Properties and Principles of Cool Pavements Usage

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With growing urban populations, methods of reducing the urban heat island effect have become increasingly important. Cool pavements altering the heat storage of materials used in pavements can lead to lower surface temperatures and reduce the thermal radiation emitted to the atmosphere. Cool pavement technologies utilize various strategies to reduce the temperature of new and existing pavements, including increased albedo, evaporative cooling, and reduced heat conduction. This process of negative radiation forces helps offset the impacts of increasing atmospheric temperatures.

Keywords: urban heat island ; cool pavements ; reduction of carbon dioxide

1. Introduction

The phenomenon of observed air temperature differences ranging from 1 to 9 °C and being developed between urban, semi-urban and rural areas, is widely known as Urban Heat Island (UHI) effect [1][2][3][4][5][6]. UHIs, in combination with climate change effects, are considered to be the main causes for the significant increase in urban temperatures [7][8][9][10][11][12][13][14][15]. A significant increase in the energy consumption in buildings (due to enhanced cooling loads) is attributed to the UHI effect [16][17][18][19][20][21][22][23][24][25][26][27][28]. At the same time, a remarkable increase in ozone (O_3) has been recorded due to higher urban air temperatures, emissions, and the presence of urban pollutants [29][30], while the ecological footprint of cities suffering from the UHI phenomenon has deteriorated [31].

Surface temperatures have an indirect, but significant, influence on air temperatures, especially in the canopy layer, which is closest to the surface. For example, parks and vegetated areas, which typically have cooler surface temperatures, contribute to cooler air temperatures. Dense, built-up areas, on the other hand, typically lead to warmer air temperatures. Because air mixes within the atmosphere, though, the relationship between surface and air temperatures is not constant, and air temperatures typically vary less than surface temperatures across an area, as **Figure 1** demonstrates [32].

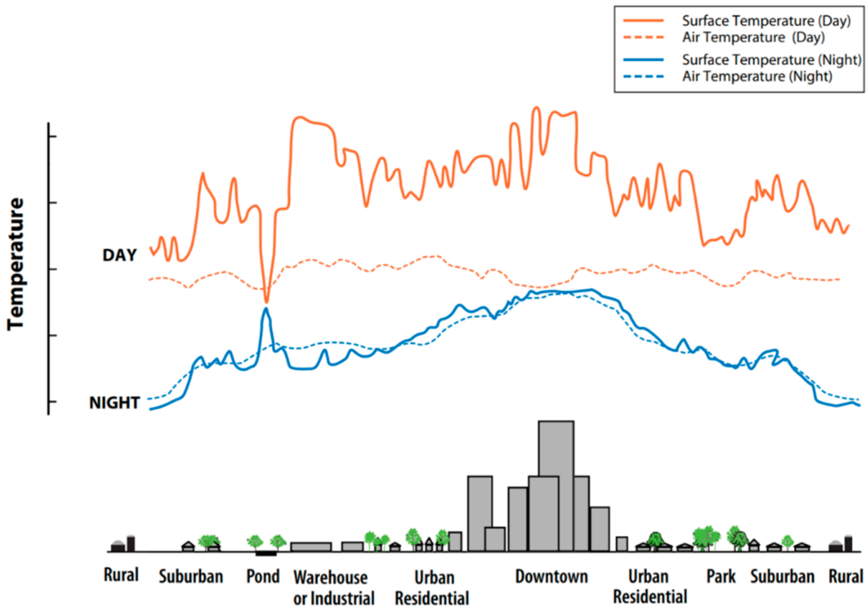

Figure 1. Illustration of how nighttime temperatures remain warmer in the urban areas due to the UHI [32].

In order to minimize the effects of the UHI, mitigation measures have been proposed, including modified pavements, as they have a significant area footprint (i.e., up to 60% in some urban areas) and can play an important role in the overall mitigation of the urban heat effect. “Pavements” in cities may refer to all surfaces on the ground, such as roads, sidewalks, parking areas, squares, pedestrian streets, etc. The effect of pavements on the development of the UHI phenomenon is significant. Many recent studies have shown that pavements play an important role in the formation of the overall urban thermal balance [33][34][35].

