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Review

Cool Pavements: State of the Art and New Technologies

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Abstract: 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. This paper presents an extensive analysis of the state of the art of cool pavements. The properties and principles of cool pavements are reviewed, including reflectivity, thermal emittance, heat transfer, thermal capacity, and permeability. The different types, research directions, and applications of reflective pavements are outlined and discussed. Maintenance and restoration technologies of cool pavements are reviewed, including permeable pavements. Results show that cool pavements have significant temperature reduction potential in the urban environment. This research is important for policy actions of the European Union, noting that European and international business stakeholders have recently expressed their interest in new ways of reducing energy consumption through technologically advanced pavements.

Keywords: urban heat island; cool pavements; reduction of carbon dioxide; energy savings; reflectivity; thermal emittance; heat transfer; thermal capacity; energy policy

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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 [1–6]. UHIs, in combination with climate change effects, are considered to be the main causes for the significant increase in urban temperatures [7–15]. A significant increase in the energy consumption in buildings (due to enhanced cooling loads) is attributed to the UHI effect [16–28]. 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].

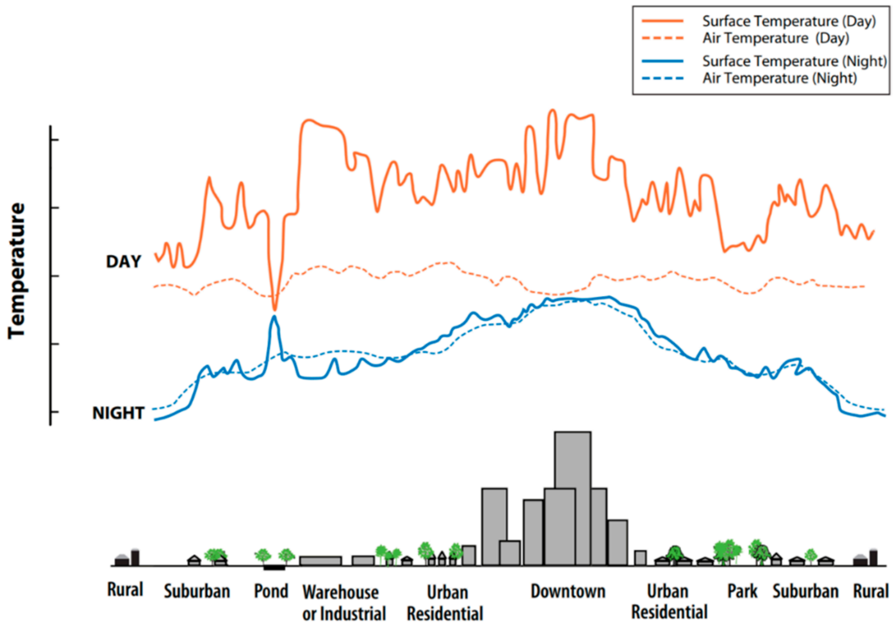

Figure 1. Illustration of how nighttime temperatures remain warmer in the urban areas due to the UHI [32].

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 [33–35].

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 [37–39]. 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 [40–42].

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.

This paper aims to describe the state of the art in the field of cool pavements. The main technologies are presented, and existing applications are described, with a focus on reflective and permeable/water retentive pavements. Issues related to the thermal and optical performance, relevant parameters and performance data are also provided. Moreover, various case studies with cool pavements used in real-scale projects are presented. The results presented are discussed and indicate that cool pavements can significantly contribute to the reduction in temperature in urban environments.

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).

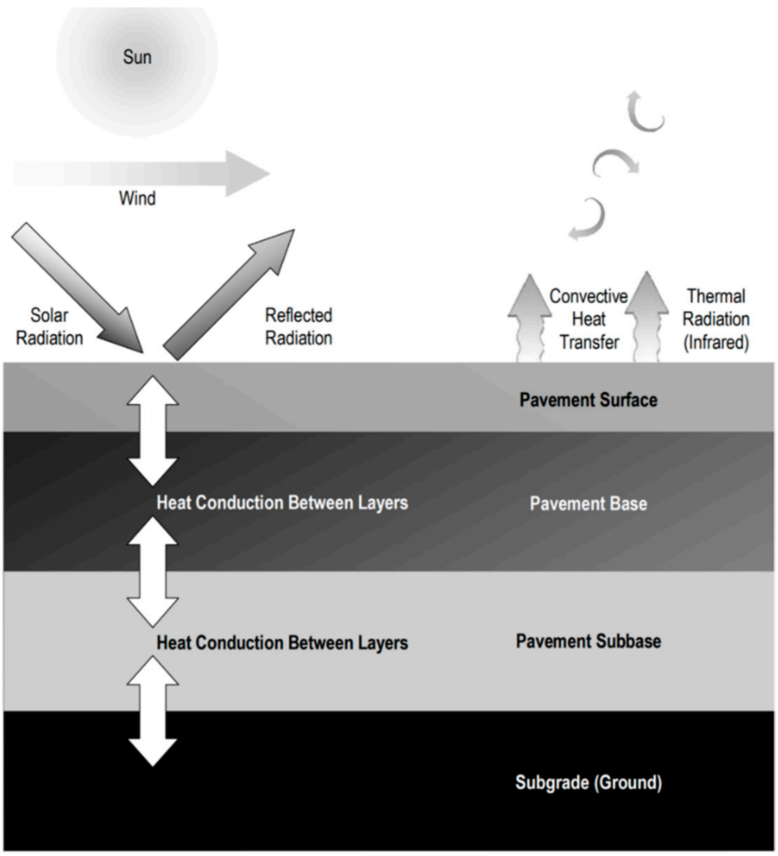

Figure 2. Heat-exchange-related processes in typical urban pavement [42].

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) [46–48]. 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].

