect of wind is considered when designing urban structures both large and small, the effect that airflow has on the UHI and on the thermal properties of pavement materials appears to not have been comprehensively considered within studies to date. The work of Oke (1982) has long since deduced that in terms of the meteorological variables, wind speed is the most significant characteristic affecting UHI intensity, followed by cloud cover. In addition to this, Yavuzturk et al. (2005) illustrate that a longer segment of pavement with uninterrupted wind flow results in increased heat transfer from the pavement, and effectively cools the pavement surface. Various other factors within the local atmosphere directly contribute to the heat island intensity and its existence within a city, including the moisture and rainfall availability, geometric properties of a site, thermal properties of surface and building materials, and local anthropogenic heat (Oke, 1982).

3. Timeline of contributions to study

The first studies on the UHI were conducted in the early 1800s, making studies on the topic more than a century old (Yang et al., 2015). The timeline in Table 1 below illustrates some of the most critical contributions to the study of thermal conductivity of asphalt pavements and the associated UHI, and is derived from the various references listed at the end of this paper.

3.1. Consequences of the urban heat island

The UHI effect has significant consequences for the liveability in our cities, and is the source of a significant number of environmental problems in urban areas (Yang et al., 2015). The warming effect of urbanisation has critical impacts on health and wellbeing, as well as human comfort and the local atmosphere (Grimmond, 2007). Ichinose et al. (2008), Synnefa et al. (2011), and Yang et al. (2015), illustrate the various consequences associated with the UHI effect; these include:

- Increased cooling energy usage and associated costs;
- Significant increases in peak energy demand;
- The formation of large amounts of smog and air pollutants, and a resulting degradation in the quality of air;
- Increased thermal stress on residents and the public;
- Strong impact on urban ecosystems;
- A living environment that is significantly degraded; and
- A significantly increased level and risk of morbidity or illness due to heat.

Heat stress is a direct consequence of the UHI effect. The negative impact of elevated temperatures on urban infrastructure, ecosystems, and human health and comfort provides the motivation for finding UHI mitigation measures. Heatwaves are responsible for a range of serious health issues, and, at their extreme, can account for a large number of fatalities. Heatwaves also cause an increase in electricity and water usage (Hatvani-Kovacs et al., 2016). Santamouris (2013b) also illustrates that various studies have been able to measure significant increases in urban temperatures resulting in double the cooling energy usage of buildings. In addition to this, Clarke (1972), cited in Stone et al. (2010), show that most deaths as a result of heatwaves are associated with urban environments and the UHI effect. Hatvani-Kovacs et al. (2016) argue that an emphasis on the public health risks of heatwaves outweighs discussion on the water and electricity usage. The authors suggest that these three consequences of heatwaves are intertwined, and that, to increase a city's heat resilience, an integrated framework assessing all three of these consequences is required. Such a policy framework would aim to reduce the dependency on air-conditioning, and increase the knowledge and awareness of heat stress resilience in relation to the built environment. Lemonsu et al. (2015) also argue that urban planning and transport policies affect the magnitude of the UHI effect and suggest that compact cities have a higher risk of heatwaves than areas of urban sprawl. The authors, however, make the point that measuring heatwave vulnerability depends largely on the choice of heat stress indicators. Therefore, one must be cautious in the design of mitigation measures for the UHI to ensure that solutions such as increasing albedo or thermal conductivity do not have an added adverse effect. It is a common understanding that an increase in reflected UV radiation, glare and temperature affects the health and wellbeing in our urban environments (Yang et al., 2015).

4. Key causes of the urban heat island

Fig. 1 below illustrates the relationship between atmospheric heat, increased use of manufactured materials, and various other causes that can be attributed to the UHI, which will be discussed further.

4.1. Urbanisation, urban sprawl and increasing population

The most significant cause of the UHI is urbanisation. The constant increase in hard and heat absorbing surfaces, the density of our cities, and the reduction in natural vegetation are the main contributors to the heat island effect (Akbari et al., 2001; Doulos et al., 2004; Rossi et al., 2014). Takebayashi and Moriyama (2012), in their study of surface heat budget of various pavement materials in Japan, show that the daytime temperature of normal asphalt can be up to 20 °C hotter than grass. The changes in our cities mean that the amount of vegetation is decreasing, and pavements now cover an increasingly high proportion of our cities, contributing significantly to the heat island phenomenon (Santamouris, 2013b). The network of paved surfaces and roads that our cities are increasingly developing, have been shown to account for a larger percentage of elevated surface temperatures per unit volume compared to any

Table 1
Timeline of contributions.

Year	Reference	Findings/Description
1833	Howard, L cited in (Oke, 1982)	First to illustrate higher air temperature in cities relative to surrounding countryside.
1957	Barber, E.	Pioneered work in asphalt pavement temperatures. Sought to match surface temperature with standard weather report information.
1968	Straub, Schenck and Przbycien	Studied asphalt pavements in New York. Developed computer model of temperature against air temperature and solar radiation. Showed solar radiation was critical to surface temperature.
1970	Dempsey and Thompson	Evaluated frost action in multilayered pavements.
1971	Rumney and Jimenez	Studied pavement temperatures in Tucson, Arizona, southwest USA; a hot desert-like climate.
1972	Williamson	Used finite difference models to predict temperatures in pavement at various depths over a short time period. Found albedo significantly influenced pavement surface temperature. Did not consider humidity or precipitation.
1972	Christison and Anderson	Used finite difference model to predict thermal behaviour of pavements in low temperature environment. Model and practice agreement was found.
1973	Noss	Analysed pavement temperatures in subgrades as a result of frost penetration in cold winters.
1974	Berg, R.	Analysed surface energy balance of Portland cement concrete pavements. Found this approach not perfectly valid for frost and thaw depth interpretation.
1975	Southgate and Deen	Correlated with a linear relationship pavement temperature at depth, and surface temperature, over a five-day mean air temperature history.
1976	Wilson	Attempted use of heat flow equations for the prediction of heat gradients in asphalt pavements. Results were inaccurate.
1982	Spall	Calculated thermal conductivity and diffusivity of asphalt concrete by designing a modified calorimeter.
1984	Highter and Wall	For various asphalt mixtures, determined thermal properties. Found variance in thermal conductivity from changing asphalt content.
1987	Wolfe, Heath and Colony	Created heat-transfer equations for the determination of the cooling rate of fresh asphalt in defined environments.
1989	Huber, Heiman and Chursinoff	Developed models for short-term and long-term assessment of pavement and subsoil temperatures in thawed and frozen pavements
1989	Hsieh, Qin and Ryder	Created 3D estimation models for concrete pavement temperature and infiltration of rainwater into soil/subgrades.
1992	Choubane and Tia	Determination of the temperature of rigid pavements in Florida using a developed quadratic equation.
1993	Solaimanian and Bolzan	Related latitude to maximum and minimum pavement surface temperature with a parabolic equation.
1995	Inge and Kim	Improved AASHTO method for temperature correction for asphalt concrete deflections by creating a database method.
1996	Asaeda, Ca and Wake	Analysis of the effect that heat storage of pavement has on the atmosphere.
1998	Gorsevski, Taha, Quattrochi and Luvall	Environmental Protection Agency (EPA) launches Urban Heat Island Mitigation Initiative (UHIMI).
1998	Voller, Newcomb, Chadbourn, De Sombre, Timm and Luoma	Predicted construction phase thermal profile of asphalt concrete pavement with a computer tool.
1998	Lukanen, Han and Skok	Selection of asphalt binder dependent on surface temperature using a probabilistic method.
1998	Mohseni	Refined work done by Lukanen et al. (1998).
2004	Doulos, Santamouris and Livada	Analysed 93 commonly used pavement materials for their thermal characteristics and effect on the urban heat island.
2005	Yavuzturk, Ksaibati and Chiasson	Assessment of changes in temperature due to thermal environmental conditions.
2006	Golden and Kaloush	Interpreted the use of mesoscale and microscale techniques for measurement of surface temperature and albedo of asphalt pavement.
2007	Scholz and Grabiowecki	Permeable pavement system review.
2012	Stempihar, Pourshams-Manzouri, Kaloush and Rodezno	Analysis of thermal performance of porous pavements.
2012	Takebayashi and Moriyama	Study and comparison of surface heat for various commonly used pavements.
2013a,b	Santamouris	Analysis of cool pavements and their effect on urban heat island.
2015	Li, H	Evaluation and comparison of the thermal performance of different pavement materials.

other man made material or structure (Golden and Kaloush, 2006).

The cities of today continue to increase in size and breadth; a phenomenon known as urban sprawl. Stone et al. (2010) illustrate that urban sprawl contributes to an increasing number of heat-waves, and sprawling cities result more frequently in extreme heat events when compared with compact metropolitan cities. According to the United Nations Population Fund, cited in Stempihar et al. (2012), by 2030, 61% of the world's population will live in cities. Rapid increases in the world's population is also a key driver of change in the urban and global environment through global warming, loss of biodiversity and deforestation (Grimmond, 2007). This will result in a significant contribution to the UHI and to the environment as our urban areas continue to get larger and denser, vegetation reduces, and energy and cooling costs escalate. Changes due to urbanisation will also influence the climactic, hydrologic and biophysical cycles in the environment, and adversely affect not only humans, but natural ecosystems (Gorsevski et al., 1998).

4.2. More manufactured materials

The increase in the use of engineered materials in our cities, which have greater heat storage capacity as well as lower albedo, and the associated reduction in native vegetation, have a major influence on the UHI effect (Golden and Kaloush, 2006). The hydraulic, radiative and thermal characteristics of materials used in modern construction are completely different in comparison to natural soil and rock, vegetation, and water (Grimmond, 2007). The changing materials result in new surface and atmospheric conditions, thereby altering the exchange of energy and water, as well as the airflow. In addition, combining these changes in the conditions with the anthropogenic heat from vehicles and people, increased pollution, and the increased density of our cities, results in a completely different and distinct urban climate today (Landsberg, 1981; Oke, 1997; cited in Grimmond, 2007).

4.3. Increase in heating and cooling energy needs

Technological developments within society contribute to the UHI effect through increased heating and cooling. The most significant are air conditioning systems, which, although effective for increasing human comfort, inherently generate a greater level of heat (Grimmond, 2007). Given the density of today's cities, there are a larger number of air conditioners that are essential for the functioning of buildings and structures. Our increasingly hotter climate sees the use of more air conditioners, which significantly increase the heat of a city, creating thermal discomfort, more