Pavements can strongly influence the localized urban climate. Their thermal balance is maintained via various components, i.e., the absorbed solar radiation; the emitted infrared radiation; the heat transferred to the ambient air; the thermal energy stored in the mass of the materials; and the heat absorbed by the soil. When latent heat effects, such as evaporation, occur, the thermal regime of pavements is affected, while the effect of the rain must also be considered. Anthropogenic heat, which is mainly due to road traffic, also affects the thermal balance of materials. According to Asaeda et al. [36], pavements are the main factor for the development of the UHI effect.

A detailed analysis of the various parameters affecting the thermal balance of pavements may be realized through experimental and/or simulation techniques. The experimental assessment of the thermal properties of road surfaces is carried out either using mid-scale remote sensing techniques or micro-scale measurement methods, including infrared thermography and temperature monitoring. Additionally, satellite mesoscale imaging is used widely to estimate surface temperatures in urban areas [37][38][39]. Computer-based simulation with analytical or numerical models with very good agreement with experimental data have been employed for the accurate analysis of thermal phenomena occurring in pavements [40][41][42].

Pavements covered with or made of materials with a reduced surface temperature are known as cool pavements. Policy-wise, the European Union (EU) is currently highly interested in energy efficient pavements and the role that they can play in the development of sustainable cities. Reduction in energy consumption and road safety are the main reasons, while these two parameters are (among others) key for the creation of sustainable cities. The business community on the other hand, is keenly interested in the comparison and monitoring of pavements made by different materials. This competition between pavement industries is welcomed by EU states, as it can save millions in public money.

2. Properties and Principles of Cool Pavements Usage

Cool pavements have been applied to cities worldwide as technologies that are used to mitigate UHI consequences. A typical pavement absorbs and emits heat, while a cool counterpart may release heat during the day and at night is minimized by employing an increased convection coefficient (see **Figure 2**).

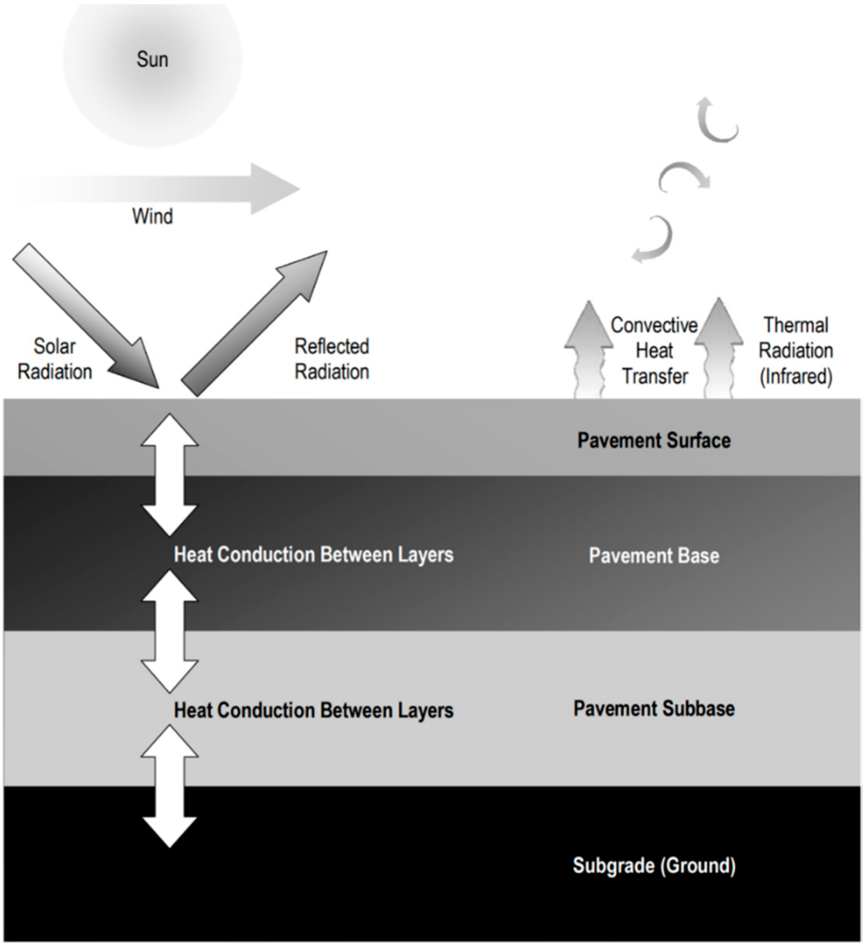

Figure 2. Heat-exchange-related processes in typical urban pavement [42].