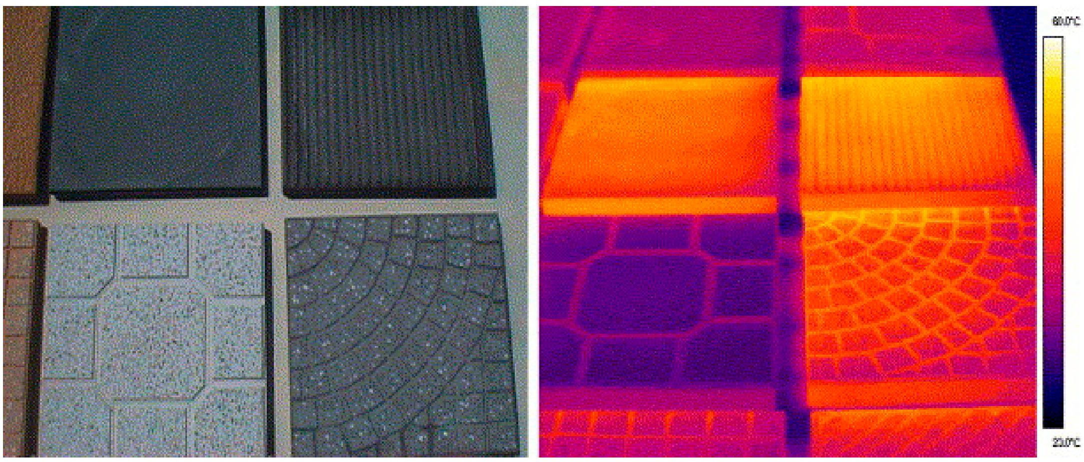

Figure 3. Visible and infrared image of selected building materials [49].

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 [69–71]. 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.

3. Toward the Improvement of Thermal Performance of Cool Pavements

3.1. Improving the Thermal Performance of Pavements

The effective mitigation of the impacts of pavements on the UHI effect requires a significant reduction in the flow of heat released into the atmosphere by the pavement surfaces, in other words, a reduction in their surface temperature during day and night. Pavements covered or made of materials of reduced surface temperature are known as cool pavements. The decrease in pavement temperature may be achieved either by the replacement of existing pavements with new, or by reconstruction, maintenance, and the replacement of existing pavements with materials and technologies that help toward this function [75].

The construction of new cool pavements includes the following [76]:

a. Modified mixes: conventional asphalt/concrete pavements, resin-based pavements, rolled compacted concrete pavements, PCC, ACP, rubberized asphalt pavements, texturing of open-grated course with cementitious materials, gritting with light-colored aggregates, white cement, titanium oxide (photocatalyst), and concrete additives;
b. Permeable pavements: with/without vegetation, porous asphalt surfaces, pervious concrete, paving blocks/grid pavements made of concrete or plastic, or metal lattice filled with grass or soil;
c. Use of photovoltaic systems.

The cool pavements intended for maintenance and replacement of existing ones include the following:

a. Reflective coatings and seals: chip seals, sand and scrub seals, conventional and rubberized slurry seals, and microsurfacing;
b. Whitetopping [44];
c. Use of pigments and coatings with small stones on pavements having seals, pavement tiles of different colors with the use of pigments with nanomaterials to reflect in the infrared part of the spectrum;
d. Diamond grinding;
e. Shot/abrasive blasting.

Moreover, reducing the surface temperature of cool pavements may be achieved by using several techniques and methods, such as the following:

a. Increase in the albedo of pavement surfaces in order to absorb less solar radiation (reflective pavements);
b. Increase in the permeability of surfaces of vegetated or non-vegetated pavements in order to reduce their surface temperature through evaporation (permeable, porous, pervious or water retentive pavements);
c. Enhancement of the thermal storage capacity of surfaces with the addition of thermally conductive or latent heat storage materials. Common materials used on pavements have high thermal capacity, which is quite difficult to increase further. However, the addition of latent heat storage materials to the mass of pavements helps to cool the surface during the day and reduces the amount of sensible heat released into the environment;
d. Use of external mechanical systems to reduce the surface temperature of paving materials. For the removal of the excess heat, this includes air or water circulation above the mass of pavement [77] and the circulation of groundwater below the mass of the pavement [78];
e. Shading of pavements using natural or artificial methods of solar control (e.g., trees and green pergolas). Shaded surfaces have a much lower surface temperature, as the absorbed direct sunlight is reduced significantly.

The state of the art of the main categories of reflective and permeable pavements is presented in the following section. Reflective pavements are used for the maintenance and replacement of existing pavements, while permeable pavements are better suited for the construction of new pavements.

3.2. Reflective Pavements

The increase in pavement albedo helps to reduce surface temperature and the amount of sensible heat released to the atmosphere, while also reducing the need for night lighting and increasing the durability of pavements [43]. The albedo of pavements may be increased with the use of suitable surface coatings, light-colored aggregates, suitable binders or a combination of the above [79].

3.2.1. Existing Commercial Applications of Reflective Pavements

There are several commercially available techniques which are widely used to increase albedo on concrete and asphalt pavements. Particularly, the resurfacing of existing pavements is implemented, using suitable aggregates and binders, which may be mixed. If the two components are not mixed prior to the application ("chip seals", "sand and scrub seals", and conventional and rubberized "slurry seals") the surface temperature of the asphalt is reduced by approximately 9 °C. When the binder and aggregates are mixed, the techniques is called "*micro-surfacing*", "*fog coating*", "*overlay*" or "*slurry coating*" [80,81]. The following is a more detailed analysis:

a. "*Chip seals*" is a common preventive maintenance technique used for asphalt pavements, which creates a significant improvement in the SRI extending the pavement lifetime. A chip seal is made by applying a thin layer of asphalt emulsion to the existing pavement surface and then disseminating and embedding graded aggregates with a pneumatic roller. This results in an initial surface that mimics the aggregate used in the seal. The inclusion of light-colored aggregates in the chip seal results in a surface that is substantially more reflective than a typical existing asphalt pavement; however, this reflectivity will decline with time, especially when subjected to vehicle activity, which drives the particles into the asphalt [81].

Processing the surface of the pavement with light-colored materials to increase their reflectivity is a relatively simple process. There are various techniques, but they all adopt the same simple approach, applying the treatment on existing pavements and increasing the reflectivity without rebuilding the entire pavement. The materials used consist of gravel or light-colored aggregate with polymers, emulsion, or resin bonded in wet asphalt, and they are often used to reconstruct the surface of low-volume asphalt pavements and occasionally motorways. The cost of such interventions depends on whether the aggregate is locally available or not. Chip seals are commonly used on pavements that have low traffic volumes, because of the tendency of the stones to loosen and drift from the movement of vehicles, e.g., when a vehicle speeds up to overtake another vehicle, there is a risk of a fragment cracking the windshield. Texas, in particular, is experienced in implementing such pavements on highways (including interstate highways) [32].

