Sustainable pavement: A review on the usage of pavement as a mitigation strategy for UHI

SFI Al-humairi1,2,*, AH Alias1, NA Haron1, S Hassim1, and F Mohd Jakarni1

1Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
2Alliance Geotechnical Group, TX 77535, USA
*Corresponding author: sarmadfismael@gmail.com

Abstract. Urban Heat Island (UHI) phenomenon is currently affecting many millions of people worldwide. The higher temperatures are experienced in urban areas as compared to the surrounding countryside. The UHI effect has been a great threat to human habitation, and the way to mitigate this problem has been a global concern over decades. Artificial and manmade pavements have been recognised as one of the major origins that deteriorate the thermal environments for living. On the one hand, commonly used pavement materials could lead to a reduced latent heat flux and an increased sensible heat flux to the environment. Following this, there is a series of experiments and numerical analysis that has been conducted by researchers. The selection of pavement type requires an understanding of a local context of an area and characteristics of the pavements. This current study emphasises on reviewing the features, factors and impacts of different type of pavements, as well as determining the suitability of different types of pavements. It is expected that the outcome from this study can assist in further understanding of pavements and its effects on UHI, as well as can ultimately assist in reducing the effect of UHI on human population.

1. Introduction
The rapid urbanisation is documented as a main cause of replacement in most of the green surfaces, vegetation or natural soil by artificial land covers, such as asphalt mixtures and cement concrete pavements [1]. Dark surface, higher heat storage capacity and large thermal inertia of concrete material contribute to a large solar radiation which will be stored in day time and emitted into the atmosphere at night [2,3]. This heat release has a significant impact on the thermal climate. The high air temperature of city centres is termed as the urban heat island (UHI) effect as compared to the sub-urban rural areas [4].

The local climate change is considered a global issue and has been a major concern for researchers. Many studies had reported on the UHI influence on residents, in which it was found that UHI deteriorated thermal comfort, increased the concentration of pollutants and threatened human health [5]. Apart from that, it was found that UHI would increase the energy demand during high temperatures days, in which an increase of one degree of outside thermal air would result in 0.45 to 4.6 per cent of increment in electricity usage [6,7].

To counterbalance the influence of urban heat island, cool pavement technology has been developed to reduce the emission of heat flux, hence, mitigating the urban heat island phenomenon [8]. Cool pavement is proposed by United States Environmental Protection Authority (USEPA) to achieve lower
surface temperature and reduce heat island effects [9]. The cooling pavement term refers to the paving materials that remain cool, reflect more solar energy and enhance water evaporation as compared to the conventional pavement [10,11].

The aim of this review paper is to present and define conventional pavement types, to explain consequences, such as the increasing urban temperature, as well as discuss the influence of UHI on the residents and service life of the structure. Apart from that, this paper will clarify the strategies to mitigate the UHI effect with an emphasis on new cool pavements technology, including discussion on the benefits, costs, strengths, and policy of cool pavement.

2. Conventional pavements
Pavements cover about 40 per cent of the urban area of cities[10,12]. The dark colour for pavement material contributes to a high percentage of heat absorption, storage, as well as re-radiation to the atmosphere [13]. Most studies indicated that pavement had a temperature of at least 60 degrees Celsius in summer [14]. Pavement can be generally classified into three types: flexible, rigid or a combination of flexible and rigid. A flexible pavement consists of three essential layers: 1) surface layer, 2) base and 3) subbase layers, with all these layers installed on the subgrade. Nevertheless, the rigid pavement does not have a base layer; thus, concrete is used instead of asphalt in the surface layer. In some cases, an upper layer of a rigid pavement is layered with a thin asphalt to generate rigid-flexible composite pavement [15]. The asphalt surface layer provides a comfortable driving and long service life, while a rigid base supports a pavement structure that bears the great traffic loads.

2.1. Asphalt concrete pavement
Asphalt pavement or known as flexible pavement consists of a mixture of asphalt, air voids and various sizes of aggregates depending on the design to handle any load from light to heavy vehicles. Studies had shown that over 80 per cent of paved surfaces are made of asphalt concrete as compared to other paving types [1,16,17]. Under continuous heavy load, paired with moisture and rising temperature, this type of pavement is subjected to a number of damages, including rutting, cracking and corrugation [18].