A case study of the application of cool pavements in a dense urban area in Marousi, Athens, is a typical example of the importance of cool pavements [43]. That research involved the restoration of a 16,000 m^2 area, using new high-reflectivity pavements, green spaces, and earth-to-air heat exchangers. It was estimated that replacing conventional pavements with cool pavements could reduce the maximum ambient temperature in the region by 1.2 to 2.0 °C.

Cool pavements are based either on the use of materials with high reflectance in solar radiation and high emissivity in infrared radiation (i.e., reflective pavements), or the use of latent heat of evaporation (evaporative cooling) to reduce their surface temperature (i.e., water retentive pavements) [44]. These may be accomplished in the following ways:

- *Replacement of conventional pavement with other new surfaces characterized by lower surface temperatures, especially during the summer.* This kind of cool pavements includes various constructional components, such as modified mixes (roller compacted concrete, conventional Portland Concrete Pavement (PCC)), light gravel on asphalt concrete (ACP), porous or pervious or permeable asphalt surface (permeable concrete, perforated concrete blocks or plastic filled with grass or soil, and vegetated pavements) and the use of photovoltaic systems.

- *Reconstruction, maintenance, and restoration of existing pavements to improve their thermal performance.* These include reflective coatings, chip seals, scrub seals, microsurfacing treatment, whitetopping [45] and use of pigments (pigments and coating with small minerals as a pavement sealing (or sealcoating), and pavement tiles of different colors, using pigments with nanoparticles that are reflected in the infrared).

- Shading pavement surfaces to reduce the absorption of solar radiation [46].

2.1. The Role of Reflectivity (Solar Reflectance or Albedo)

Albedo is the ratio of reflected radiation to the incident solar radiation at a surface, which is averaged over the entire solar spectrum. The reflectivity of a surface also determines the amount of solar radiation received by the reference surface and absorbed by the surface, and further determines the surface's ability to deflect the incident solar radiation as stated by the American Concrete Pavement Association in 2002 [46]. Albedo values range from 0 (for perfect absorbers) to 1 (for perfect reflectors) [46][47][48]. These values may occur only at a theoretical level, and albedo values of 0.70 and 0.20 refer to surfaces with light and dark colors, respectively. Lime and surfaces covered with snow exhibit extreme albedo values of around 0.90, while values close to 0.10 correspond to the typical surfaces of dark asphalt pavements [20]. Doulos et al. provided detailed data regarding reflectivity values for various materials used for road surfaces, as indicated in **Figure 3** [49].

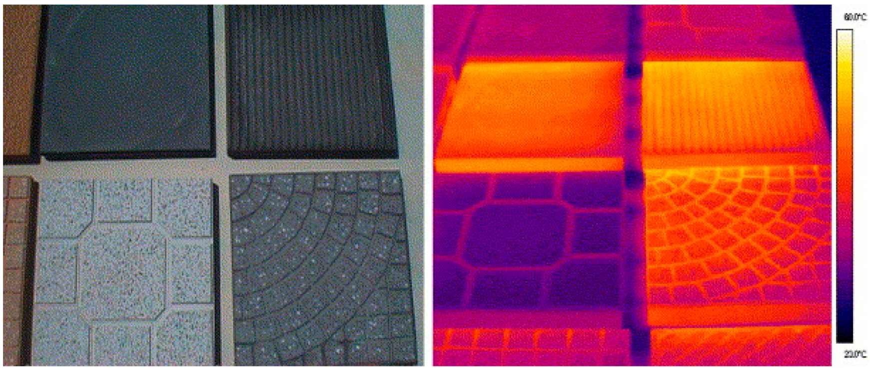

Figure 3. Visible and infrared image of selected building materials [49].