b. "*Sand and scrub seals*" are similar surface treatments, but they use fine aggregates (such as sand) and are constructed differently. A common sand seal is built similarly to a chip seal. After spraying an asphalt emulsion on the existing pavement surface, the fine aggregate is applied and compacted into the emulsion, with any surplus material removed. In the case of a scrub seal, the emulsion and aggregate are separately injected into pavement cracks and voids before being rolled into position by pneumatic tires. Due to the difference in construction methods, scrub seals are more expensive yet remain longer than sand seals. Additionally, they can be utilized to raise the SRI of a surface by applying light-colored particles [81].
c. "*Microsurfacing*", or sealing the surface with a highly reflective layer, can increase the reflectivity of a pavement and extend its lifetime. Many of these coatings are designed to have a high coefficient of friction in order to be safe in wet circumstances. Typically, light-colored materials are utilized to boost asphalt's sun reflection. The researchers applied a light-colored microsurfacing material composed of cement, sand, and other materials, as well as a liquid mixture of emulsified polymeric resin, and found that the solar reflection was comparable to that of newly concrete [32]. EKrete by PolyCon Manufacturing, Inc. is an example of such a microsurfacing material. For general-purpose parking lot pavements, the E-Krete microsurfacing and Street-Bond coating may be employed. On the pavement surface, a very thin coating (1/8 to 1/4 inch) of these materials is placed [81,82].

3.2.2. Current Research Directions in Reflective Pavements

Apart from commercial applications, significant research efforts have been published in the field of reflective pavements. The main features and results of the most prominent research approaches are presented below.

a. *Use of high reflective paints.* Newly white paints have very high solar reflectivity, often exceeding 0.9 [82]. The usage of such paints has the potential to dramatically reduce the temperature of the pavement's surface and the amount of sensible heat discharged into the atmosphere. Santamouris et al. investigated the application of reflective paints to the surface or mass of concrete tile pavements. Summer conditions were used to conduct the experiments, and the results were compared to those obtained with ordinary white tiles. In both cases, the albedo was between 0.8 and 0.9 [83]. Another research group evaluated the thermal performance of 14 high-reflectance white pavement surfaces that were coated with reflective colors using a variety of different technologies during the summer. Almost all materials tested had an albedo of between 0.8 and 0.9. Aluminum-free coatings had a radiation emittance greater than 0.8, while aluminum-based paints had a radiation emittance of between 0.3 and 0.4. The use of highly reflecting coatings was shown to reduce the daily surface temperature of white concrete by 4 °C and the temperature during summer nights by 2 °C. These tiles were only 2 °C warmer than air during the day and 5.9 °C colder at night, indicating a strong correlation between material emission and surface temperature at night. Pavements with aluminum-based coatings had a greater surface temperature than other types of tiles [3].

Aging paints have a significant effect on the thermal performance of pavements. Acrylic elastomeric coatings remained rather cool throughout the first month of observation but got much warmer during the second and third months of experimental testing. Additionally, highly reflective white coverings (albedo near 0.88) based on the usage of calcium hydroxide were created and tested in summer settings versus typical white pavements (albedo near 0.76). The material has an infrared emittance of approximately 0.85. These low-cost, ecologically friendly coatings permit air to travel through while providing a high level of resistance to environmental pollution. Chalking is the major disadvantage of these materials, and an acrylic binder is recommended to mitigate this effect. The original reflecting materials were reported to have lower temperatures ranging between 1 and 5 °C during the day, but only about 1 °C at night [83].

b. *Use of infrared reflecting colored paints.* Infrared reflective pigments can be used instead of non-white pavement materials in order to increase the albedo of pavements [82]. In such a case, the pavement surface can exhibit strong reflectance in the near infrared part of the spectrum, compared to a conventional material of the same color [84,85]. The albedo of colored concrete and asphalt pavements has been modified using infrared reflective color paints [2,52]. Santamouris et al. investigated the direct application of infrared reflective color paints on concrete pavement surfaces [82]. Synnefa et al. investigated the effect of thin layers of various reflecting color paints using infrared reflective pigments on typical asphalt pavements [52]. Another study compared 10 standard cool-colored pavement materials made with infrared reflective pigments against traditional materials of the same color during the summer. As previously stated, the reflecting black material had an albedo of around 0.27 and a daily *average* surface temperature nearly 10 °C lower than a typical black surface with an albedo of 0.05. Simultaneously, reflecting blue had a reflectance of 0.33 and an average surface temperature of 4.5 °C lower than traditional blue [2]. In general, a nearly linear relationship between the average surface temperature and material albedo was discovered. During the night, much lower surface temperatures were also measured.

As previously stated, using cool pavements can help reduce surface temperatures by 11–22 °C. Thin asphalt layer pavings have been produced by combining colorless elastomeric asphalt binders with infrared reflective pigments and particles with specified properties [52]. Under summer conditions, five samples (green, red, yellow, beige, and off-white) were compared to typical asphalt samples. Albedo values for thin asphalt layers ranged from 0.27 for the red and green samples to 0.55 for the off-white sample. The reflectivity of typical asphalt was approximately 0.04. All samples exhibited a high level of absorption in the ultraviolet region and a high level of reflection in the infrared region (ranging between 0.39 and 0.56). Thermal monitoring of the samples revealed that their surface temperatures were greater than the ambient temperature during the day but were always lower than the ambient temperature at night, owing mostly to the high emittance of the materials used. The off-white sample had an average daily surface temperature of 36 °C, while the red sample had an average daily surface temperature of 43.6 °C. The standard asphalt's surface temperature was approximately 60 °C. All samples had an overnight surface temperature nearly 1 to 2 °C lower than normal asphalt. The prospective usage of asphalt pavements on roads was projected to reduce the ambient temperature by 5 °C under low wind speed conditions, as the CFD simulation techniques revealed.

c. *Use of heat-reflecting paints to cover asphalt aggregates.* Boriboonsomsin and Reza advised that aggregates used in asphalt pavements be covered with infrared reflecting paints. They evaluated four different types of high albedo asphalt pavements in which a heat reflecting paint was applied to each aggregate, as opposed to traditional reflective asphalt pavements, where the paint was applied solely to the surface. Pavements have an albedo of between 0.46 and 0.57. Tracking revealed that upgraded pavements have a significantly cooler surface temperature than conventional pavements, with temperature differences ranging from 10.2 to 18.8 °C [86]. Simultaneously, a similar approach was proposed for the preparation of high-albedo coatings for asphalt pavements [87]. The experiment was conducted in Japan during the summer season. When the albedo of the pavement was increased to 0.25, its surface temperature was nearly 6.8 °C lower than that of normal asphalt, while increasing the albedo to 0.6 resulted in a nearly 20 °C reduction in surface temperature. In general, it was discovered that increasing the albedo by 0.1 resulted in a decrease in surface temperature of close to 2.5 °C.