As the pavement aged, the environmental conditions will assist in oxidising the binder in the surface layer, exposing the aggregates and consequently, increasing the albedo in the asphalt concrete, which can range from 0.09 to 0.18 [6,12–14]. Apart from the environmental conditions, it is observed that the asphalt concrete exposure to abrasion will increase the albedo significantly. The albedo increases rapidly in the first year after placement before staying in a steady state value [20,21].

2.2. Cement concrete pavement
Portland cement concrete pavement (PCCP) basically comprises cement, water, as well as fine and coarse aggregates. Reinforcement steel bar is utilised in some form to mitigate crack prevention that constitutes the basic problem of concrete pavement design. As a result, PCCP has a higher bearing capacity as compared to the flexible pavement. In contrast with asphalt concrete, the albedo of cement concrete will decrease over time due to the exposure of dirt and tire wear, which will darken the colour of the pavement surface.

3. Heat mitigation strategy
To reduce the possible effects of global warming and urban heat island phenomenon, cooling strategies are proposed to contribute to improving the urban thermal environment and thermal comfort of a city dwellers. The climate condition, the area intended and expectations of the economic effects should be considered to choose an appropriate strategy. Cooling strategy can be divided into 3, which were green surface, cool roofs and cool pavement [22].
3.1. Green and blue surface

Research had found that adding 10 per cent of vegetation to the urban areas would have a significant impact in improving the UHI effect by reducing the air temperature of up to 0.5 to 0.8 degrees Celsius [23]. Water ponds, river and water sprinkle can be considered as significant strategies to mitigate heat urban in areas that could provide the required water easily [24]. Nonetheless, although green and blue infrastructures have been common in mitigating the UHI effect, using these strategies without proper consideration to gray surfaces may not be significant to cooling the climate. This is because pavements are still by and large the basic infrastructure in developing cities, as well as constitute a large percentage of the cities’ area. Therefore, apart from green and blue surfaces, it is equally important to use pavement technologies as heat mitigation strategy.

3.2. Cool roofs

Reflective or cool materials can be used to provide cool roofs in urban buildings. Studies’ results reported that roof surface covered with albedo can result in a reduced electricity demand in the building, as well as a reduce sensible heat emission to the atmosphere [6, 25]. Moreover, the changes of the cooling surface temperature can increase the materials’ life time of the roof due to the decreasing chemical interactions as compared to the conventional roof [11, 26].

3.3. Cool pavement

Cool pavements are basically an implementation of light coloured materials on a structure surface[27–29], which will then reduce the air-surface and the pavement temperature. The cooling techniques used by cool pavements include the installation of albedo [12], heat evaporation[10], as well as heat storage and harvesting [30].

Multiple studies had displayed that the technique of cool pavements undoubtedly reduced the surface temperature of pavements [31, 32]. For example, research had demonstrated that cool pavement stayed cooler in the sun than traditional pavements. It is also noted that cool pavement had several benefits as compared to conventional pavement, such as energy savings and emission reductions[33], improved comfort and health[5], a long-life and safe road [18], improved water quality and noise reduction[34, 35], as well as increased driver safety and decreased billions of tons of carbon dioxide emissions [6].

4. Cool pavement strategies to reduce urban heat island

Cool pavement technologies tend to store less heat resulting to lower surface temperatures. Reflective pavements, evaporation pavements and heat-harnessing pavement can be classified as cooling pavements. The surface of cooling pavements remains cooler than conventional pavements due to either reflecting more solar radiation, as well as decreasing the pavement temperature and sensible heat emits evaporation of the water existing in the top and bottom pavement layers or suppression of the surface heat absorbed to extraction of the heat from the pavement as a form of renewable energy for other usages and cooling the pavement[10, 11]. Viewed from above, the UHI issue cannot be limited to only colour materials or rough surface of the pavement but developed widely to also include open-pore structures [36].

Besides several benefits of cool pavements in achieving environmental profit, another benefit is related to an improved construction performance and long-live service of pavements. The high temperature of asphalt pavement in summer can cause rutting distress and aging, while increasing surface temperature in cement concrete pavements produced risk by thermal cracking [37].