Albedo is the main factor that contributes to increasing temperatures on outdoor urban surfaces. Albedo also affects the temperatures below the surface of pavements, as less heat is available on the surface to be transferred to the pavement [35]. The use of materials determines the magnitude of global albedo in cities, with typical values for European and American cities approaching 0.15 to 0.30. A much higher albedo is found in some cities of North Africa, in the range between 0.45 and 0.60 [35]. Akbari and Taha provided albedo data for urban areas without snow for several cities, as well as the difference between urban and rural albedo [50]. Cantat measured the albedo of various surfaces as well as their temperature in the greater area of Paris, and found that urban areas have much lower albedo, while the albedo in Paris is about 16% lower than in rural areas [51].

Numerous research studies have been performed to determine the effect of color on the surface temperature and sensible heat release of pavement materials. Doulos et al. compared many types of pavements during summer and found that the maximum temperature difference between dark granites and white marbles is 19 °C, while surface temperature differences between other pavement color categories are bigger (near 24 °C) [49]. Another study measured the surface temperature of thin-layer bituminous materials of various colors that were subjected to solar radiation. Off-white asphalt with a visible spectrum albedo of 0.45 demonstrated a nearly 12 °C lower maximum surface temperature than black asphalt with a visible spectrum albedo of 0.03. Yellow, beige, green, and red asphalt materials (albedos in the optical spectrum of 0.26, 0.31, 0.10, and 0.11) had a maximum surface temperature of 9.0, 7.0, 5.0, and 4.0 °C lower than black asphalt, respectively. It is self-evident that the specific reflectivity of materials in the near infrared region of the spectrum influences the surface temperature practically proportionally [52]. Using satellite data, a comparative assessment of several pavement materials utilized in the Athens metropolitan area was conducted during the summer. The temperature of the asphalt surface was between 77.6 and 81.8 °C, that of the concrete between 56.2 and 78.6 °C, that of marble between 48.6 and 67.3 °C, and that of stone between 47.5 and 75.1 °C [53]. Significant research has been conducted and published on the topic of increasing the reflectivity of coating materials, with technological advancements focusing on two distinct directions: increasing the albedo of light-colored or white pavements, thereby increasing the spectral reflectance in the visible portion of the solar spectrum; and increasing the spectral reflectance of colored materials in the near infrared portion of the solar spectrum.

Gustavsson and Bogren investigated the influence of surface temperature on the pavement's construction. They discovered a nighttime maximum difference of 1.5 °C between surface substrates composed of blast furnace slag and those made of gravel using a test road [54]. Berg and Quinn observed that in mid-summer, white-painted roads with an albedo around 0.55 were virtually as warm as the ambient environment, but unpainted roads with an albedo near 0.15 were 11 °C warmer [55]. Taha et al. evaluated the albedo and surface temperatures of a variety of urban construction materials. They state that a white elastomeric coating with an albedo of 0.72 had a maximum surface temperature of 45 °C, the same as a black coating with an albedo of 0.08. Additionally, they claim that a white surface with an albedo of 0.61 is only 5 °C warmer than ambient air, but ordinary gravel with an albedo of 0.09 is 30 °C warmer [56].

Regarding the empirical measure of albedo, the Solar Reflectance Index (SRI) determines the ability of a surface to reflect solar radiation and emit the absorbed energy in the form of infrared radiation and in accordance with the increase in its temperature, compared to a standard black and white surface [57]. SRI indicates how hot a surface may be compared to a standard surface and is mainly used to measure the efficiency of cold technologies integrating both solar reflectance and thermal emission [45][58]. From a physical point of view, it is like comparing a paving material to a black and a white surface by measuring the temperature of all three surfaces under the sun. SRI takes values between 0 (as hot as a black surface) and 100 (as cold as a white surface) [48][59].