d. *Use of color changing paints.* Numerous authors have advocated for the introduction of color changing coatings to pavements [88–90]. Thermochromic coatings are capable of thermally responding to the environment and reversibly altering their color and reflectivity as the temperature rises. These coatings have been created, and their thermal performance in contrast to other reflecting and common coatings has been evaluated in pavements. Eleven distinct colored tiles were produced and tested in hot summer ambient temperatures. Organic thermochromic pigments and other stabilizing elements were used to create the coatings. All pavements tested emitted a similar amount of infrared light. Daily average surface temperatures of thermochromic pavements were consistently lower than those based on infrared reflecting pigments and conventional coatings. Temperatures for thermochromic coatings ranged from 31.0 to 38.4 °C; for infrared reflective coatings, from 34.4 to 45.2 °C; and for common coatings, from 36.4 to 48.5 °C. The temperature at night was comparable for the three coating types. Spectral reflectance measurements of thermochromic coatings revealed a maximum increase in albedo of 43 percent from the colored to the colorless phase. The primary disadvantage of thermochromic coatings is their quick loss of optical properties. Significant research has been conducted to find a solution to the aging problem, and the results appear to be quite encouraging [88].

e. *Use of fly ash and slag as constituents of concrete* leads to the production of surfaces with improved albedo values. When 70% slag was employed as a cement replacement, the combination had an albedo of 0.582, which is 71% higher than the standard blend. Although the findings are significant, there has been little progress in this field, and it is not considered a major research trend [91].

3.2.3. Actual Applications of Reflective Pavements

The application of cool pavements in a crowded urban region in Athens, Greece was presented [44,92]. The project entailed the restoration of a 16,000 m^2 area, which included the installation of new high-reflectivity pavements, green spaces, and earth-to-air heat exchangers. Black asphalt is used in the roadways, while dark-colored concrete tiles with an albedo of less than 0.4 are used on sidewalks. Because of the high ambient and surface temperatures, the region was thoroughly monitored, and it was discovered that present comfort conditions are below acceptable limits. All conventional asphalt has been replaced with colored bituminous material with a reflectivity of 0.35 [52], while natural reflective materials, such as marbles and concrete coated with high reflectance colors, have been used for open areas and pavements. Marbles have a reflectivity of 0.7, whereas colored concrete pavements have a reflectivity of 0.78. To examine the potential of the approaches used, detailed computational fluid dynamics (CFD) simulations were run. It is estimated that replacing conventional pavements with cool pavements can reduce maximum ambient temperature by 1.2 to 2.0 °C, with a total possible temperature reduction of 3.4 °C if all proposed measures are implemented.

Fintikakis et al. described the use of cool pavements as part of an extended bioclimatic restoration of public open spaces (with a total surface about 25,000 m^2) in an urban area in Tirana, Albania. Aside from the reflective pavements, the whole idea includes the installation of more green areas, sunlight control pergolas, and substantial use of earth-to-air heat exchangers to deliver chilly air. Pavements were previously built of very dark concrete or stone tiles with an albedo of 0.15 to 0.2. Depending on the color chosen, the albedo of the proposed tiles ranged from 0.65 to 0.75. Using modern simulation techniques, the influence of the suggested thermal mitigation measures on the climate was analyzed, and it was projected that they can reduce the maximum ambient temperature by 1.2 to 2.0 °C, with a total temperature reduction of 3.4 °C due to the adoption of all measures. Additionally, passive cooling techniques such as cool materials, solar control, and additional vegetation, as well as earth-to-air heat exchangers, were found to reduce peak summer ambient temperatures by up to 3 °C, while surface temperatures were reduced by up to 6 to 8 °C (as depicted in Figure 4), contributing to improved thermal comfort and quality of life for urban citizens [93].

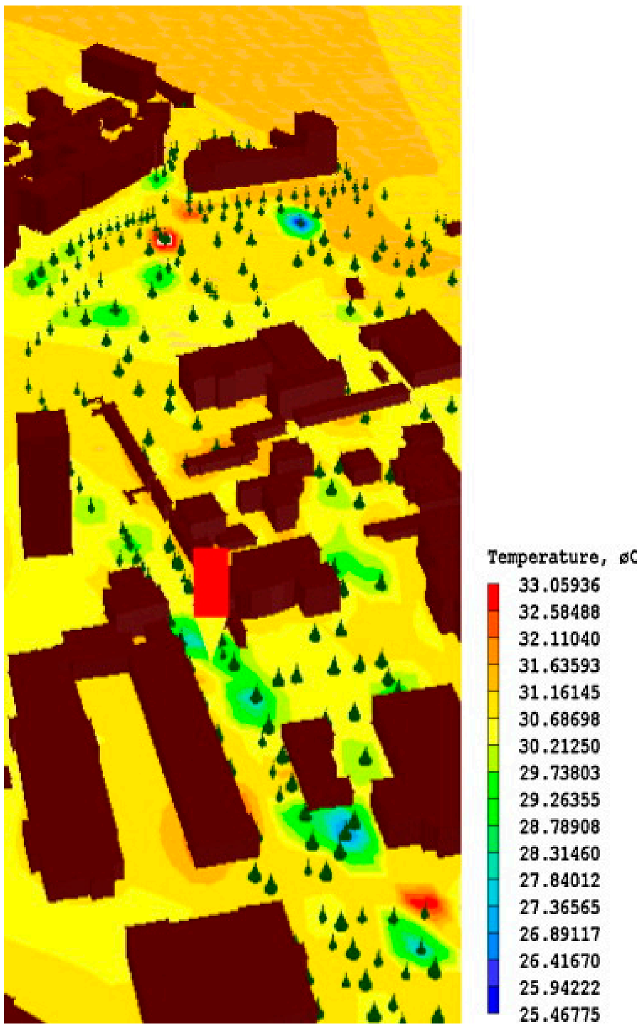

Figure 4. Surface temperature distribution along the main pedestrian road during summer peak conditions (height 1.5 m) [93].