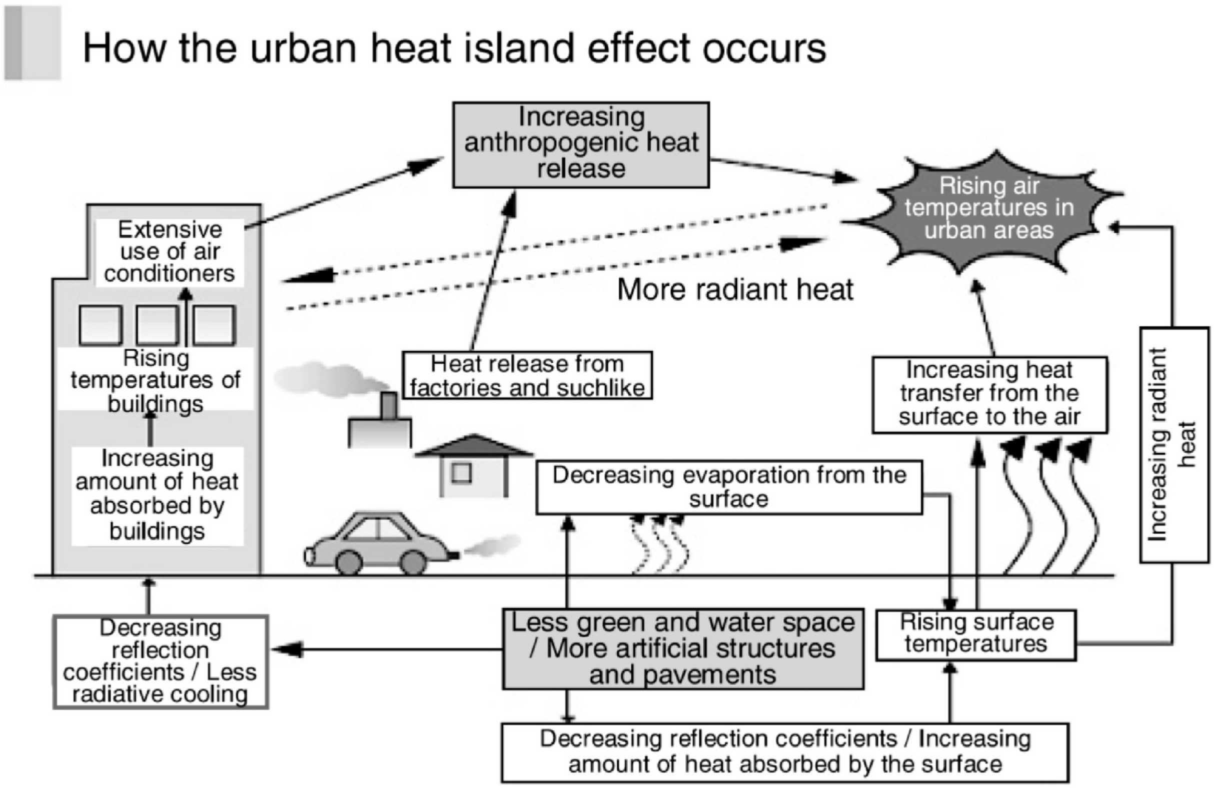

Fig. 1. How the Urban Heat Island occurs - image sourced from Yamamoto (2006).

greenhouse emissions, and affecting human wellbeing (Rossi et al., 2014). In addition to this, electricity demand for heating and cooling as a result of UHI has a significant effect, with Akbari et al. (2001) finding that for each 1 °C increase in temperature, electricity demand increases by between 2 and 4%.

5. Pavement structure

Pavements form the arterial transport connections within our cities, and research shows that they are a powerful contributor to the UHI. Many paths in our cities are referred to as pavements. From pedestrian footpaths and garden paths to highway roads, the term 'pavement' is applied to a diverse array of structures. Although there are many studies researching the effect of pavements on UHI, they often do not specify what sort of pavement structure they are researching. Roads are perhaps the most significant pavement type affecting the UHI, and asphalt is widely used as the surfacing material for Australia's roads. The overlay thickness is designed to provide additional structural strength as required and densely graded AC is often used (Fig. 2) (Austroads, 2007). The properties of asphalt vary widely, depending on such factors as void capacity and mixture content. However, it has been widely confirmed that asphalt pavements contribute to the UHI.

Most studies focus on the albedo, density, permeability and water retention of the top pavement layer because these properties have been shown to have a strong influence on the pavement's surface temperature. However, the structure and purpose of a pavement will impact the mitigation strategies utilised. Therefore, an understanding of the whole pavement structure is important to adequately assess the viability of UHI mitigation strategies.

Pavements are categorized as either flexible or rigid. Flexible and rigid pavements are composed of several layers. A flexible pavement has a wearing surface, typically asphalt, laid on top of a base and then a subbase. Together, these three layers, and sublayers, form the pavement structure which sit upon the subgrade. A rigid pavement generally has a thick concrete layer that sits upon a subbase and then the subgrade. A rigid pavement can leave the concrete exposed as the wearing surface or it can be surfaced with a thin asphalt layer. Flexible pavements are designed to deflect under loads as horizontal tensile and compressive strains are produced in the pavement's layers. Rigid pavements have a high flexural strength and distribute the load over a wider area of the pavement. Therefore, rigid pavements do not transfer deformation throughout the layers.

5.1. Asphalt concrete and the urban heat island

According to much of the literature, pavements make a significant contribution to the UHI effect (Santamouris, 2013b). This is due to the significant geographical area that pavements cover in our cities, and the relatively low albedo of a dark pavement surface (Synnefa et al., 2011). According to Akbari et al. (2009), pavements cover about forty per cent of the urban environments of cities today. In various studies, mesoscale imagery from satellites of infrared and thermal activity has shown that pavements are strong sources of heat radiation (Gorsevski et al., 1998). The albedo of a surface can be defined as the fraction of light incident that it reflects (Golden and Kaloush, 2006; Bobes-Jesus et al., 2013). According to Pomerantz et al. (2003), fresh AC absorbs approximately 95% of sunlight, or, in other words, it has an albedo of 5%. It is important to note that solar radiation typically comprises 43% solar energy, 52% near infrared light and 5% ultraviolet light (Golden and Kaloush, 2006), and a significant percentage of this is absorbed by the asphalt surface. Consideration must therefore be given to the implementation of appropriate measures and materials to improve the thermal characteristics of our cities, a topic which has garnered

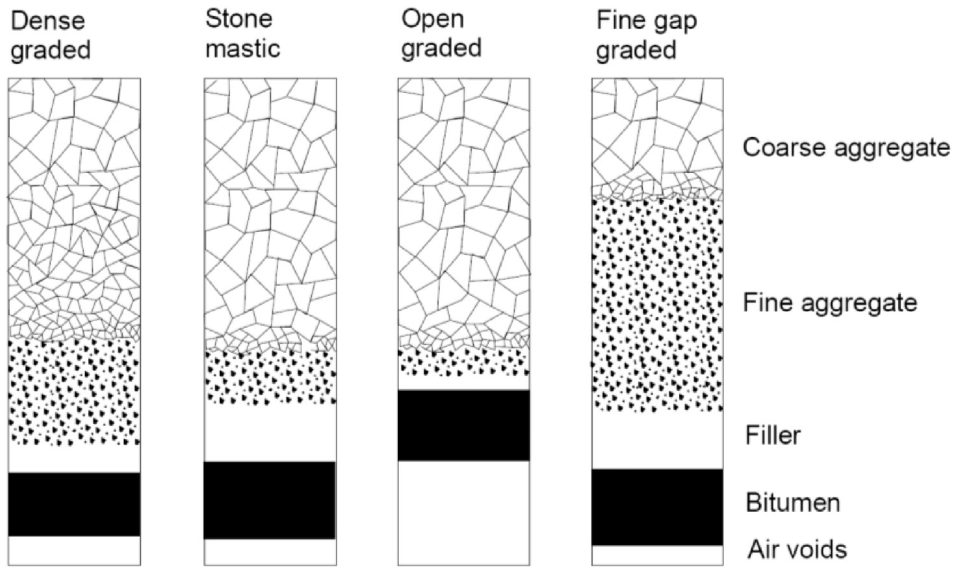

Fig. 2. Typical mix components for asphalt pavement - image sourced from Austroads 2007.

greater support in recent years (Doulos et al., 2004).

5.2. Thermal properties of asphalt concrete

An understanding of the thermal conductivity of various forms of AC, and its related contribution to the UHI effect, is critical to this study. The thermal properties of pavement materials and their albedo are quite significant determining factors in their performance and behaviour (Li, 2015). Dense graded asphalt, commonly known as Asphalt concrete in Australia, is usually composed of coarse aggregate, fine aggregate, mineral filler and a bituminous binder (Underwood, 1995). It is mixed such that the aggregates are distributed evenly between coarse and fine, and compacted such that the asphalt pavement is mostly impervious (Underwood, 1995).

In most of the studies undertaken, ordinary black AC pavements in a summer climate have a temperature range upwards of 60°C (Doulos et al., 2004; Bobes-Jesus et al., 2013; Higashiyama et al., 2016; Santamouris, 2013b). This is due to the relatively low albedo of AC compared with other pavement materials, and its affinity for thermal absorption and conductivity. According to Stempihar et al. (2012), the thermal properties of pavements fall into two categories: transfer of energy properties, and thermodynamic characteristics. The transfer of energy properties relates to conduction and radiation, the characteristics that determine the movement of energy between the pavement and its surrounding environment. On the other hand, the thermodynamic characteristics refer to the energetic equilibrium in the pavement, and concern the volumetric heat capacity and thermal diffusivity (Stempihar et al., 2012). In most cases, AC with a higher volumetric heat capacity can store more heat, and hence, generally, has a lower temperature (Yavuzturk et al., 2005).

Achieving thermal balance in a pavement structure is quite a complex procedure as it is affected by various energy transfer processes and thermodynamic factors. Primarily, heat transfer is achieved through the absorption of solar and infrared radiation, through convection between the pavement surface and the surrounding air, and through conduction between and within the pavement surface and the underlying ground (Yavuzturk et al., 2005; Santamouris, 2013b). The degree to which a pavement is responsive to thermal inputs can be referred to as thermal admittance, or thermal inertia (Oke, 1982). This thermal inertia, and the thermal properties of a pavement are highly affected by the constituents of the pavement, which is why many solutions to the UHI involve changing the properties of the AC. The constantly changing properties of each solution makes the thermal conductivity of pavements quite difficult to obtain, as, according to Stempihar et al. (2012), conductivity is determined by factors such as the type of AC mix and aggregates used, size of aggregates, moisture content and mineral content. Table 2 below illustrates some sample thermal conductivities collected from the literature. It has been shown, however, that the heat flux (heat energy transfer rate through a surface, per unit area) of asphalt is quite important. An increase in thermal conductivity (heat flux) serves to decrease the surface temperature of an asphalt pavement, as there is more dissipation of heat off the surface, as well as more conduction to the ground (Yavuzturk et al., 2005).

The major variables for the thermal performance of AC are albedo, conductivity, and volumetric heat capacity, and these parameters influence the balance of transient heat throughout the pavement layers. This includes the heating of the pavement via solar absorption, the transfer of this heat via conduction, loss of heat via wind cooling from convection, and, finally, irradiation from the pavement.

Changing the thermal conductivity of the surface affects both the minimum and maximum temperatures. Lowering the conductivity of a pavement decreases the speed at which it can transfer heat to the soil, and, in return, gain heat from the soil.

The volumetric heat capacity is the combination of two terms: the specific heat constant and the material's density. The volumetric heat capacity gives the amount of energy a material can hold per cubic metre.

6. Key mitigation measures

Mitigation measures to combat the UHI effect have been well studied and well documented. Fig. 3 below illustrates some of the common mitigation measures. Many measures have been developed over time, and some of the key measures are outlined in this review. These include designing cool pavements by increasing the albedo of surfaces and making them more reflective, permeable, porous and water retentive; the increased utilisation of green

Table 2
Summary of thermal conductivities.