Finally, it is important to note that the albedo of asphalt increases rapidly over time. Although many of the studies quoted above do not take this into consideration, Sen and Roesler [60] examined the impact of pavements on UHI depending on multiple material factors, including the thermal and optical properties. They concluded that pavements with an unfavorable albedo or emissivity could nonetheless have a lower surface temperature by having high conductivity and heat capacity, so that energy that is absorbed is quickly conducted away from the surface. Another issue that needs to be mentioned is that many coatings tend to deteriorate rapidly in real-world settings, and therefore the initial boost in albedo faces away quickly. In the work of Ko et al. [61], proper measurements were accomplished in order to determine the neighborhood-scale impacts of cool pavements under real-world conditions. The results included the spatial and temporal variability of pavement albedo, the impact of cool pavement on the surface temperature and the impact of cool pavement on the ambient temperature.

2.2. The Role of Thermal Emittance

Materials emit long wavelength radiation as a function of their temperature and emissivity. High emission values correspond to positive long wavelength emitters that can easily release the absorbed energy. The infrared emission factor is the parameter that determines the ability of a certain material to transfer heat in the form of infrared radiation. The higher the emission capacity, the more heat is emitted from the body. Thus, it is a crucial parameter for the redistribution of heat within the structured environment, as well as heat-exchanging phenomena with the sky through radiation. As the radiant heat emitted between bodies is inversely proportional to the square of their distance, the role of emission in the formation of a heat island depends on the urban geometry and the view factor of the urban surfaces with the sky. Thermal emittance is the efficiency with which a surface emits thermal radiation (with values ranging from 0 to 1). Almost all non-metallic surfaces have high thermal emittance, typically ranging between 0.80 and 0.95, whereas uncoated metals have low thermal emittance. A bare metal surface reflects as much sunlight as a white surface, allowing it to stay warmer in the sun due to its lower emission of thermal radiation.

Several studies have been performed in order to demonstrate the effect of emission on the thermal performance of materials used in the urban environment. The emission of solar radiation can affect the surface temperature of materials significantly during the night. It has been reported that a strong correlation is found between the average nocturnal surface temperature and the corresponding emission of the material [3]. Gui et al. performed a sensitivity analysis on the role of emission at the maximum and minimum surface temperatures of various pavement materials and found that when the emission value is increased from 0.7 to 1.0, the maximum and minimum surface temperatures are reduced by 5.0 and 8.5 °C, respectively. It has been reported that differences in emission capacity between urban and rural areas may have a potential influence on the formation of the UHI effect [42]. However, Grimmond et al. simulated the effect of the optical and thermal characteristics of materials, which are responsible for the UHI, and found that the role of the emission capacity is secondary. As the emission capacity increased from 0.85 to 1.00, there was a slight overnight increase of 0.4 °C in the heat island intensity for very narrow urban street canyons [62]. For the phenomenon of urban street canyons with higher viewing factors, practically no changes were observed [63]. Shi and Zhang evaluated the combined effect of surface reflectivity and heat emission of building materials using simulation, reporting that the heat emission plays a very important role when the reflectivity of materials decreases, while for high albedo values, the relative increase in emission offers few advantages regarding the cooling load of buildings [64]. Gui et al. concluded that both the albedo and the radiation emission of coating materials have the highest positive effect on the surface temperature of the materials presented in their study [37].

White et al. reported that different pavement materials contribute to UHI [65]. Robinette reported relative surface temperatures around 38 °C on the grass, 61 °C on the asphalt, and 73 °C on artificial grass [66]. Ikechukwu conducted a study comparing the urban temperature asphalt, concrete, bare ground and grass. It was found that pavement materials affected the surface temperature. Asphalt had the larger impact on the urban heat island with a 4 °C increase, followed by concrete with a 3 °C increase, soil with a 2 °C increase, and grass with a 1 °C increase in air temperature [67]. Santamouris reported surface temperatures close to 63 °C for asphalt and close to 45 °C for white pavements [4]. Oke et al. studied the effect of thermal emittance on the UHI with simulations, showing that the role of thermal emittance in the intensity of the overnight UHI effect is quite small. When the thermal emittance increased from 0.85 to 1.0, the air temperature difference between urban and rural environments varied by 0.4 °C, and only for very narrow urban street canyons [68]. Instead, the influence of the thermal properties of the material is more important. For a ground flat, it was found that when the urban admittance was 2200 J/m^2/K, and the agricultural conductivity was 800 units lower, a heat island of approximately 2 °C developed during the night, while when the urban admittance was reduced to 600 J/m^2/K, a cool island over 4 °C was formed [49]. A study presented results for a variety of paving materials commonly used in an urban environment and tested them during the summer. The results showed that surface temperature, heat storage and the atmospheric emissions that followed were significantly higher in asphalt than in concrete and bare ground. Thus, the asphalt pavement emitted an additional 150W/m^2 in infrared radiation and 200 W/m^2 of conveying sensible heat, compared to the bare ground surface. Additionally, the rate of infrared absorption from the lower atmosphere with respect to the asphalt pavement was 60 W/m^2 higher than that on the ground or pavement made of concrete [36].