Gaitani et al. reported how a mix of approaches, including cool pavements, were used to restore the bioclimatic conditions of a particularly congested region of 4160 m^2 in Athens, Greece. On the roadways, black asphalt was utilized, and in the remaining open areas, white concrete tiles with an initial albedo of 0.45 were employed. The area's observed ambient and surface temperatures were extremely high, and it was expected that using adequate mitigation strategies would greatly improve the area's current conditions. Photocatalytic asphalt in the streets, concrete tiles sprayed with infrared reflecting paints, more shading and green areas, and earth-to-air heat exchangers were all part of the recovery strategy. The use of cool pavements can reduce the average maximum summer ambient temperature by 1.6 °C, while the average surface temperature of pavements can be reduced to 4.5 °C over the summer period, according to a simulation of the current and suggested scenario under average summer conditions [94].

Santamouris et al. detailed the restoration of an urban park in Athens, Greece, with a total surface area of 4500 m^2. The park's surfaces were mostly asphalt, concrete, and dark materials before the restoration. Pavement surfaces had an albedo of 0.35 to 0.45, whereas concrete and asphalt-covered regions had an albedo of less than 0.2. Excessive use of cool pavements and the installation of green spaces were part of the rehabilitation. In the park, concrete pavements with an albedo of 0.60 were painted with infrared reflective cool paints. The average maximum ambient temperature was reduced by 1.9 °C after completion, while the maximum surface temperature in the area was reduced by 12 °C [43].

Shahidan et al. reported the findings of a study in Putrijaya, Malaysia, that looked into the feasibility of mitigating green spaces and cool pavements. The projected area was 420,000 m^2, with existing coating materials being replaced with new ones with an albedo of 0.8. Simulations were conducted, and it was shown that all applicable mitigation strategies contributed to a 1.5 °C reduction in ambient temperature, with cool pavements contributing roughly 0.1 °C [95].

The preceding studies reveal a number of major benefits of reflective pavements, including a reduction in surface temperature and sensible heat movement in the atmosphere, which contributes to more effective UHI mitigation.

3.3. The Impact of Cool Pavements on Outdoor Thermal Comfort and Building Cooling Loads

A special mention should be made of reflected solar radiation since it has the ability to alter both building loads and pedestrian thermal comfort. Xu et al. developed a coupled physical simulation and machine learning model that allows for the calculation of the effect of increased albedo on the energy demand of buildings; their findings were positive for densely built and medium-density neighborhoods, but mixed for low-density neighborhoods in Boston, Massachusetts [96]. Using a building-to-canopy model, Yaghoobian and Kleissl evaluated the effect of changing albedo on a four-story building in Phoenix, Arizona. They discovered interactions occurring at the microclimate level, referring to material qualities, anthropogenic heat, geometry, and features of urban landscapes, and how these may affect surface temperatures and energy fluxes between the ground and the atmosphere. In an urban environment, reflective pavements and mirrored windows with adjacent buildings must be considered, as buildings adjacent to reflective pavements exhibit a high energy demand and use [97]. Given that the stated findings were obtained under a variety of meteorological and functional settings, it is impossible to compare different cases and their related performances in general without doing local simulations. Gilbert et al. added the environmental element by comparing less typical (cool) pavements to more typical (warm) alternatives over a 50-year period; their findings emphasize the impact of material manufacture [78]. Li et al. conducted a life cycle assessment of various reflective coatings used in cool pavements and determined that the durability of reflective coatings could be increased, while the emissions and possible toxicity of such coatings should be quantified [98].

At this point, it is noted that reflected solar radiation affects pedestrians. The thermal sensation of people over reflective pavements has been studied and analyzed. Erell et al. [99] investigated the effect of the use of high-albedo materials on the thermal comfort of pedestrians through computer modeling; the Thermal Stress index (TS index) was adopted, while analysis was extended to four different cities globally. According to their findings, even while the air temperature may be dropped, the reduction is insufficient to compensate for increased radiation loads, and so pedestrian thermal comfort may be compromised as a result of this. They came to the conclusion that, while the use of such materials on building roofs is often a win–win situation, their application on pavements or wall surfaces in pedestrian zones may be less acceptable. Faragallah and Ragheb [100] used ENVI-MET to investigate the thermal comfort of pedestrians in a street with traffic in Alexandria, Egypt (which has a hot, arid climate). Different scenarios for the use of cool pavements were applied, and simulation outcomes demonstrated that the outdoor thermal comfort in the suggested layout was inferior compared to the present situation (referring to the surface air temperature). Future work on the integration between buildings, paving materials, and external thermal comfort is suggested, concentrating on factors such as building geometry, albedo materials, and vegetation.

In a similar setting (Cairo, Egypt), Aboelata [101] investigated the impact of cool paving, as an alternative strategy, on the air temperature and the reduction of the energy demand of buildings, for three built-up areas with varying densities of 25%, 50%, and 85%; ENVI-MET was used for thermal comfort analysis. Cool paving raised the Physiological Equivalent Temperature (PET), so other scenarios combining vegetation and cool paving were discussed as possible solutions for the dilemma between air temperature and PET reduction. Mohammad et al. [102] made a pertinent suggestion based on their analysis of a straight urban street in Roorkee, India, using ENVIMET. Djekic et al. [103] investigated the thermal comfort of humans on pedestrian areas in Niš, Serbia, through the combined use of measurements and calculations according to the RayMan model for PET. Their findings revealed that heating pavement surfaces had a significant impact on the heating of the surrounding air as well as the thermal comfort of pedestrians. As a result, while selecting a pavement material, extra consideration must be given to the selection and application of lightweight and smooth materials. In a study of an urban main square in Toronto, Canada, Taleghani and Berardi [104] used ENVI-MET software and concluded that a reduction in air temperature and an increase in solar re-radiation to pedestrians are linked to an increase in the albedo. It was concluded that the effect on thermal comfort was not positive.

4. Maintenance and Restoration Technologies for Cool Pavements

4.1. Whitetopping (WT) and Ultra-Thin Whitetopping (UTW)

Whitetopping (WT) is a layer of concrete with a thickness greater than 10 cm, often containing carbon fibers for improved mechanical properties. Whitetopping includes a concrete pavement installed on top of asphalt, as a form of maintenance or reconstruction of the already existing surface. Since cement has a much higher albedo compared to asphalt concrete, the white coating reduces the surface temperature of the pavement. Typical applications of this technology include the reconstruction of the surface of pavement sections and parking areas [32]. Asphalt pavement repair is also carried out using a mixture of asphalt emulsion aggregates. Oil-based or tree-based resin coatings are available for the re-coating of asphalt pavements. Coloring additives along with suitable aggregates are also used to increase pavement albedo. Measurements show a decrease in surface temperature by 12 °C, compared to damaged asphalt. Tran et al. conducted a comparative experimental test of eight commercial technologies to improve the albedo of asphalt pavements. They found that six of the technologies had an SRI value greater than 0.29 [45].