Reference	Year	Asphalt type	Thermal conductivity (W/mK)	Conditions
Luca and Mrawira	2005	Dense Graded Superpave Asphalt Concrete	1.4–1.8	2295–2450 kg/m^3 bulk density, 3–7% air voids, edge heat losses accounted for
Kavianipour and Beck	1977	Dry Asphaltic Pavement	2.28–2.88	
Garcia, Norambuena-Contreras and Partl	2013	Dense Asphalt Concrete	1.2–1.6	
Takebayashi and Moriyama	2012	Asphalt	1.03	
			Thermal Conductivity (W/m°C)	
Carlson	2010	Hot Mix Asphalt (HMA)	0.896	2281 kg/m^3 bulk density
Li	2015	Dense Graded Asphalt (DG1)	DG1 = 1.73	DG1 = 2399 kg/m^3 bulk density (impermeable)
		Open-Graded Asphalt (OG1)	OG1 = 1.24	OG1 = 2269 kg/m^3 bulk density (permeable)

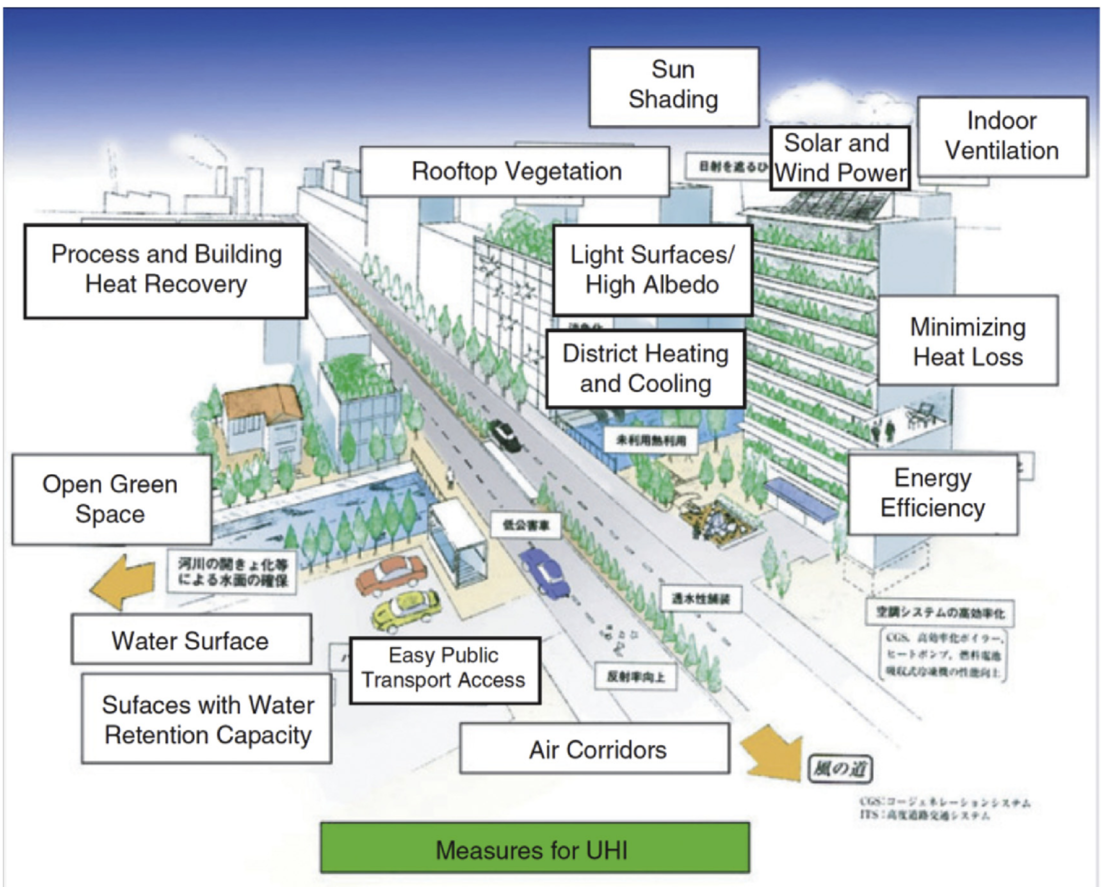

Fig. 3. Mitigation Measures for the Urban Heat Island – image sourced from Ichinose et al. (2008).

spaces within our urban landscape (Gorsevski et al., 1998; Santamouris, 2013b); and harnessing the cooling effects of wind and water.

6.1. Cool pavements

Cool pavements do not have a standard definition. The United States Environmental Protection Authority (USEPA) defines cool pavements as “paving materials that … have been otherwise modified to remain cooler than conventional pavements” (Qin, 2015a). Many studies interpret an element of this definition to mean that a cool pavement must be able to suppress its daily maximum surface temperature relative to AC (Qin, 2015a; Zheng et al., 2015; Toraldo et al., 2015; Jiang et al., 2016; Higashiyama et al., 2016).

Qin (2015a) derives the following mathematical equation for the daily maximum surface temperature (T_{smax}) of a pavement:

$$T_{smax} = \Gamma \frac{(1-R)I_0}{P\sqrt{\omega}} + T_0 \qquad (1)$$

- Γ is the percentage of the thermal absorption to the thermal conduction

- R is the albedo
- I_0 (W/m^2) is the daily peak solar irradiation
- P is the thermal inertia of the pavement
- ω (1/s) is the angular frequency
- T_0 (°C) is a regressed constant

Based on Equation (1), suppressing the daily maximum surface temperature of a pavement can be achieved by increasing the albedo, reducing the percentage of thermal absorption to thermal conduction or by increasing the thermal inertia of the pavement.

Defining a cool pavement by its ability to suppress its daily maximum surface temperature is limited because it does not account for temperature fluctuations across the time of day, season or other environmental conditions. For example, increasing the thermal inertia of a pavement may result in a lower daily maximum surface temperature; however, more heat will be released in the early evening and night-time (Qin and Hiller, 2014). Another limitation of this definition is the assumption that lowering the surface temperature of a structure will contribute to the mitigation of UHI effects, which is not always the case. Nevertheless, reducing the daily maximum surface temperature of a pavement remains a key element within the literature of cool pavements.

6.2. *Reflective pavements*

The use of reflective pavements is one of the most well studied and most cost effective mitigation measures for combatting the UHI effect by reducing the surface temperature of the pavement (Synnefa et al., 2011; Rossi et al., 2014). It is easier to vary the albedo of a pavement than its thermal inertia. Therefore, increasing albedo is the simplest method for lowering the maximum daily surface temperature, according to Equation (1), and a reflective coating can even be applied to existing pavements.

Essentially, to make a pavement more reflective, two parameters can be changed, the colour of the pavement, and its surface roughness (Santamouris, 2013b). According to most studies, the most efficient and practical means for mitigation of the UHI effect is to make pavement surfaces whiter, or as light-coloured as possible (Pomerantz et al., 2003; Santamouris, 2013b). In its essence, making a pavement surface a lighter colour decreases the amount of solar radiation that it absorbs, and increases the amount of light and heat radiation that it reflects back into the atmosphere. The reflectivity of a pavement structure and the percentage of associated solar radiation absorbed are also known as the albedo (Golden and Kaloush, 2006; Santamouris, 2013b; Li, 2015; Sen and Roesler, 2016). In general, lighter coloured materials, or smoother surfaced pavements have a higher albedo, and, hence, reflect, rather than absorb, more solar radiation (Doulos et al., 2004; Santamouris, 2013b). A reflective pavement with an increased albedo can be developed by applying a reflective paint or a sealant of thin bitumen with exposed light coloured aggregates to the surface of the pavement.

Reflective pavements can also be referred to as cool pavements, because of their inherent capability to significantly reduce surface temperature as a result of the higher albedo and increased level of thermal emissivity. According to Santamouris (2013b), a global expert and key researcher on the UHI effect, creating cool pavements is a critical heat island mitigation and management method. This is simply because pavements make up such a high percentage of the heat absorption and re-radiation in our sprawling cities. Hence albedo is a significant factor in pavement technology and in reducing the UHI. Ideally, cool pavements would be used on every road construction site; however, their application is often limited for economic or aesthetic reasons, and, instead, warm or hot pavements are used (Doulos et al., 2004). The global implementation of reflective roofing, pavements and other structures would reduce the air and pavement temperature, offset billions of tons of carbon dioxide emissions, reduce smog and aid the ailing environment (Pomerantz et al., 2003; Yang et al., 2015). Hence, making cool pavements more available, durable and affordable may be an effective area of future study.

Studies have shown that although higher albedo undoubtedly reduces the surface temperature of pavements, to date, studies considering the detrimental environmental effect of more reflective pavements, and their contribution to glare, thermal comfort and human health for residents are limited (Yang et al., 2015). Solar reflective coatings change the original surface texture of AC, and, hence, the possible detrimental effects of reflective coatings need to be studied in order to ensure that UHI mitigation techniques do not have negative and unintended consequences. Kinouchi et al. (2004) developed darker paint pigments with high solar reflectivity in near-infrared light but low visual brightness in an effort to reduce the negative consequences of increased glare; a particularly important consideration for roads. Another important consideration for road design is the skid performance of the road surface. Increasing albedo by increasing the smoothness of the road surface will negatively impact skid performance. Zheng et al. (2015) developed and compared solar reflective coatings that had sufficient anti-skid performance and low impact on driving glare whilst retaining their cooling properties (Fig. 4). Hard machine-made sands and ceramic particles were used as additives to the reflective coating to improve the anti-skid performance. They found that without these additives the skid resistance of the coating was half that of regular AC pavement.

Developing and supplying paints and particle additives for pavement surfaces will increase consumer demand for manufactured materials, which, in turn, will produce more waste and anthropogenic heat, and perhaps offset the UHI benefits of the materials. Utilising recycled materials as construction materials will help to alleviate the environmental stresses associated with increased landfill and will contribute to a reduced demand for newly manufactured materials. Sano et al. (2009) developed a method for producing ceramic waste aggregates from recycling ceramic porcelain insulators, and Higashiyama et al. (2016) used light coloured ceramic waste powder as an aggregate in their cement-based grouting materials (CBGMs) for cool pavements.

Combining the properties of cement and AC has become an important feature of current research. Pomerantz et al. (2003), in their study of cooler and more reflective streets for heat island mitigation, analyse the difference between normal Portland cement concrete and AC. In addition, they consider the use of chip seal pavements as a cooler and more efficient surface treatment. It was found that Portland cement pavement, given its smooth texture and light colour, presents a much higher albedo and lower surface temperature than AC pavement (Pomerantz et al., 2003). In addition to this, Portland cement concrete pavement was found to be cooler due to the fact that it is a mineral that attracts rather than repels water, unlike the oil based asphalt binder. Water has a passive cooling effect on the pavement, which is mainly due to evaporation. This is consistent with studies done to date, illustrating that more reflective pavements are positive for the environment.

By resurfacing that achieves a lighter colour, chip seals have also been shown to work quite well at increasing albedo (Akbari et al., 2001; Santamouris, 2013b). This is because chip seals are generally an overlay type structure, in which the aggregate remains exposed, meaning that the albedo is almost the same as the exposed aggregate (Pomerantz et al., 2003), thereby resulting in greater heat and light reflection than thermal conduction by the pavement. Whilst the albedo tends to decrease for a chip sealed pavement due to age and use, it remains higher than that of AC for

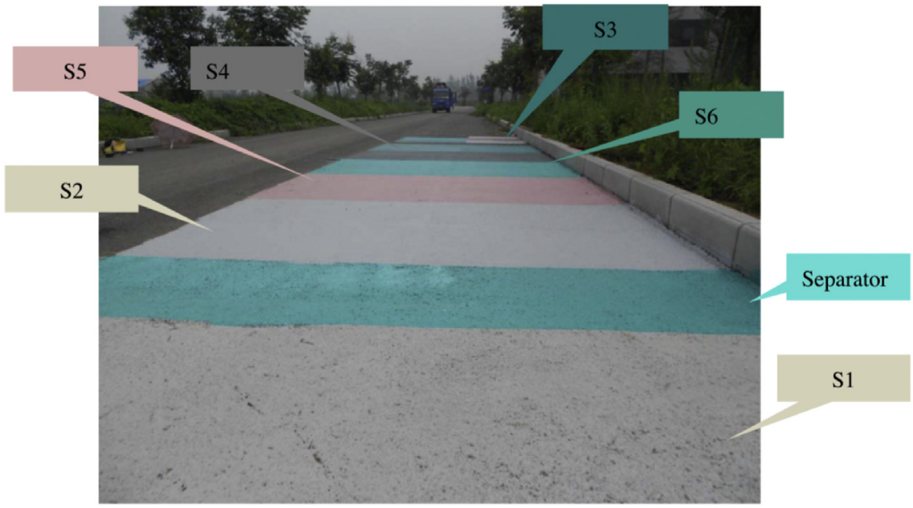

Fig. 4. Outdoor test of various solar reflective coatings - image sourced from Zheng et al. (2015).

about five years, resulting in a reduction in the environmental impact over its life cycle (Qin, 2015a). Chip seals are often only used on rural roads of low traffic volume, and, therefore, whitetopping is a more appropriate sealing method for medium to high density roads. Whitetopping is the process by which an aged pavement is resurfaced with around 10 cm of light coloured concrete. Low-traffic volume pavements can be resurfaced with an even thinner surfacing of concrete (Qin, 2015a).