The difference in economic factors of cities influences directly on the cost of cool paving technologies that will be affected significantly to choose the best type. For these reasons, it is proposed that a comprehensive study for all pavement types should be conducted. This study depends on documented work of literature by a committee to make a decision to be then applied in the project. Nowadays, conventional pavements which have been developed with a light-coloured surface
4.1. Reflective pavements
The utilisation of a reflective pavement can be considered as one of the ways to mitigate the UHI effect, since it is the most cost-effective and can significantly decrease the surface temperature of the pavement [30]. Slurry seal is considered a typical treatment, which is applied over the existing pavement to get reflective pavements, while existing conventional asphalt pavement is replaced with yellow thin layer asphalt through the mixture of asphalt emulsion binder with infrared reflective pigments and fine aggregates to present much higher reflectivity [1]. In United States, a chip seal is applied as a reflective coating with a higher albedo in addition to its function to a treatment of a bituminous surface. The chip seal is typically used on the roads with lower traffic volumes, such as rural roads, walking sides and parking lots. [38]. In another case, white concrete pavements are employed instead of grey concrete pavements by adding pigments of titanium dioxide (TiO2) with a concrete mixture [6].

There is a number of benefits through the usage of reflective pavements. First, the reflective pavements can reduce the surface temperature and consequently, reduced sensible heat is emitted to the atmosphere [39]. This will enhance thermal comfort and mitigate the urban heat island [40]. Second, preventing glare and visual discomfort to provide driving safety will consequently minimise eye-related disorders and road accidents [19]. In contrast, since the application of solar reflective coatings will change the original surface texture of the pavement, further studies are needed to determine the suitability of the application of this technique. It is reported that in the warm-weather climates the reflective pavements with a high albedo value reduces the pavement surface temperature but will give an output of discomfort thermal for the humans in the ground level [41].

4.2. Evaporation and permeable pavements
Permeable pavement technology has been developed to significantly reduce air temperature [42]. It allows water to filtrate through the pores to supply the sub-layers and storage in the top surface. This in turn will provide a cool surface that will affect the air temperature on the level ground. Generally, there is a number of benefits of permeable pavements, which includes an increased skid resistance and a reduced tire-pavement noise [43], a higher sound absorption [41], an increase in snow and ice melting rates [42], and an improvement of the quality of water supplied to the groundwater [37]. This type of pavement is usually used in places with light traffic loads, low speeds, commercial areas, and parking surfaces [34]. Permeable pavements can be classified into porous pavers, pervious pavers and water retaining pavements.

4.2.1 Porous pavers
Porous paver is a type of concrete or plastic geocells that form a cellular grid system with a similar performance as compared to rigid pavement [10]. The surface-air cooling of porous pavers depends on the evaporation capability through a channel for the water stored in the pavement layers. The cellular grid system has internal holes filled with materials, such as grass, concrete or fired-clay bricks that have a high capacity to hold moisture [10]. When grass is used to fill the holes, the roots aid to transport moisture from deeper soil to cool the surface-air of the pavement. On the contrary, when concrete or fired-clay bricks are used, this allows the water to pass around the pavement into the base or sub-base layers as in permeable interlocking concrete pavements. The rough surface and the low thermal inertia cause a high thermal if the water is not available. This type of pavers is usually used for pedestrian walkways, sidewalks, pathways, and driveways.

4.2.2. Pervious pavers
Various development strategies pervious pavements have a lesser impact on the environment. Sustainable materials and eco-friendly strategies play an important role to become a suitable candidate
application on roads. Pervious pavement layer is made of asphalt or concrete with a high ratio of air voids that allows the water to pass directly through the pavement into sublayers of crushed aggregate, then it is infiltrated into the ground. Pervious pavements are designed to accept precipitation; hence, during application, side drains are not required, so the construction cost is reduced. The aggregate physical characteristics have a significant influence on the properties of pervious concrete and controlled porous proportion on the water permeability through pavement layers. The pavement layer typically is thicker than the traditional concrete to increase the bearing capacity of heavy weight. The usage of pervious concrete in low volume roads, such as parking lots[35], sidewalks and roads without heavy load is due to weaker durability and mechanical properties of the structure[44].

Evaporation process can keep pervious pavements cooler than conventional pavements about one to two days after sprinkling under hot conditions. Cooling is negligible with a loss of water and more absorption of solar irradiation because pervious pavements have a rough surface and a lower thermal inertia than conventional pavements[32]. Continuously, maintenance of pavements is important to sustain a structure and keep life cycle performance. This is done by using a high-pressure washing with water and/or vacuum to remove dust and other foreign particles from the upper layer of the pavement [43].