Ultra-thin Whitetopping (UTW) is a newer renovation process, in which cement of thickness 5 to 10 cm is installed on a treated asphalt surface, and has high tolerance, as it is reinforced with carbon fibers. UTW is different from the whitetopping on conventional road surfaces, as it is based on its connection to the asphalt surface, which increases the tolerance of the pavement as the distance between them (typically 2 to 6 ft for UTW, compared to 5 to 25 ft for WT). As a possible cool pavement construction technology, UTW provides color and enhances the reflection of cement on an already existing asphalt surface. This method has been used in various construction projects for the redevelopment of pavements and parking areas [32]. The benefits of these techniques may be summarized as follows [58]:

- Easy to use;
- Avoids traditional stresses of an asphalt overlay;
- May be used on existing pavement systems;
- Quick to apply and re-open to traffic;
- Less sensitive to seasonal variations.

4.2. Use of Pigments

Pigments and coating with small rocks on pavements that contain seals are used to change the color of an asphalt surface, providing a lighter appearance. However, these products are expensive, and they are often used only in special cases where the color plays a significant role and is an important factor for the pavement. These pigments are also available for concrete pavements; however, these have a light color already, so their cooling is not improved [32]. Pavement tiles of different colors, using phase change materials (PCM) in the bulk mass of the pavement, is another such technology involving the use of infrared reflective pigments with nanomaterials that change phase based on concentrations and melting points. Increasing the thermal capacity of coating materials reduces the surface temperature and the amount of sensible heat released into the atmosphere. Karlessi et al. presented the use of phase change materials in pavements in order to increase the heat stored in the form of latent heat [105]. The phase change materials have been extensively studied, aiming to reduce the maximum surface temperature and eliminate the maximum cold load observed in buildings.

Colored tiles employing infrared pigments with and without PCM were experimentally tested and compared under summer conditions with tiles made of conventional pigments, as depicted in Figure 5. It was found that the tiles with reinforced PCM materials showed significantly lower temperatures (by 2.9 to 8.3 °C). Temperature differences were observed mainly in the morning (7:00–10:00 a.m.) when the PCM melts, while during the rest of the day and night the effect of PCM was not significant and the surface temperature of all types of tiles was similar. At the same time, it was noted that the concentration of PCM was not significant above a certain value, whereas the melting point of PCM determined the time period that the tile surfaces exhibited their lowest temperatures. It was concluded that PCM contributes to reducing the surface temperature of pavement surfaces, but their relative impact and contribution is not as important.

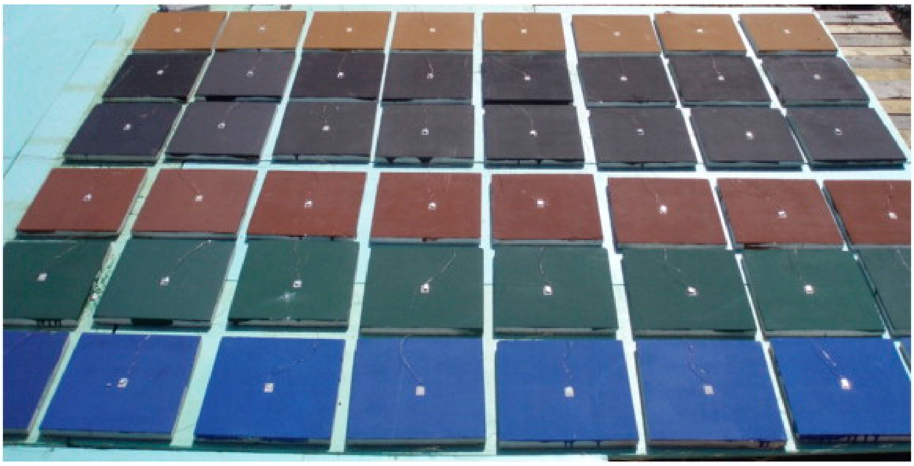

Figure 5. Tested tiles coated with common, cool and PCM coatings [105].

The idea of cooling asphalt via water circulated through pipes installed beneath the surface, has been proposed [106–108]. Due to the high surface temperature of the asphalt during the summer, water circulation could reduce the body and asphalt surface temperature and reduce the transfer of sensible heat to the atmosphere. Experiments and simulations have indicated that the thermal capacity of such systems is excessively high, but several technical problems should be resolved. This solution was applied to real-scale projects in the Netherlands [77].

4.3. Permeable Pavements

Permeable and water retentive pavements often have more open gaps than traditional pavements to enable water to flow into the substrates and soil and may incorporate water-filled materials with water-holding ability to store the water. The evaporation of water leads to the reduction in pavement surface temperatures, hence mitigating the UHI impact and minimizing the danger of floods. Three performance criteria are applicable to water-retaining pavements: (a) the ability to reduce surface temperature during favorable weather conditions, (b) the ability to maintain any temperature increase following rainfall, and (c) maximum durability and minimal performance degradation over time [109,110]. Permeable pavements are classified as those with and without vegetation as well as those made of concrete or asphalt.

Both permeable and impermeable cool pavements can also help to reduce the temperature of the trapped water, resulting in no thermal stress within the aquatic ecosystems, which is the ultimate destination of rainwater through sewers. In addition, pervious permeable pavements reduce vehicle tire noise by 2 to 8 dB and can keep traffic noise levels below 75 dB [58]. Among other things, permeable pavements improve safety by reducing water in the form of spraying from vehicle movement and increasing adhesion through improved water drainage. Another advantage is that they are visible during the night, as their reflectivity enhances visibility and reduces night lighting requirements, saving money and energy [58].

4.3.1. Existing Development and Commercial Applications of Permeable Pavements

In 2005, Ferguson [109] presented permeable pavements in detail, while Scholz and Grabowiecki [110] attempted a review of the main advantages and disadvantages of permeable pavements.

a. *Porous asphalt pavements* are made of water permeable blocks and are mainly used to prevent floods, reduce noise, and mitigate the UHI effect. Porous asphalt is a bituminous material mixed with aggregates that is porous due to the absence of very fine particles from the mixture.

A porous asphalt surface can improve slip resistance, reduce traffic noise, and help avoid the splashing of accumulated surface water onto the windshield of vehicles, making it difficult to drive. However, the benefits of noise reduction may decline over time, as the strength and durability of these pavements can be reduced as opposed to conventional surfaces [32]. Further research is needed to determine the extent to which these pavement surfaces are used on high-speed, high-volume roads [44].