Age and weathering can degrade or even enhance the reflectance of cool pavement coatings. The current practise of assuming a constant albedo over the lifetime of AC pavement overestimates the warming potential of the pavement. As an AC pavement ages its albedo can increase from 0.05 to 0.15; this occurs because the binder oxidises and its aggregates become exposed (Qin, 2015a). Sen and Roesler (2016) (Fig. 5) developed an aging albedo model to determine the significance of the change in albedo of AC pavement over time, and found that assuming a static albedo over the life of a pavement overestimates the global warming potential of the pavement by 25%. According to their model the albedo of a pavement increases rapidly in its first year.

In contrast to the increasing albedo of AC, the albedo of concrete decreases over time, as dirt, tyre wear and exposure darken the pavement. Research in this field is important to determine the economy of using reflective coatings on AC pavement. Future research needs to consider the durability of reflective coatings to adequately assess whether altering the albedo of AC pavement is actually the most economically viable way of addressing the UHI effect of AC pavement in the long term.

6.3. Evaporative and water retentive pavements

In addition to reflective pavements, evaporative and water

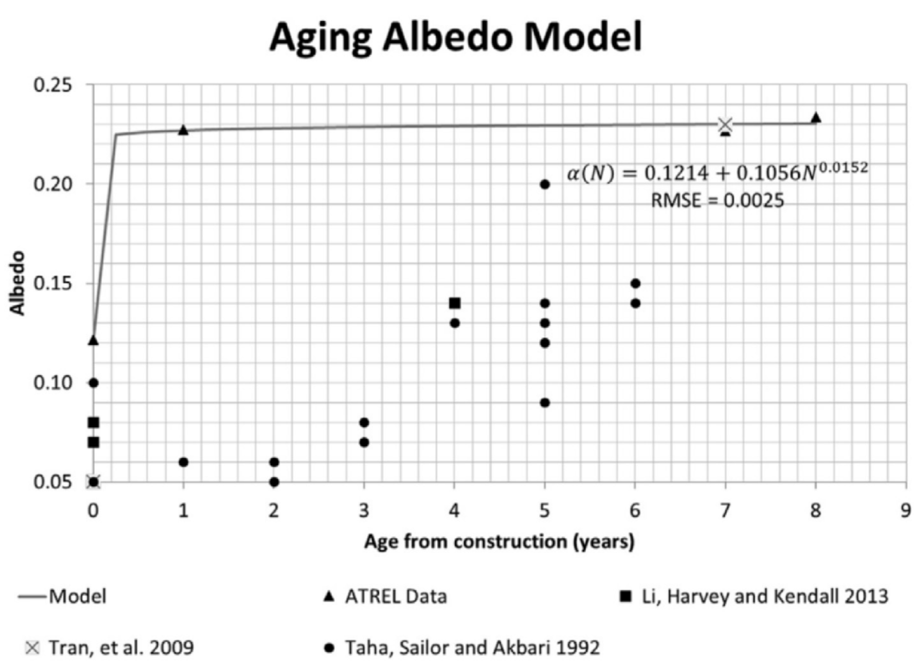

Fig. 5. Sen and Roesler's aging albedo model (2016).

retentive pavements have been topics of much study, due to their in-built ability to cool a pavement through water evaporation. Evaporation of water is critical to the creation of urban cool islands within cities and urban environments (Nakayama and Hashimoto, 2011). Porous, water retentive and permeable pavements essentially eliminate the finer particles from their structure, or replace the finer particles with more porous materials, such as pozzolans, slag, fly ash, or silica fumes (Santamouris, 2013b). The amount of air voids in asphalt depends on the mixture and can vary between 5 and 30% of the total volume (Hassn et al., 2016). The increased degree of air voids within the pavement means that water can pass into the voids either by seepage from the soil below, or through surface rainfall. Solar absorption causes heat convection from the pavement to the air and a conductive heat flux with the lower pavement layers. A saturated pavement emits less heat because part of the absorbed energy is diverted to evaporate the water into the atmosphere (Hassn et al., 2016). Once thermal exchanges heat the pavement by solar radiation to a certain temperature, evaporation of the liquid within the voids requires energy usage, thereby cooling the pavement (Santamouris, 2013b). This evaporative cooling technique suppresses the parameter Γ (Equation (1)): the percentage of the absorption to the thermal conduction of solar radiation.

A higher air void content in asphalt decreases the thermal conductivity of the pavement as well as lowers its specific heat capacity. Hassn et al. (2016) determined experimentally in a laboratory that the surface temperature increase rate was higher for dry asphalt slab samples with a high air void content than for dry samples with a low void content. This suggests that low thermal conductivity detrimentally affects a dry pavement's ability to dissipate heat. However, the surface temperature increase rate was lower for wet asphalt slab samples with a higher air void content. In wet conditions, a pavement that holds more water can divert more energy to evaporate the water than a pavement with a higher conductivity and heat capacity but lower void content. This indicates a key concept in porous pavement design: the ability to hold water for longer periods of time will increase the cooling ability of an evaporative pavement.

The easing of stormwater runoff is critical, as it is rainfall that determines the effectiveness of a permeable, porous and water retentive pavement. The cooling properties of an evaporative pavement depend on whether the evaporative cooling effects outweigh the low thermal inertia of the pavement. It is critical to note here that permeable or porous pavements should not be used in areas of the world that do not experience tropical fluctuations in weather. This is because in hot arid environments the temperature of these pavements can actually be hotter than ordinary AC, and have a more detrimental effect on the surrounding environment than their counterparts (Santamouris, 2013b).

Evaporative pavements can be designated as porous, permeable, or pervious. Although the terms permeable, porous and pervious are often used interchangeably when discussing evaporative pavements, Qin (2015a) offers separate definitions as all three exhibit unique properties. In addition, when discussing evaporative pavements, it is important to note the entire structure of the pavement. For high traffic load pavements *permeability* or *porosity* often only refers to the top layer of the pavement. If water is able to permeate throughout the pavement structure it would undermine the base and sub-base. For this reason, when studies refer to permeable or porous pavements, it is important to qualify the structure of the entire pavement and to refer to its utility.

6.3.1. Porous pavers

Porous asphalt pavement allows water to pass through voids in the pavement structure. Porous pavers are used in non-road pavement design. These pavers comprise a cellular grid system with holes filled with materials designed to hold moisture. Grass is the most effective infill for these pavers as grass has a higher albedo than other fillers (such as dirt), and the transpiration from the grass aids evaporative cooling (Qin, 2015a).

6.3.2. Permeable pavement

Permeable pavements operate on a different principle than porous or pervious pavements. Rather than allowing rainwater to pass directly through the pavement to the base, permeable pavements specifically refers to pavements that have a permeable top layer that diverts the water flow to channels so that water passes around the pavement (Qin, 2015a). Permeable pavements have been shown to effectively mitigate urban issues, such as the heat island effect, and also slow the stormwater runoff of pavements (Li, 2015). They are also gaining wider use within the paving industry, not only due to this ability to reduce stormwater runoff, but also because of the increased friction properties from the rough texture and the associated improved safety for vehicles (Stempihar et al., 2012).

According to Takebayashi and Moriyama (2012), in their study of the surface heat budget for various pavement materials, the albedo and thermal properties of a porous material surface are highly dependent on the distribution of aggregate within the pavement. The reflectance of solar radiation for porous pavements during daytime periods is generally considered to be lower than for smooth surfaced pavements due to the open and coarse structure of the pavement (Golden and Kaloush, 2006; Stempihar et al., 2012; Santamouris, 2013b; Qin, 2015a). In addition to this, the less dense structure results in less heat storage and transfer to the surface and subsurface layers, often resulting in a hotter daytime surface temperature (Stempihar et al., 2012; Qin and Hiller, 2014; Coseo and Larsen, 2015). Porous [permeable] pavements, however, are significantly more effective during night periods due to their high void ratio, giving them increased thermal insulation and storage properties (Stempihar et al., 2012). In addition, porous and permeable pavements also effectively mitigate the UHI effect through their evaporative efficiency, and because they do not store as much heat during the day for re-radiation into the atmosphere (Golden and Kaloush, 2006). According to Equation (1), low solar reflectance combined with a lower thermal inertia means that a permeable pavement will be hotter during the day and cooler during the night than a densely graded AC. Porous pavements have been shown through studies (Stempihar et al., 2012) to have the lowest night-time temperature compared to other solutions, and should be considered as an effective tool for UHI mitigation in tropical environments.

As with reflective pavements, using recycled materials in evaporative pavement design can decrease dependence on newly manufactured materials to further reduce UHI effects. Composites of recycled rubber, and chitosan, a by-product from the seafood industry, can be used for permeable pavements and can exhibit stormwater filtration performance comparable to typical stormwater treatment practices (Murray et al., 2014). However, permeable pavements are often less durable than AC, and, due to clogging of the pores, require more maintenance. Both the lower durability and the associated maintenance increase the costs of the pavement over its lifetime.

6.3.3. Pervious pavement

According to Qin (2015a) a pervious paver refers to a special type of concrete that has a high level of porosity that allows water to pass directly through the pavement. The large internal cavities in the concrete allow water to drain quickly and therefore the cooling effects of this concrete vary greatly. The high solar absorption of pervious pavers combined with a low thermal inertia causes the pavement to be hotter during the day.

Qin (2015a) includes pervious asphalt concrete under his designation of pervious pavement. However, in much of the literature, this is referred to as porous asphalt concrete. Porous asphalt concrete is achieved by eliminating the finer aggregate in AC, which causes air voids between the larger aggregates. Water can then filter through the voids and into the sub-base of the pavement. A modified approach can even be used for highway road engineering by laying a thin surfacing of porous pavement over the impermeable AC layer. This allows the road to absorb rainwater and divert it to the side of the road as stormwater runoff while contributing to road safety and cooler pavement design. This porous asphalt behaves similar to most evaporative pavements with a cooling effect during wet periods and a heating effect during dry periods.

An increasing amount of literature highlights the importance of the evaporation rate on the efficacy of permeable and porous pavements to reduce the pavement's temperature. Studies show that keeping water near the surface of the pavement is critical for improving the thermal capabilities of the pavement. This can be achieved by improving the capillary action of a pavement or by sprinkling water over the pavement surface (Li et al., 2014). The capillary effect depends on the air void content, pore size and permeability of the pavement structure. It is important to note that the positive effect of evaporation on UHI is dependent on a high air temperature (Li et al., 2014). An evaporative pavement will only decrease the sensible heat released if the evaporative flux remains high enough to counter the negative effects of the lower thermal inertia of a porous pavement (Qin and Hiller, 2014). More research on the amount of water required to be held in a pavement's structure to counter the effects of other heating sources is required. The dual uses of porous pavement (to promote quick stormwater runoff and combat the UHI) may not be mutually attainable as the water needs to be held in the pavement structure to cool the pavement from evaporation. In a compact urban environment there is no quick fix solution and UHI mitigation measures must consider all the urban geometry and environmental factors to be successful.