Finally, after the permeable pavement types are explained, it can be concluded that due to the absence of water in air voids, it reduced the amount of water used for water evaporation. Consequently, the water evaporation rate is suddenly reduced, while the temperature rate increases rapidly [45]. During hot days the permeable pavement temperature is found to be higher than another type of impermeable pavement under dry condition. An open-graded asphalt mixture absorbs more solar radiation and increases the top layer temperature during the day. Irrigation water reduces surface pavement temperature and then, it reduces the significant effect of mitigating the near air surface temperature. The sprinkling assist is observed to cool the pavement surface and directly decrease 10 degrees Celsius after wetting the surface[42].

4.2.3. Water-retaining pavements
Any pavement of water-holding and water-retentive is indicated for the longest period by a water-retaining pavement. It is developed to solve the problem of fast infiltrate water through the pervious concrete. Water-retentive pavements have a porosity similar to permeable pavements, but the water permeability of the water-retentive pavements is lower than the other one[10]. The component essentially for this type of pavement is asphalt or cement. The different fillers are added to the mixture to assist in retaining the amount of water. After raining, the water-retaining pavements are expected to stay cooler than permeable pavements. The high capillary force assists the water to be sucked from the sub-base of the pavement because of a lack of water in the upper surface. This type of pavement illustrates a better efficiency in cooling the air-surface when the water is held in the surface layer that had a range of 25 millimeters [10,46].

4.3. Heat storage and harvesting
Heat-harvesting pavements cannot only reduce surface temperature, but also extract absorbed heat as renewable energy for other usages [11]. For this type of pavement, the usage of asphalt pavements as the surface material can perform better than the concrete pavements. This is because the black colour of asphalt mixture can absorb solar irradiation better as compared to concrete’s solar absorption coefficient. Technique design of harvesting pavement is formed by combining an asphalt solar collector, installing pipes with a circulating fluid inside and installing a generator beneath the pavement. Water is usually used as the fluid in the pipework to extract the pavement heat [10,47]. Apart from water, natural air can be used in the pipework to harness heat from the pavement [10,48]. In case of water fluid, the pipe systems can be eliminated and a multiplayer asphalt pavement system can keep the water inside the structure. This multiplayer asphalt pavement system circulates in the porous middle layer between impermeable layers.
Due to the temperature difference between the fluid circulating into pipes and the pavement, the pavement absorbs formed solar radiation. This solar radiation is transferred to the fluid by counterbalance and then, decreases pavement temperature to provide a comfortable near surface air and a sustainable structure. The harvested energy can be stored in a roadside water tank for other usage or for snow-melting systems in winter time [11]. To apply this system, more studies regarding durability and scrutiny on the power output are needed. In addition, continuous maintenance activities that add extra cost should be done as most studies had also been conducted in laboratories.

4.4. Innovative methods recently

i. Evaporation-enhancing permeable pavement is developed as a new permeable pavement to contribute mitigation of the UHI effect. In addition, storm water in cities, in which the groundwater is high is managed. The evaporation-enhancing permeable pavements have a good capillary capacity, which causes the evaporation to stay for a long period as compared with the conventional permeable pavement that only lasted for the first two days after raining [49].

ii. A new technology is applied to a reduced temperature of pavement surface and sub-layers [37]. Implanting of steel rods with high thermal conductivity in different levels is carried out to accelerate the flow of the absorbing heat by the top layers, and the heat is transferred to the bottom layers to decrease heat accumulation. Then, the influence on the air-surface is decreased in the ground level. Additionally, the structure will be strong to increase rutting resistance and long-term service.

5. Factors affecting cool pavement selection

5.1. Albedo

One of the important parameters in assessing the temperature in pavement is albedo. Albedo can be defined as a ratio of solar radiation reflected to the radiation incident on a surface [50]. A higher value of surface albedo reflects more proportion of the solar radiation, therefore, reducing pavement surface temperature. There are two methods to measure albedo. First, albedo is measured by using an albedometer or a double pyranometer, in which the accuracy of the results is high depending on the size of the sample and weather conditions [20, 51]. The other test is carried out in a laboratory using a spectral reflectance obtained from a spectrophotometer to obtain an approximate estimate of the albedo value [20, 19].