Porous asphalt consists of both fine and naturally inert (gravel) stone particles attached to a bitumen-based binder and is mainly used to reduce issues caused by rainwater, i.e., reduce traffic noise and mitigate the effect of UHIs in parking areas or small urban areas. Porous asphalt is composed of a surface layer filter that must be at least 5 cm in thickness and contains broken rock particles of 1.3 cm size, a filter layer, a storage layer, a geotextile filter fabric (a type of pavement material made up of pin-sized pores), and pre-existing soil that should be permeable to water. The porous asphalt could be composed of an open graded asphalt concrete with gaps near 18% [44]. Open graded asphalt concrete is a mixture of porous asphalt shaped to provide large gaps in excess of 20%, in order to allow water to drain from the surface of the pavement, thereby increasing the safety of moving vehicles. The reflectivity of porous asphalt is determined by the reflectivity of its individual materials. Porous pavements, on average, have a lower solar reflectance than equivalent non-porous solutions [44].

b. *Pervious/permeable concrete* is produced using cement and concrete admixtures, such as fly ash, blast-furnace slag, pozzolans, aggregates, and water. Water permeability is normally measured between 20 and 40 mm/s; however, lower and higher values have been observed [73]. It is possible to make permeable concrete by combining cement and cement substrate substitutes, such as fissured feathers, pulverized blast furnace slag, and pozzolans or silica fumes, with cement. Its porosity is accomplished through the use of three types of pores: pores in the cement, gaps in the aggregates, and air gaps. Pores in the cement are the most common. When it comes to water permeability, air gaps are the most important factor to consider. It is mostly the binder used, the aggregates utilized, how the mixture is combined and how it is condensed, and ultimately how the calibrated aggregates are classified that determine how permeable the concrete will be in its final stage. Permeable concrete can be used in areas where rainwater runoff is undesirable, and it is suitable for low-speed traffic (less than 35 miles per hour). Views differ as to whether porous pavements are problematic in the winter: if the road surface remains completely dry, there should be no cooling issues. However, if water is trapped in pavement gaps for an extended period of time during frost, it can cause the pavement layer to deteriorate. Road sand can clog pavement pores, so other methods of controlling ice and snow for porous pavements (e.g., chemical use) might be used [32].

c. *Concrete pavers* come in many different forms. This category comprises non-vegetated permeable concrete block and segmented concrete pavers, as well as vegetated concrete grid pavers that incorporate a concrete lattice to allow flora to grow in between. Typically, block pavers are utilized on driveways, footpaths, patios, and other outdoor recreational spaces. These pavers come in a variety of colors and are frequently utilized as decorative elements. Segmented concrete pavers are frequently used in industrial and warehouse settings due to their interlocking nature, which enables them to handle greater load conditions. Because the gap between the blocks allows water to penetrate but is insufficient for considerable growth, block pavers and segmented concrete pavers are termed non-vegetated permeable pavements. The bulk of pavers currently in use are interlocking concrete pavers, which include those for impermeable and permeable pavement applications [81].

d. *Non-concrete permeable pavers.* Vegetated permeable pavements include grass pavers with a plastic or metal lattice. The space between the lattices is ideal for plants, such as grass, to grow. While these pavements are capable of supporting vehicle weight on a level with conventional pavements, they are often utilized in low-traffic areas, such as alleys, parking lots, and trails, to avoid harm to the vegetation. Additionally, they thrive in regions with sufficient summer moisture [32,81].

Additionally, permeable pavements may be separated into the following:

a. *Permeable pavements without vegetation* contain gaps and are designed to allow water to drain from the surface to the substrates and to the ground. These materials may have the same good structural condition as conventional pavements, e.g., porous surfaces (pervious surfaces), such as the Open-Graded Friction Course (OGFC) [32]. More specifically, OGFCs is a type of pavement that has been used in the US since 1950. These bituminous mixtures contain only a small amount of fine aggregates, constructing a pavement with a relatively large percentage of air vents that improve pavement abrasion in a wet environment. These bituminous mixtures are made of a single coarse aggregate and have high ash content [32]. Evaporation on pervious pavements (without vegetation) and on water-holding pavements is highly dependent on the distribution of particles of the paving material and the water holding capacity of the surface [32]. Rubber asphalt has been used on roads and motorways to reduce noise. Certain types of permeable pavements may be used in areas with less traffic, such as parking areas, alleys, or paths. These types of pavements reduce rainwater drainage and improve water quality because pervious sidewalks allow rainwater to permeate the road and soil, reducing runoff and filtering dirt.

b. *Permeable pavements with vegetation* are surfaces on which plants (usually grass) grow. A mesh of plastic, metal, or concrete is installed on the ground, which allows the vegetation to grow through the gaps. Vegetation has good reflective ability that reduces road surface temperature, and there is also the advantage of cooling the pavement through plant breeding. Pavements covered with vegetation are also permeable, which is good for water drainage. However, they require more frequent maintenance, especially during the winter and the dry season [40]. Grass coverings and concrete grids use plastic, or metal to support and allow grass or other vegetation to grow through the gaps. Although their structural integrity allows them to support the weight of a vehicle better than conventional pavements, these materials are used more often in areas with minimal traffic so that vegetation damage, demand for parking spaces, and trails are minimized. Finally, those pavements may be more suitable for climates with sufficient humidity during the summer [32].

4.3.2. Current Research Directions in the Field of Permeable and Water-Retentive Pavements

Considerable research has been carried out to improve the thermal performance of permeable and water-retentive pavements. Below are the main features and results of the six main technological approaches to asphalt, concrete, and ceramic pavements that have been developed and tested.