6.3.4. Water-retaining pavements

Water-retaining pavements were developed in response to the fast draining of pervious and permeable pavements, which caused negligible cooling effects in the pavement (Qin, 2015a). The most effective cooling of pavements occurs when water held within the top 25 mm of the pavement evaporates (Nemirosky et al., 2013). Water-retaining pavements hold water at the top of the pavement by having a similar porosity to a permeable pavement but with a considerably lower permeability. Water-retentive fillers are utilised as an aggregate in the concrete or asphalt. The high absorption of water-retentive pavements also allows the water held in the sub-base of the pavement to be absorbed. Therefore, water-retentive pavements are expected to remain cooler longer than permeable or pervious pavements. Developing water-retentive pavements has become an important aspect of current research. Designing different fillers and methods for keeping the pavement cooler longer are being researched including using recycled waste water as a watering agent on water-retentive pavements (Qin, 2015a; Jiang et al., 2016).

Water-retentive asphalt concrete has been developed by incorporating water-retentive slurry (WRS) in the air voids of porous asphalt concrete. The slurry hardens and is able to absorb water and hold it for a period of time, which significantly decreases the surface temperature of asphalt concrete and is therefore an effective heat island mitigation measure. Most studies regarding water-retentive asphalt concrete (WRAC) have focussed on the cooling effect of these pavements. Due to the slurry, WRAC has a lower air void content than porous asphalt concrete (PAC), which increases the overall strength and stability of the pavement. The analysis of the microstructure of hardened WRS combined with laboratory testing has demonstrated that WRAC develops good moisture resistance and rutting resistance compared to PAC. WRAC has a higher resistance to permanent deformation under high temperatures than PAC and performs better in low temperature fracture resistance tests. However, WRAC has a lower resistance to low temperature fracture and lower deformation resistance then densely graded asphalt concrete (Jiang et al., 2016).

Higashiyama et al. (2016) developed water retaining open graded asphalt pavements by pouring cement-based grouting into the pavement voids. The CBGMs developed by Higashiyama et al. (2016), to produce a surface temperature rise reduction function (STRRF), consist of cement (C), ceramic waste powder (CWP), and fly ash (FA) or natural zeolite (NZ). CBGMs utilising recycled CWP were found to reduce the surface temperature of open graded asphalt by 10–20 °C when the open graded asphalt reached daytime temperatures of 60 °C or more.

Jiang et al. (2016) used laboratory testing and scanning electron microscopy to investigate the effect of varying the proportions of ingredients of water-retentive slurry (WRS) in porous asphalt concrete (PAC). The workability, water absorbing capacity, compressive strength and flexural strength of cured WRS are affected by the mix proportion of ground granulated blast furnace slag (GGBFS), fly ash (of a porous cellular nature), an alkali activator (calcium hydroxide), and water. The cementitious and hydraulic properties of GGBFS and fly ash contribute to the long-term strength increase and resistance to the drying shrinkage of WRAC. The study demonstrates that the optimal mass ratio of GGBSF to fly ash for compressive and flexural strength is 90%–10%. Calcium hydroxide has a significant effect on the water absorbing capacity, compressive strength and flexural strength of hardened WRS. A calcium hydroxide content of 15% provides adequate hydration with improved mechanical and water absorbing properties.

Jiang et al. (2016) also showed that WRAC has a cooler surface temperature than PAC. This is due to WRAC's moisture retentiveness and evaporative cooling, and the off-white colour that provides high reflectivity of the WRS. Jiang et al. (2016) found that the cooling effects of WRAC decreased as the water retained evaporated, thereby demonstrating that the effect of WRAC is highly dependent on rainfall or watering; however, due to its higher reflectivity, WRAC still continually shows lower surface temperatures than PAC both in the daytime and night.

A limitation to much of the current literature is that research regarding ‘cool pavements’ rely on laboratory testing or field testing that was only conducted over a short period of time and often far from true urban conditions. Toraldo et al. (2015) studied the UHI effects on five different road surfaces for a period of a year. Untreated dense and porous asphalt concretes were compared with dense and porous asphalt concretes that had been sprayed with a photocatalytic coating and with an open graded asphalt concrete filled with a cement mortar. The authors confirmed that solar irradiance has a great effect on pavement temperature and that relative humidity influences open graded pavements. Lighter coloured pavement reduces the surface temperature and open graded asphalt filled with a cement mortar lowers the surface temperature by about 14 °C compared to dense asphalt concrete. Toraldo et al. (2015) found that open graded asphalt with cement mortar has the lowest temperatures and the least amount of heat transferred compared to the other mixtures.

6.4. The urban canyon

Urban geometry can greatly affect the efficacy of UHI mitigation methods, particularly reflective pavements. The urban canyon (UC) is a descriptive term for roads and pathways surrounded by the buildings, walls and roofs of an urban environment. This combination of roads and buildings essentially creates canyon-like structures that are subjected to many reflections. The geometry of an urban canyon will affect the magnitude of radiation reaching street level and escaping back into the atmosphere (Santamouris, 2015a). The urban canyon of tall buildings and narrow streets trap heat, and prevent air circulation (Rajagopalan et al., 2014). The urban geometry is also the greatest man made influence on wind flow characteristics through an urban zone (Memon et al., 2010). Therefore, understanding the holistic effect of UHI mitigation measures on the entire urban street environment is an important point of the current research.

An increasing number of studies are exploring the actual effectiveness of UHI mitigation techniques on the air temperature of an urban area. Many cool pavement studies in the past have focussed on surface temperature and have often assumed that reducing pavement surface temperature will have a positive effect on UHI mitigation on a city-scale level. Qin and Hiller (2014) found that the sensible heat released to the air from the pavement typically follows the pattern of surface temperature and can be reduced by cool pavements. However, this is not always the case, as environmental factors, such as urban canyons, complicate the issue.

The *height/width* aspect ratio of a canyon has an enormous effect on the urban canyon albedo (UCA) and can cause an increase in air temperature (Memon et al., 2010). Urban canyons have lower albedo than roads and pavements, and absorb more solar radiation (Qin, 2015b); an urban canyon will also act as a reflector, preventing radiation from escaping into the urban boundary layer. An increase in pavement albedo will only raise the UCA if the *h/w* aspect ratio $\leq$1.0 (Qin, 2015b). This has immediate ramifications for urban planning as it constricts the context in which reflective pavements will reduce the UHI effect. In fact, raising the pavement's albedo in an urban canyon can have negative effects as it increases the amount of solar radiation reflected into the surrounding walls of the buildings and can increase air temperature (Coseo and Larsen, 2015). This additional energy will increase the sensible heat of the urban zone and may increase night-time heat emission as it is difficult for heat to advect out of an urban canyon. Increasing the albedo of pavements in an urban canyon will also increase the energy usage of the surrounding buildings (Yaghoobian and Kleissl, 2012). This occurs because the buildings absorb a greater amount of heat, and, therefore, need to expend more energy for cooling. The exact effect of increasing pavement albedo needs site specific research because it can be affected by variables such as wind, sky view factor, building insulation, mirrored windows, building aspect ratios and shapes. More research is required to determine the adequacy of high albedo pavements in urban zones.

6.5. *Making the environment green*

One of the easiest solutions to mitigate the UHI effect is to revert back to the environment of the past. This is because the reduction in vegetation, and the greater prevalence of hard materials and structures, as outlined earlier, is a significant cause of the UHI effect (Oke, 1982; Akbari et al., 2001; Stone and Norman, 2006; Stone et al., 2010). More trees not only provide shade for buildings and people, but also reduce the wind speed under the canopies, and cool the air through evapotranspiration (Akbari et al., 2001; Santamouris, 2015b). The surface temperature and the air temperature of urban green areas are lower than those of the surrounding cityscape and even a relatively small green area can contribute a cooling effect (Doick et al., 2014; Tan et al., 2015). This cooling effect extends its benefits to the surrounding cityscape.

Golden and Kaloush (2006) have been able to illustrate in their subject site that increased canopy coverage is an effective mitigation measure, as temperatures below the canopy are up to twenty degrees cooler in the mid-afternoon and at most times during the day. Takebayashi and Moriyama (2012), in their study of the surface heat of pavements, made a comparison between AC pavements and grass, as many other studies have done. They illustrated that the average daytime temperature of AC pavements is up to 20 °C higher than the grass surface. This is a significant increase, and causes a detrimental effect on the environment. Urbanisation has undoubtedly created this hazard to the environment and general wellbeing.

Not only does the higher amount of vegetation reduce heat within a city, it also contributes to environmental impact management. More vegetation prevents smog formation (Gorsevski et al., 1998), results in less reflection and glare, and greater thermal comfort for an area's inhabitants (Mullaney et al., 2015; Tan et al., 2016). The heat related health impacts are also minimised as a result of the greater prevalence of vegetation in the environment (Stone et al., 2010; Tan et al., 2015). There are many ways to increase the prevalence of vegetation in an urban zone. For example, urban greenery can be enhanced through the increased installation of city parks, private gardens, street trees and rooftop gardens.

Research suggests that localised tree planting in small parks with high sky view factors (SVF) significantly cools down urban air temperatures and that planting trees in the wind path will increase the cooling ability of each tree (Tan et al., 2016). In a five-month case study of a park in central London, Doick et al. (2014) found that the cooling effect of the urban greenery was greatest on warm nights with low wind speed. However, the boundary of the cooling effect was largely variable and they suggest that urban planners should seek to develop a higher number of small, wooded green spaces for more efficient and stable cooling effects. The sky view factor (SVF) is an important parameter for the cooling effect of trees, because a low SVF causes heat to dissipate more slowly at night (Oke, 1982; Rafiee et al., 2016). Rafiee et al. (2016) also found that a 40 m radius around greenery will experience the greatest reduction in UHI effects.

Research into the role of cool roofs is increasingly placing an emphasis on green roofs. Cool roofs and green roofs are both effective strategies against the UHI effect. Roofs represent, on average, 20–25% of urban surfaces in Italy and 60–70% of the building envelope, and, therefore, are an important urban component to consider (Costanzo et al., 2016). A cool roof increases the albedo of the roof surface and therefore decreases the amount of solar radiation that is absorbed by the building (Razzaghmanesh et al., 2016). However, this will only provide a benefit in summer. Reducing the solar heat gains from the roof in winter will actually increase the energy needs of the building (Costanzo et al., 2016). In contrast, a green roof replaces the roof surface exposed to solar radiation with soil and plants, and creates a more natural environment with many benefits.

Green roofs reduce both the surface temperature and the air temperature of an urban area during a hot summer day (Razzaghmanesh et al., 2016). This direct benefit demonstrates that the UHI effect is resisted by increasing evapotranspiration and by converting solar radiation into latent heat. Costanzo et al. (2016) found that both reflective and green roofs decrease the roof's surface temperature. Reflective roofs perform better in summer; however, green roofs also improve stormwater runoff mitigation, reduce noise and improve a building's insulation (Tan et al., 2015; Razzaghmanesh et al., 2016). This can have positive effects on energy costs in both summer and winter, and can reduce carbon emissions. Green roofs lower the annual energy needs by providing shade and insulation in summer and insulation in winter (Tan et al., 2015; Costanzo et al., 2016). Reflective roofs, on the other hand, may even require an increase in energy use during winter. If a city wide green roof strategy was implemented, the air quality would also likely improve (Gorsevski et al., 1998).

A deeper green roof lowers the daytime temperature more than a shallow green roof, but increases the night-time temperature (Razzaghmanesh et al., 2016). The heat flux during the day moves from the top of the garden layer to the bottom, and at night moves from the bottom layer to the surface. This follows the same pattern as dense AC pavements. An increase in the volumetric heat capacity of a material results in less energy being released immediately during the day with the absorbed energy being released over a longer period of time. This typically results in higher night-time temperatures.