Albedo affects local microclimate, energy consumption and pedestrians. Most of the previous studies focused on the influence of an increased albedo of the inside and the outside environment. Part of solar radiations reflects from a pavement surface back to the sky without influencing the thermal atmosphere, while the remaining part influences the surrounding buildings. As a result, it is recommended not to use pavements with albedo as a surface in cities with high buildings [52]. A number of research is done in analysing the impact of pavements on the ground level related to the thermal comfort for pedestrian [23].

5.2. Cost

Economic factors and local availability of materials have a direct impact on the cost of projects. Thus, managing the project cost requires a customisation of optimal pavement designs for site-specific conditions. For instance, asphalt pavements are favoured because of their low initial costs and short project lengths. Moreover, asphalt pavements are preferred in some cases which expected to do additional activities related to infrastructure, such as water, power, sewage, and pipeline after the initial construction [11]. Conversely, although rigid pavement is less prone to damages due to environmental conditions and heavy-vehicle loading, the rehabilitation work for this type of pavement is more expensive than asphalt concrete [53].

Prior studies had also noted the importance of cost in selecting cool pavement technologies [54]. Rehabilitation and maintenance of pavements are considered a requirement to sustain the quality and
functionality of the pavements. Assessing the phases of cool pavement before the overall implementation includes production, construction, maintenance, use, and post-construction maintenance of the pavement to avoid extra costs. Therefore, many studies have been conducted to investigate the costs of cool pavement technologies [16,11]. Nonetheless, there is no any international standard since the cost depends on the pavement type and its location. When reflective and permeable pavements are compared, lower cost and easy potential installation in reflective pavements makes reflective pavement preferred for marketing than other applications. In addition, extra cost of permeable pavement is used to dislocate the clogging dirt in the cavity because the open porous structure is prone to clogging. [30].

5.3. Strength
Pavements are critical to land transportation use (roads, walking, commercial plazas, and parking). The large proportion of these paving should be able to carry a heavy loading. Rigid or flexible pavements are built and cured until they were strong enough to carry traffic. A rigid base can greatly improve the bearing capacity of a pavement structure [15]. Structural design and material composition can influence the pavement behaviour. In asphalt pavement case under heavy loads, the void spaces of porous asphalt deteriorate with time due to deformation, resulting in a reduction in air voids of the surface pavement and consequently, reducing the efficiency of the pavements in allowing rainwater to pass through the pavement to the underlying layers [44].

Due to strength, heat-harvesting pavements cannot be used under high traffic loadings without specific engineered techniques to support the pavement structure [11,55]. Besides that, in the case of permeable pavements, the strength of pervious concrete decreases with the increase in porosity and permeability [44]. Thus, it can be seen that the majority of existing cool pavement is used for low vehicle volumes, such as parking lots and commercial areas with low speeds and light traffic loads. Further studies are needed to ensure that the structural design and material properties of cooling pavements could be used effectively on roads with high loads and speed.

6. Conclusion
The local climate changes contribute to the urban heat island phenomenon. Urban climate change has a significant impact on electricity consumption, indoor and outdoor ambient temperature, citizens comfort, threatening human health, economic impacts, as well as passive impact on the paving life service. To counterbalance the effect, this paper has reviewed cooling strategies, including green, blue and grey surfaces to mitigate the UHI effect. It is discovered that apart from green and blue surfaces, focus must be given to grey surfaces and cool pavements since grey surfaces has a significant effect on the ambient temperature and covered most of the roads of the cities.

Cool pavements can also be achieved by modifications of the materials or designs for the existing pavements. To select either reflective pavement surface, evaporative pavements, or heat-harvesting pavements, the effect of the urban heat needs to be observed. Benefits of using cool pavements to battle the urban heat island effect, strength, cost, pros and cons during implementation the project should also be considered.

The cool pavement techniques were applied in some countries, such as Toronto[24], Greece[6], USA[35], Malaysia[2], China[4], and Japan[56] in this study. In short, it could be concluded that reflective pavements were appropriate for climate areas with hot dry summer and for the open area with long-hour insolation. However, evaporative pavements may be more suitable for tropical regions with sufficient water available over the year. In conclusion, it is recommended to conduct more practical studies of cool pavements, in addition to a combination of the methods under variable conditions to address the gaps and reducing the UHI effect.

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