2.3. The Role of Heat Transfer and Thermal Capacity

In general, heat transfer may be performed in three ways: conduction in solids, convection in fluids, and radiation. Heat transfer through convection to and from the pavement surface is a function of the temperature difference between the ambient air and the pavement surface, as well as the heat convection coefficient (h_{conv}). Thermal convection depends on the wind speed and the temperature difference. Asaeda et al. carried out measurements on asphalt and concrete surfaces, which showed that the maximum and minimum convective heat transfer during the warmest day were 350 and 200 W/m^2, respectively [36].

Thermal capacity is the body’s ability to store heat. Thermal conductivity and heat capacity are the primary additional parameters that affect the thermal performance of pavements. Urban constructions tend to have high thermal capacity, whereas the thermal capacity of plants is almost negligible. Due to the high thermal capacity of the building materials, the heat in urban areas is stored and released later, when the ambient temperature is lower than the surface temperature, typically increasing the night air temperature. On the other hand, plant surfaces do not store heat. Additional heat stored in the urban environment can slow down, prevent (or even stop in extreme situations), the night cooling in extremely hot days with high solar radiation and clear sky. In dense urban geometries, with limited vegetation and shading, this phenomenon is quite common during the summer period.

The thermal properties of concrete pavements have been extensively studied [69][70][71]. The pavement surface’s higher thermal conductivity aids in the quick transmission of heat from the pavement to the ground and vice versa. Thus, during the day, when the pavement’s temperature is greater than the soil’s, heat is transferred from the pavement to the soil, and at night, the process is reversed. Likewise, materials with greater conductivity have a significantly lower average maximum temperature and a significantly higher average minimum temperature. Gui et al. simulated that when the thermal conductivity is increased from 0.60 to 2.60 Wm^{-1} $°C^{-1}$, the average maximum surface temperature reduces by 7 °C while the average lowest temperature increases by 4.5 °C [42]. Hermanson conducted simulations with significantly lower solar radiation and surface pavement temperatures and determined that conduction had a negligible effect on the temperature of the pavement at its surface [72].

Thermal capacity has a similar effect on the maximum and minimum surface temperatures of paving materials as thermal conductivity does. The increased thermal capacity decreases the average maximum surface temperature while increasing the average minimum surface temperature. To investigate the influence of thermal capacity, simulations were run, and it was discovered that when the value was increased from 1.40 to 2.80 × 10^6 Jm^{-3} $°C^{-1}$, the average maximum surface temperature decreased by about 5 °C [42].

2.4. The Effect of Permeability

Permeable pavements allow water to permeate typically impermeable surfaces and evaporate when the material's temperature rises. The rate of evaporation is a function of the moisture content of the substance and the surrounding environment and is highly dependent on the medium's temperature.

Results about the correlation between the surface temperature and the permeability of pavement materials are mixed: experiments carried out by Haselbach indicate that permeable pavements demonstrate a higher surface temperature compared to non-permeable pavements [73]; on the other hand, Karasawa et al. demonstrated that there is no connection between the surface temperature of concrete blocks and their permeability [74]. Permeable pavements are more suited to hot and humid conditions, as rainfall is primarily used to cool the pavement's surface. Wastewater can also be used as a source of evaporation. Permeable pavements may not be an appropriate option in dry climates, where water availability is a concern.

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