More research is required to determine the optimum green roof depth and possible ways to mitigate energy release at night. Despite this, green roofs and green walls are valuable UHI mitigation strategies and would work well when implemented with reflective pavements. Instead of excess energy being reflected from the pavement into the buildings it would be absorbed by the green walls and roofs (Razzaghmanesh et al., 2016). This highlights the fact the UHI mitigation relies on a multifaceted approach.

Stone et al. (2010), in their studies on urban form and sprawling cities, indicate that it is the responsibility of urban planners to make a difference in the use of vegetation and greenery. By predicting the effects of heat, they can promote and enforce the installation of trees, green roofs, and greater water sensitive urban design. Anthropogenic heat production can also be reduced by promoting mass transport, bicycling and walking. Therefore, it is evident from the literature that increasing tree planting and vegetation within an urban environment is positive, resulting in less need to consider the effect of the thermal properties of AC pavements within cities.

6.6. Wind, water and atmosphere

The surrounding atmospheric conditions of an urban zone will affect the UHI. The rapid development of urban areas disrupts the natural wind patterns and water bodies of the world. Wind and water play an important role in the UHI phenomenon. Wind speed is one of the most important natural variables on the UHI effect (Morris et al., 2001; Memon et al., 2010). Higher wind speeds can decrease urban temperatures, improve air circulation, improve cooling systems, and dissipate pollutants (Morris et al., 2001; Memon et al., 2010; Rajagopalan et al., 2014; Santamouris, 2015a). The greatest night-time UHI intensity is often recorded in clear and calm conditions. The UHI intensity will decrease with higher wind speeds, higher relative humidity and increased cloud cover (Morris et al., 2001; Santamouris, 2015a). The UHI of specific urban zones is influenced by the urban geometry as well as local atmospheric conditions. The causes of the urban heat island effect are not the same for different cities or different climates (Mirzaei and Haghighat, 2010). Region specific mitigation strategies can effectively model the urban environment of particular cities. This confirms that climate and region specific models are important for clearly defined UHI mitigation strategies.

The tall buildings of modern cities prevent air circulation and disrupt the convection of heat away from the city, which also prevents the dissipation of pollutants. In addition, many UHI mitigation techniques would be improved by circulating the cooler temperatures throughout the urban zone. Wind moves along paths of low surface roughness and it is therefore possible to model and predict wind paths. Computational fluid dynamics (CFD) provide a valuable tool for evaluating urban wind paths and the effect of water bodies on the urban environment (Memon et al., 2010; Tominaga et al., 2015). Hsieh and Huang (2016) developed a methodology for analysing urban wind corridors at a scale that would be useful for urban planners. Detailed quantitative analyses of wind corridors can be used to effectively regulate urban design in order to utilise wind to ventilate areas and advect heat away from its source to prevent local heat accumulation. In their case study of Muar, Malaysia, Rajagopalan et al. (2014) determined that a step up configuration, Fig. 6, can distribute the wind efficiently and allow ventilation to reach the leeward side of the building. The step up configuration places towers towards the windward side of the block rather than in the middle or leeward.

The effect of water bodies on the UHI is becoming an increasingly relevant area of study. The concept of a water cooling island (WCI) to mitigate the UHI is based on the principle that water evaporation uses energy that would otherwise be converted into sensible heat. Several studies have found that proximity to a water body decreases the air temperature. The air temperature above a river can drop by over 5 °C compared to a surrounding urban zone during warmer seasons, and this cooling effect can be propagated a few hundred metres horizontally and about 80 m vertically when a sea breeze blows along the river (Murakawa et al., 1991). A WCI was also observed from field data in Sheffield, UK, as a mean temperature reduction of 1.5 °C was found above a river in spring; this temperature reduction was again related to wind speed and direction. However, the cooling effect of the river was reduced in summer as the water temperature of the river increased (Hathway and Sharples, 2012).

The reduction in temperature from a water body can increase the human thermal comfort in the WCI zone. Even relatively small water bodies can increase the human thermal comfort, as Xu et al. (2010) found that a small water body (0.087 km^2) in an urban park in Shanghai increased human thermal comfort during the hottest part of a summer day. This study observed that the WCI effect was greatest for an area 10–20 m from the water's edge. Tominaga et al. (2015) used CFD simulations to reproduce the WCI effect of small water bodies and found that a water body could decrease the pedestrian level temperature by 2 °C and that a wind velocity of 3 m/s at a height of 10 m could propagate a cooling effect downwind up to a distance of 100 m.

Du et al. (2016) also confirmed the WCI effect in Shanghai and based their research on an analysis of eighteen lakes and three rivers. The authors also correlated the cooling effect of a water body to several variables. They found that the cooling effect of water bodies is related to their geometry and that simple shapes, such as squares, rectangles and circles, have a greater cooling effect than complex shapes. Improving the microclimate around a water body, by surrounding the water body with a green zone, vastly improves the water body's cooling ability (Doick et al., 2014; Du et al., 2016). Surrounded by impervious urban surfaces on hot days the water body is heated by these materials and the WCI decreases. Green spaces will also improve local air circulation which was again found to have a large influence on the cooling ability of the water body.

Most of these studies compare the temperatures of and around the water bodies with the surrounding urban zone. Steeneveld et al. (2014), however, found that water bodies in Rotterdam actually have higher temperatures than the surrounding rural areas. The harbour in Rotterdam in summer was cooler than the surrounding urban zone in the hotter daytime periods, but increased the UHI effect in the evening and at night. This is due to water's relatively high volumetric heat capacity and confirms the significance of combining a water body with a green zone and air circulation to effectively mitigate the UHI effect.

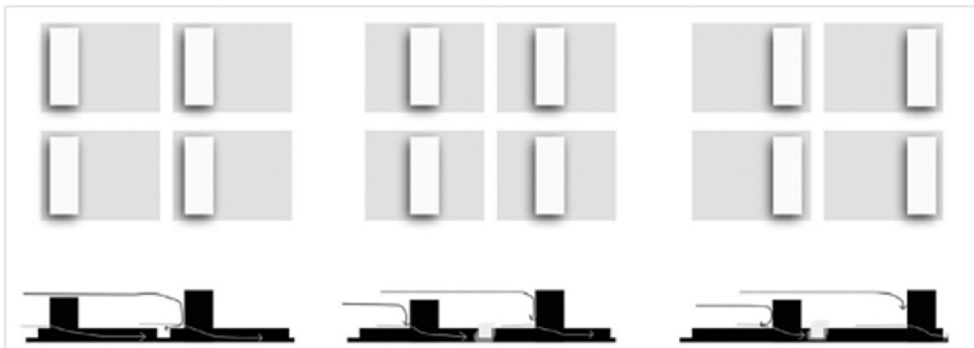

Fig. 6. Step up configuration of towers showing a) most ventilated, b) less ventilated and c) least ventilated option (Rajagopalan et al., 2014, pp. 167).

6.7. Combined effects

Mitigation methods should not be considered in isolation. Whilst many studies have shown that it is possible to produce energy gains and lower temperatures through a pavement with a higher albedo (Pomerantz et al., 2003; Golden and Kaloush, 2006; Santamouris, 2013b; Yang et al., 2015), this must be combined with other heat island mitigation initiatives (Doulos et al., 2004). Adding vegetation and planting at all levels of the urban canyon make a significant contribution to evaporative cooling and temperature reduction when in combination with more reflective pavement (Pomerantz et al., 2003; Doulos et al., 2004). Green roofs and walls would prevent the increased energy consumption of buildings in an urban canyon due to reflective pavements (Razzaghmanesh et al., 2016). Doick et al. (2014) found that green spaces should be combined with other cooling strategies and Du et al. (2016) emphasised the importance of water bodies being surrounded by green zones with good air circulation.

Trees planted in an urban environment typically have a shorter lifespan and require more maintenance than trees in natural settings. Mullaney et al. (2015) studied the effect of permeable pavements on the growth and nutrient status of urban trees and found that tree growth is improved when a pavement base layer of 20 mm diameter drainage aggregate is installed beneath permeable pavements over wet clayey, and, therefore, poorly-draining soil. This again demonstrates the importance of combining UHI mitigation strategies.

6.8. Other methods and future developments

There are many other mitigation measures for the UHI effect that can be used that will not be discussed in this review, but are listed here for completeness. First and foremost, as suggested by Takebayashi and Moriyama (2012), and Doulos et al. (2004), substituting pavement materials and surfaces for an alternative surface or construction material is an effective and established mitigation measure. Alternative materials can have desirable thermal properties, of which the benefits cannot be realised with current solutions. Recycled products and substitutes may also be used to enable the greater thermal efficiency of pavement structures.

In addition to this, more research should be done on the thermal conductivity and capacitance of AC pavements to better transmit the heat from the pavement and the subsurface to the air. Whilst a higher thermal capacity pavement will significantly increase the minimum temperature of pavements, as more heat is stored, the maximum temperature will be reduced when compared with current methods (Santamouris, 2013b).

There are various future developments for which investigation and analysis is beginning to materialise. These involve either the substitution of materials or an improvement in current systems; as follows:

- Improvements in Reflective Pavements and permeable/porous/water retentive pavements – Infrared reflective paints would allow for a greater reduction in the heat that pavements absorb as compared with only the reflection of solar radiation. In addition, changing the material constituents of permeable pavements would have a significant effect on the cooling of the environment and reducing the UHI. Santamouris (2013b) provides an effective summary concerning the potential for the betterment of reflective and permeable/porous/water retentive pavements in his published literature.
- Thermochromic materials can change their albedo in response to surface temperature by undergoing a molecular structure transformation. This is a thermally reversible process that changes the visible colour of the material (Qin, 2015a). Thermochromic materials are gradually broken down when exposed to an outdoor environment.
- Harnessing the Heat – The circulation of water beneath pavements in pipework, otherwise known as asphalt solar collectors, is a key avenue of research. Bobes-Jesus et al. (2013) have conducted a literature review into the topic, and analysed the effect of various thermal parameters of pavements for this process. The conclusions state that comprehensive reviews on the topic are lacking, with almost all studies to date being conducted within a laboratory, and only analysing individual parameters in each individual research paper. There is scope for large-scale future development in this field in order to determine its effectiveness as a mitigation method. In addition to this, Pascual-Muñoz et al. (2013) undertook a study on multilayered asphalt pavements that contain a highly porous middle layer through which water can circulate. This eliminates the need for pipe systems, and uses the inherent properties of the pavement material to advantage. The authors suggest that this is a promising source of future research. Thirdly, García and Partl (2014) have conducted a study into the use of air circulation conduits within pavements to harness heat. Whilst some aspects of the experimental study proved inefficient, the study removed the inherent issues related to the circulation of water, and warrants future research.
- Photovoltaic pavements – A fairly new system and solution that involves completely substituting the AC pavement in the road for solar cells that convert solar energy into electrical power. At

present this is an expensive solution, and whilst small-scale systems have been implemented in some locations around the world, further research needs to be done within this field to make the solution feasible and cost effective.

- Studies into green roofs on buildings – Buildings cover a large percentage of the urban environments we live in; creating a green canopy on the top of existing buildings, and potentially between buildings, could significantly reduce the effects of the UHI. Studies should be undertaken to estimate and outline the benefits of covering the buildings of our cities with natural vegetation, and to quantify the potential costs. Santamouris (2015b) has provided a brief outline of studies conducted and the benefits of green roofs in the associated literature.
- Harnessing the heat with small thermocouples – This does not appear to have been studied within the literature. Given the current technological advancements, there may be a way to convert heat to electricity using thermocouples. Making such devices small enough and efficient enough to be housed within raised reflective pavement markers (RRPMs) or similar could be an effective means of generating electrical energy from natural heat exchange processes.
- Increasing the use of phase-change materials in pavements, and alternate colour pavements for the reflection of solar and infrared heat, or for improved thermal properties during certain times of the day or night.
- Determining which plants are most effective at UHI mitigation in an urban zone is an important area of current research. Tan et al. (2015) suggest a methodology to determine the selection of plants that are most suitable to enhance the positive effects of rooftop greenery.
- Affordable methods using recycled water to absorb the excess energy in urban gardens of high volumetric heat capacity should be developed.

7. Discussion

The most common theme within the literature is the need to conduct a greater number of studies within the field. The issue with studies to date is that demonstration projects are not at a large enough scale to quantify the effects of a given mitigation method on an urban environment or city (Santamouris, 2013b). Researchers suggest that a city of the world needs to implement solutions on a large scale to allow researchers to better quantify the effects of the UHI. The range of studies on UHI is well developed but also suffers from inconsistencies in the experimental and analytical methods. This questions the accuracy of results and conclusions and makes comparison between studies difficult. Diverse monitoring techniques, measuring equipment, duration of study, variables considered and rural reference sites all contribute to this problem. In addition, the methodology to measure UHI intensity has not been agreed upon (Santamouris, 2015a).

It has also been suggested that many of the studies conducted with regard to the UHI effect have been conducted during the summer and in hot environments. This is because summer is the time of the year when temperatures are expected to be the hottest, and when it is anticipated that the most detrimental and negative results will be measured. However, this cannot be proven as there have not been enough studies in seasons other than summer, and in cooler climates, and researchers insist that this should be considered in the future (Stempihar et al., 2012; Yang et al., 2015). Observational research on the urban heat island is also limited by time and cost restraints. Current research techniques focus heavily on model simulation to quantify the urban heat island (Mirzaei and Haghighat, 2010). However, the complexities of urban environments make it extremely difficult to model all possible variables and generalisations are often made. More research is required to enable integration of the various simulation methods and to make climate and regional specific models.

The implementation of reflective materials for mitigation of the UHI is well documented and researched, and recognised as an innovative solution. However, to date, studies have not adequately explored the effect that these materials and the increased reflected heat and light have on the local environment (Yang et al., 2015). Future studies need to consider the effect that reflective materials also have on the surrounding building envelope and the air temperature. Reflective pavements may also undesirably reduce the pavement temperature in winter, further reinforcing the importance of studies considering longer time frames. Santamouris (2014) has begun his research to quantify the effect on buildings of reflective materials; however, more studies need to be undertaken.

Buchin et al. (2016) argue that the effects of UHI countermeasures are often only considered on the outdoor environment. The effect of these countermeasures on an indoor environment is also important to evaluate the health risks of the UHI. The highest potential for reducing the health related risks of UHI lies in reducing the heat of the indoor environment. Classic UHI countermeasures, such as cool pavements and urban greenery, often only have a marginal direct impact on the indoor environment (Buchin et al., 2016). Passive or active indoor cooling measures are a far more important variable for combating the heat related health effects of the UHI.

The UHI countermeasures will have a negligible effect on indoor heat risk in cities with a high prevalence of air-conditioning. In cities and areas without many air-conditioned buildings the effect of UHI counter measures and passive cooling on heat related health risks will be higher. Reducing the net heat flux of an urban environment will have a positive effect on the indoor environment; however, passive cooling potential is limited by existing building design. Therefore, when considering the health implications of the UHI a balance needs to be struck between continued air-conditioning and urban planning. Buchin et al. (2016) suggest that air-conditioning should be powered by renewable sources and that only by rigorous passive cooling building design and UHI countermeasures at the urban scale can the heat related health risks be possibly mitigated without air-conditioning.

The potential negative consequences of UHI countermeasures need to be fully understood before implementing large scale urban projects. As was already discussed, reflective pavements can cause an increase in glare for pedestrians and drivers, and may even increase the UHI effects in urban canyons. There is also some evidence to suggest that water bodies may increase the UHI effects in the early evening (Steeneveld et al., 2014). Although urban greenery and reflective surfaces can reduce the temperature and near surface levels of ozone in an urban environment, a decrease in temperature may actually cause an increase in the concentration of primary pollutants (Fallman et al., 2016). This occurs due to a lowering of the turbulent kinetic energy that is responsible for diffusing these pollutants into the atmosphere (Fallman et al., 2016). All UHI mitigation strategies need to be critically evaluated to ensure successful implementation and combination.

8. Conclusion

In conclusion, it has been found that the thermal properties of asphalt concrete are a strong contributory factor to the UHI effect in cities. There is a constant need to reduce the effects of the UHI, due to the adverse effect it has on liveability, wellbeing and health in urban environments. The constantly expanding nature of cities and the increased use of hard, heat absorbing substances make a significant contribution to the UHI. Various mitigation measures have been proposed within the literature, which include reflective pavements, evaporative pavements, making the environment greener, and harnessing the cooling effects of wind and water. It is often found that using several methods in combination with each other is the most effective strategy for reducing the UHI effect. There are many methods being investigated, and further studies are required for these measures across all seasons of the year, to ensure that the best possible solution for mitigation of the UHI is found. The greatest issue concerning the UHI is that conditions are not identical in every urban environment. Cities around the world are vastly different, and solutions must be found that meet and exceed the needs of each individual city around the globe.

References

Austroads, 2007. Guide to Pavement Technology, Part 4b: Asphalt. Austroads Inc, Sydney, Australia.

Akbari, H., Menon, S., Rosenfeld, A., 2009. Global cooling: increasing world-wide urban albedos to offset CO_2. Clim. Change 94, 275–286.

Akbari, H., Pomerantz, M., Taha, H., 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Sol. Energy 70 (3), 295–310.

Akbari, H., Rose, L.S., 2008. Urban surfaces and heat island mitigation potentials. J. Hum. Environ. Syst. 11 (2), 85–101.

Asaeda, T., Ca, V.T., Wake, A., 1996. Heat storage of pavement and its effect on the lower atmosphere. Atmos. Environ. 30 (3), 413–427.

Barber, E.S., 1957. Calculation of maximum pavement temperatures from weather reports. Highw. Res. Board Bull. 168, 1–8.

Berg, R., 1974. Energy Balance on Paved Surface. USA Cold Regions Research and Engineering Laboratory, Hanover (N.H. Technical Report).

Bobes-Jesus, V., Pascual-Muñoz, P., Castro-Fresno, D., Rodriguez-Hernandez, J., 2013. Asphalt solar collectors: a literature review. Appl. Energ 102 (0), 962–970.

Buchin, O., Hoelscher, M.-T., Meier, F., Nehls, T., Ziegler, F., 2016. Evaluation of the health-risk reduction potential of countermeasures to urban heat islands. Energy Build. 114, 27–37.

Carlson, J., Bhardwaj, R., Phelan, P., Kaloush, K., Golden, J., 2010. Determining thermal conductivity of paving materials using cylindrical sample geometry. J. Mater. Civ. Eng. 22 (2), 186–195.

Choubane, B., Tia, M., 1992. Nonlinear temperature gradient effect on maximum warping stresses in rigid pavements. Transp. Res. Rec. 1370, 11–19.

Christison, J., Anderson, K., 1972. The response of asphalt pavements to low temperature climatic environments. In: Paper Presented at the Third International Conference on the Structural Design of Asphalt Pavements, Grosvenor House, Park Lane, London, England, pp. 41–52.

Coseo, P., Larsen, L., 2015. Cooling the heat island in compact urban environments: the effectiveness of Chicago's green alley program. Proced. Eng. 118, 691–710.

Costanzo, V., Evola, G., Marletta, L., 2016. Energy savings in buildings or UHI mitigation? Comparison between green roofs and cool roofs. Energy Build. 114, 247–255.

Debbage, N., Shepherd, J.M., 2015. The urban heat island effect and city contiguity. Comput. Environ. Urban 54, 181–194.

Dempsey, B.J., Thompson, M.R., 1970. A heat transfer model for evaluating frost action and temperature-related effects in multilayered pavement systems. Highw. Res. Rec. 342, 39–56.

Doick, K.J., Peace, A., Hutchings, T.R., 2014. The role of one large greenspace in mitigating London's nocturnal urban heat island. Sci. Total Environ. 493, 662–671.

Doulos, L., Santamouris, M., Livada, I., 2004. Passive cooling of outdoor urban spaces: the role of materials. Sol. Energy 77 (2), 231–249.

Du, H., Song, X., Jiang, H., Kan, Z., Wang, Z., Cai, Y., 2016. Research on the cooling island effects of water body: a case study of Shanghai, China. Ecol. Indic. 67, 31–38.

Fallman, J., Forkel, R., Emeis, S., 2016. Secondary effects of urban heat island mitigation measures on air quality. Atmos. Environ. 125, 199–211.

García, A., Norambuena-Contreras, J., Partl, M.N., 2013. Experimental evaluation of dense asphalt concrete properties for induction heating purposes. Constr. Build. Mater 46, 48–54.

García, A., Partl, M.N., 2014. How to transform an asphalt concrete pavement into a solar turbine. Appl. Energy 119, 431–437.

Golden, J.S., Kaloush, K.E., 2006. Mesoscale and microscale evaluation of surface pavement impacts on the urban heat island effects. Int. J. Pavement Eng. 7 (1), 37–52.

Gorsevski, V., Taha, H., Quattrochi, D., Luvall, J., 1998. Air pollution prevention through urban heat island mitigation: an update on the Urban Heat Island Pilot Project. In: Proceedings of the ACEEE Summer Study, Asilomar, CA, vol. 9, pp. 23–32.

Grimmond, S., 2007. Urbanization and global environmental change: local effects of urban warming. Geogr. J. 173 (1), 83–88.

Hassn, A., Chiarelli, A., Dawson, A., Garcia, A., 2016. Thermal properties of asphalt pavement under dry and wet conditions. Mater. Des. 91, 432–439.

Hathway, E.A., Sharples, S., 2012. The interaction of rivers and urban form in mitigating the Urban Heat Island effect: a UK case study. Build. Environ. 58, 14–22.

Hatvani-Kovacs, G., Belusko, M., Skinner, N., Pockett, J., Boland, J., 2016. Heat stress risk and resilience in the urban environment. Sustain. Cities Environ. 26, 278–288.

Higashiyama, H., Sano, M., Nakanishi, F., Takahashi, O., Tsukuma, S., 2016. Field measurements of road surface temperature of several asphalt pavements with temperature rise reducing function. Case Stud. Constr. Mater 4, 73–80.

Highter, W., Wall, D., 1984. Thermal properties of some asphaltic concrete mixes. Transp. Res. Rec. 968, 38–45.

Huber, G.A., Heiman, G.H., Chursinoff, R.W., 1989. Prediction of Pavement Layer Temperature during Winter Months Using a Computer Model. Canadian Technical Asphalt Association, Canada.

Hsieh, C., Qin, C., Ryder, E., 1989. Development of Computer Modeling for Prediction of Temperature Distribution inside Concrete Pavements. University of Florida, Mechanical Engineering Department, USA.

Hsieh, C.-M., Huang, H.-C., 2016. Mitigating urban heat islands: a method to identify potential wind corridor for cooling and ventilation. Comput. Environ. Urban 57, 130–143.

Ichinose, T., Matsumoto, F., Kataoka, K., 2008. Chapter 15-Counteracting Urban Heat Islands in Japan. In: Droege, P. (Ed.), Urban Energy Transition. Elsevier, Amsterdam, pp. 365–380.

Inge Jr., E.H., Kim, Y.R., 1995. Prediction of effective asphalt layer temperature. Transp. Res. Rec. 1473, 93–100.

Jiang, W., Sha, A., Xiao, J., Wang, Z., Apeagyei, A., 2016. Experimental study on materials composition design and mixture performance of water-retentive asphalt concrete. Constr. Build. Mater 111, 128–138.

Kavianipour, A., Beck, J., 1977. Thermal property estimation utilizing the Laplace transform with application to asphaltic pavement. Int 20 (3), 259–267. J. Heat Mass Tran.

Kinouchi, T., Yoshinaka, T., Fukae, N., Kanda, M., 2004. Development of Cool Pavement with Dark Colored High Albedo Coating. Fifth Conference for the Urban Environment (Vancouver, Canada).

Lemonsu, A., Viguie, V., Daniel, M., Masson, V., 2015. Vulnerability to heat waves: impact of urban expansion scenarios on urban heat island and heat stress in Paris (France). Urban Clim. 14, 586–605.

Li, H., Harvey, J., Ge, Z., 2014. Experimental investigation on evaporation rate for enhancing evaporative cooling effect of permeable pavement materials.Constr. Build. Mater 65, 367–375.

Li, H., 2015. 4-A comparison of thermal performance of different pavement materials. In: Pacheco-Torgal, F., Labrincha, J.A., Cabeza, L.F., Granqvist, C.G. (Eds.), Eco-efficient Materials for Mitigating Building Cooling Needs. Woodhead Publishing, Oxford, pp. 63–124.

Luca, J., Mrawira, D., 2005. New measurement of thermal properties of superpave asphalt concrete. J. Mater. Civ. Eng. 17 (1), 72–79.

Lukanen, E.O., Han, C., Skok, E.L., 1998. Probabilistic method of asphalt binder selection based on pavement temperature. Transp. Res. Rec. J. Transp. Res. Board 1609 (1), 12–20.

Memon, R.A., Leung, D.Y.C., Liu, C.-H., 2010. Effects of building aspect ratio and wind speed on air temperatures in urban-like street canyons. Build. Environ. 45 (1), 176–188.

Mirzaei, P.A., Haghighat, F., 2010. Approaches to study urban heat island - abilities and limitations. Build. Environ. 45, 2192–2201.

Mohseni, A., 1998. LTPP seasonal asphalt concrete (AC) pavement association temperature models. Office of Engineering R&D. Federal Highway Administration, Rockville, MD, USA.

Morris, C.J.G., Simmonds, I., Plummer, N., 2001. Quantification of the influences of wind and cloud on the nocturnal urban heat island of a large city. J. Appl. Meteorol. 40 (2), 169–182.

Mullaney, J., Lucke, T., Trueman, S.J., 2015. The effect of permeable pavements with an underlying base layer on the growth and nutrient status of urban trees. Urban For. Urban Gree 14 (1), 19–29.

Murakawa, S., Sekine, T., Narita, K.-I., 1991. Study of the effects of a river on the thermal environment in an urban area. Energ. Build. 16 (3 – 4), 993–1001.

Murray, C.A., Kayla, S.S., Brooke, M.A., 2014. Characterization of permeable pavement materials based on recycled rubber and chitosan. Constr. Build. Mater 69, 221–231.

Nakayama, T., Fujita, T., 2010. Cooling effect of water-holding pavements made of new materials on water and heat budgets in urban areas. Landsc. Urban Plan. 96 (2), 57–67.

Nakayama, T., Hashimoto, S., 2011. Analysis of the ability of water resources to reduce the urban heat island in the Tokyo megalopolis. Environ. Pollut. 159 (8–9), 2164–2173.

Nemirosky, E., Welker, A., Lee, R., 2013. Quantifying evaporation from pervious concrete systems: methodology and hydrologic perspective. J. Irrig. Drain. E-ASCE 139 (4), 271–277.

Noss, P., 1973. The relationship between meteorological factors and pavement temperature. In: Paper Presented to Symposium on Frost Action on Roads, Paris.

Oke, T.R., 1982. The energetic basis of the urban heat island. Q. J. Roy. Meteor. Soc. 108 (455), 1–24.

Pascual-Muñoz, P., Castro-Fresno, D., Serrano-Bravo, P., Alonso-Estébanez, A., 2013. Thermal and hydraulic analysis of multilayered asphalt pavements as active solar collectors. Appl. Energ 111 (0), 324–332.

Pomerantz, M., Akbari, H., Chang, S.-C., Levinson, R., Pon, B., 2003. Examples of

cooler reflective streets for urban heat-island mitigation: Portland cement concrete and chip seals. Lawrence Berkeley National Laboratory, Claifornia.
Qin, Y., 2015a. A review on the development of cool pavements to mitigate urban heat island effect. Renew. Sust. Energy Rev. 52, 445–459.
Qin, Y., 2015b. Urban canyon albedo and its implication on the use of reflective cool pavements. Energy Build. 96, 86–94.
Qin, Y., Hiller, J.E., 2014. Understanding pavement-surface energy balance and its implications on cool pavement development. Energy Build. 85, 389–399.
Rafiee, A., Dias, E., Koomen, E., 2016. Local impact of tree volume on nocturnal urban heat island: a case study in Amsterdam. Urban For. Urban Gree 16, 50–61.
Rajagopalan, P., Lim, K.C., Jamei, E., 2014. Urban heat island and wind flow characteristics of a tropical city. Sol. Energ 107, 159–170.
Razzaghmanesh, M., Beecham, S., Salemi, T., 2016. The role of green roofs in mitigating Urban Heat Island effects in the metropolitan area of Adelaide, South Australia. Urban For. Urban Gree 15, 89–102.
Rossi, F., Pisello, A.L., Nicolini, A., Filipponi, M., Palombo, M., 2014. Analysis of retro-reflective surfaces for urban heat island mitigation: a new analytical model. Appl. Energ 114 (0), 621–631.
Rumney, T.N., Jimenez, R., 1971. Pavement temperatures in the southwest. Highw. Res. Rec. 361, 1–13.
Sano, M., Tobi, N., Takahashi, O., Sakai, K., 2009. Study on recycling crushed insulator to safe shaped aggregate. Jpn. Inst. Aggreg. Technol. 41 (163), 117–125.
Santamouris, M., 2013a. Energy and Climate in the Urban Built Environment. Routledge, Abingdon-on-Thames, UK.
Santamouris, M., 2013b. Using cool pavements as a mitigation strategy to fight urban heat island - a review of the actual developments. Renew. Sust. Energy Rev. 26, 224–240.
Santamouris, M., 2014. On the energy impact of urban heat island and global warming on buildings. Energy Build. 82 (0), 100–113.
Santamouris, M., 2015a. Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions. Sci. Total Environ. 512, 582–598.
Santamouris, M., 2015b. Regulating the damaged thermostat of the cities—status, impacts and mitigation challenges. Energy Build. 91 (0), 43–56.
Scholz, M., Grabowiecki, P., 2007. Review of permeable pavement systems. Build. Environ. 42 (11), 3830–3836.
Sen, S., Roesler, J., 2016. Aging albedo model for asphalt pavement surfaces. J. Clean. Prod. 117, 169–175.
Solaimanian, M., Bolzan, P., 1993. Analysis of the Integrated Model of Climatic Effects on Pavements. Strategic Highway Research Program. National Research Council.
Southgate, H., Deen, R., 1975. Temperature distribution in asphaltic concrete pavements: record 549. Transp. Res. Board 39–46.
Spall, M., 1982. Developing a Thermal Model for Asphaltic Concrete: MS Thesis. Clarkson College of Technology, Department of Mechanical and industrial Engineering, New York.
Steeneveld, G.J., Koopmans, S., Heusinkveld, B.G., Theeuwes, N.E., 2014. Refreshing the role of open water surfaces on mitigating the maximum urban heat island effect. Landsc. Urban Plan. 121, 92–96.
Stempihar, J.J., Pourshams-Manzouri, T., Kaloush, K.E., Rodezno, M.C., 2012. Porous asphalt pavement temperature effects for urban heat island analysis. Transp. Res. Rec. J. Trans. Res. Board 2293 (1), 123–130.
Stone, B., Hess, J.J., Frumkin, H., 2010. Urban form and extreme heat events: are sprawling cities more vulnerable to climate change than compact cities. Environ. Health Perspect. 118 (10), 1425–1428.
Stone, B., Norman, J.M., 2006. Land use planning and surface heat island formation: a parcel-based radiation flux approach. Atmos. Environ. 40 (19), 3561–3573.
Straub, A.L., Schenck Jr., H., Przbycien, F.E., 1968. Bituminous pavement temperature related to climate. Highw. Res. Rec. 256, 53–77.
Synnefa, A., Karlessi, T., Gaitani, N., Santamouris, M., Assimakopoulos, D.N., Papakatsikas, C., 2011. Experimental testing of cool colored thin layer asphalt and estimation of its potential to improve the urban microclimate. Build. Environ. 46 (1), 38–44.
Takebayashi, H., Moriyama, M., 2012. Study on surface heat budget of various pavements for urban heat island mitigation. Adv. Mater. Sci. Eng, 2012, Article ID 523051.
Tan, C.L., Wong, N.H., Tan, P.Y., Jusuf, S.K., Chiam, Z.Q., 2015. Impact of plant evapotranspiration rate and shrub albedo on temperature reduction in the tropical outdoor environment. Build. Environ. 94, 206–217.
Tan, Z., Lau, K.K.-L., Ng, E., 2016. Urban tree design approaches for mitigating daytime urban heat island effects in a high-density urban environment. Energy Build. 114, 265–274.
Tominaga, Y., Sato, Y., Sadohara, S., 2015. CFD simulations of the effect of evaporative cooling from water bodies in a micro-scale urban environment: validation and application studies. Sustain. Cities Dev. 19, 259–270.
Toraldo, E., Mariani, E., Alberti, S., Crispino, M., 2015. Experimental investigation into the thermal behavior of wearing courses for road pavements due to environmental conditions. Constr. Build. Mater 98, 846–852.
Underwood, R.T., 1995. Road Engineering Practice. Macmillan Education Australia, South Melbourne.
Voller, V., Newcomb, D., Chadbourn, B., De Sombre, R., Timm, D., Luoma, J., 1998. A computer tool for predicting the cooling of asphalt pavements. In: Paper presented to Cold Regions Impact on Civil Works, Duluth, M.N., USA, pp. 661–671.
Williamson, R., 1972. Effects of environment on pavement temperatures. Pap. Present. Intl Conf Struct. Des. Proc. 144–158.
Wilson, A., 1976. The distribution of temperatures in experimental pavements at alconbury by-pass. Transport and Road Research Laboratory, Berkshire, England.
Wolfe, R.K., Heath, G.L., Colony, D.C., 1987. The University of Toledo Time-temperature Model Laboratory and Field Validation (Report to The Ohio Department of Transportation).
Xu, J., Wei, Q., Huang, X., Zhu, X., Li, G., 2010. Evaluation of human thermal comfort near urban waterbody during summer. Build. Environ. 45 (4), 1072–1080.
Yaghoobian, N., Kleissl, J., 2012. Effect of reflective pavements on building energy use. Urban Clim. 2, 25–42.
Yamamoto, Y., 2006. Measures to mitigate urban heat islands. Sci. Tech. Trends Q. Rev. 18 (1), 65–83.
Yang, J., Wang, Z.-H., Kaloush, K.E., 2015. Environmental impacts of reflective materials: is high albedo a 'silver bullet' for mitigating urban heat island? Renew. Sust. Energy Rev. 47 (0), 830–843.
Yavuzturk, C., Ksaibati, K., Chiasson, A., 2005. Assessment of temperature fluctuations in asphalt pavements due to thermal environmental conditions using a two-dimensional, transient finite-difference approach. J. Mater. Civ. Eng. 17 (4), 465–475.
Zheng, M., Han, L., Wang, F., Mi, H., Li, Y., He, L., 2015. Comparison and analysis on heat reflective coating for asphalt pavement based on cooling effect and anti-skid performance. Constr. Build. Mater 93, 1197–1205.