a. *Use of water holding fillers made of steel by-products as an additive to porous asphalt*. Nakayama et al. [111] showed and tested a new water-holding pavement made of steel that was mixed into porous asphalt and used in permeable pavements with a porosity of 0.3. The average temperature of the pavement was found to be 0.6 °C lower than that of the porous asphalt, while the air temperature above the water-retentive pavement was found to be nearly 0.5 °C lower than that of the conventional porous asphalt. Although the immediate drop in temperature caused by conventional porous asphalt was greater than that caused by water-retentive pavement, the evaporation and cooling impact of water-retentive pavement continued for a longer period of time, with a maximum duration of about 3 days.
b. *Use of fine blast furnace powder in water-retentive asphalt*. Takahashi and Yabuta described the use on pavements of a blast furnace powder, which has been tested under real weather conditions on pavements for extended periods of time. As regards the thermal performance of the material in the third year, it was noted that its surface temperature was still 14 °C cooler than the temperature of a conventional asphalt pavement [112].
c. *Use of fine texture pervious mortar as an additive in pervious concrete*. In 2009, Aoki [113] studied a pavement of permeable concrete combined with a fine texture pervious mortar. *Mortar* is a mixture of cementitious materials, aggregates, and water that is used to improve the texture of permeable concrete's surface. The final composition had a modest water permeability (2 to 3 mm/s), and no data on the new material's thermal performance are available.
d. *Use of bottom ash and peat moss as additives in porous concrete*. Park et al. created and assessed a novel porous pavement utilizing bottom ash and peat moss in an experimental setting. Peat moss is a porous substance that acts as an absorbent, allowing heavy metals to be removed from aqueous solutions. Experimental comparisons were made between the created pavement and conventional asphalt and porous pavements. After rain, the proposed material's surface temperature was found to be 18 °C cooler than asphalt, with a maximum difference of about 9 °C between the proposed material's surface temperature and that of conventional porous pavement [114]. Additionally, it has been demonstrated that the addition of bottom ash and peat moss to porous concrete reduces surface temperatures by roughly 0.1 °C in comparison to asphalt mixtures [115].
e. *Use of fly ash with very narrow particle size distribution in bricks*. Cultrone and Sebastián examined bricks with and without fly ash and found the texture to be very similar. The results showed that the addition of fly ash particles with diameters ranging from 0.1 to 10 μm into the bricks can cause a reduction in the density and a significant improvement in the durability of the bricks [116]. Singh et al. estimated the possibility of the production industrial bricks. Porosity affects many properties of bricks, but the most important influence is their strength. They found that, as the percentage of fly ash content increases, so does the porosity. However, temperature reduction (from 1000 to 800 °C) had a greater effect on the porosity. The firing temperature

has a significant effect on the porosity of the composition, as the addition of fly ash increases the porosity of the brick significantly at both temperatures. The results indicate that adding fly ash up to 50% by weight improves the performance of sintered bricks at 1000 °C. The test findings indicate that the combination of clay and fly ash performs rather well due to their effective micro-filling capacity and pozzolanic activity. These bricks have a higher compressive strength and the added benefit of being lighter and more eco-friendly [117].

f. *Use of industrial waste as a raw material for ceramic tiles***.** Junkes et al. developed experimentally and tested the use of industrial waste as an alternative raw material for the manufacture of ceramic tiles. They demonstrated that their use could control the plasticity and shrinkage of the ceramic body without any negative impact on product properties, and that sintering can be performed at low temperatures, resulting in energy savings [118]. Instead of being disposed of in landfills, tiles can be used in highway engineering applications, reducing environmental impacts and increasing pavement thickness. The addition of waste tile particles improved the mix's California Bearing Ratio (CBR) performance from about 8% to 14%, which can result in a significant reduction in the design thickness of highway sidewalks. Cortes et al. used asphalt as a pavement material for the ground, and a water retentive pavement as material for the main street. The water retentive pavement can reduce significantly the surface temperature. When solar radiation was most intense, the surface temperature decreased by 13.8 °C. This decrease in the surface temperature also led to cooling of the air temperature at a height of 1.5 m above the street surface. The air temperature in a water retentive pavement was found to be 0.28 °C lower. The latent and sensible heat flux resulted in a maximum decrease of up to 255 and 465 W/m^2, respectively [119].

g. *Use of urban river sediments and clay as a primary raw material in the production of highly insulating brick*. The primary objective of Xu et al. study was to determine the feasibility of fabricating porous ceramic tiles with a high thermal insulation capacity using urban river sediments as the main source. To identify the most appropriate production procedure, urban river sediments and clays were mixed in various amounts and burned at various temperatures. The thermal conductivity of burnt bricks was lowered by at least 40% when compared to clay samples due to the creation of a highly porous structure. Compressive strength decreased as the sediment content of urban rivers increased. When the thermal insulation capacity was balanced against compressive strength requirements, bricks burned at 1050 °C with 50% urban river sediments demonstrated more beneficial characteristics and met the standards of GB5101-2003 fired common bricks. The leaching test findings established that fired bricks containing urban river sediments are environmentally friendly. As a result, urban river sediments are an excellent primary raw material for the manufacture of high-insulation bricks [120].

4.3.3. Experimental Testing and Thermal Performance of Water-Permeable Pavements and Water-Retentive Pavements

Numerous investigations on the thermal performance of permeable and water-retentive pavements have been conducted. Five experimental studies [114–118] compared the thermal performance of various types of permeable and water-retentive pavements with that of conventional pavements. The primary conclusion gained from the comparative evaluation of these five experimental projects is that the performance of permeable pavements is highly dependent on their design parameters and the experimental limitation conditions. The majority of the time, the results are rather contradictory. For example, Yilmaz et al. [121] and Buyung et al. [122] discovered that permeable concrete maintained a greater surface temperature during the dry season than conventional pavements. However, Liu et al. [123] concluded that, in the same warming environment, the daily maximum pavement temperature of surface permeable and fully permeable pavements in dry state is lower than that of non-permeable pavement by about 3.4 and 4.3 °C, respectively, and may be reduced by about 5.8 and 8.1 °C, respectively, in the water-retaining state. Compared with the surface permeable pavement, the daily maximum pavement temperatures of the fully permeable pavement in the dry and water-retaining states were about 1.3 and 1.8 °C lower, respectively, and the cooling effect was better than that of the permeable pavement [123]. At the same time, comparisons of the surface temperatures of water pavements and bituminous materials indicate that water permeable materials either have lower temperatures [74,124], nearly the same temperatures [118], or a higher temperature than asphalt [115].

Comparative experimental works are now briefly presented. The thermal performance of permeable pavements was compared experimentally and theoretically to that of conventional concrete pavements [104]. Permeable concrete was reported to have higher surface temperatures during the day, while maintaining the same temperature at night. It was also found that less energy was stored in permeable concrete, while the solar reflection was lower than conventional cement pavements for similar cement mixtures. Similar results were obtained by Kevern and Schaefer [125], Kevern et al. [115] and Haselbach and Gaither [126]. In all cases, permeable concrete showed higher surface temperatures than conventional concrete pavements; however, the temperature below the concrete pavement decreased rapidly.

Asaeda and Thanh [124] evaluated experimentally the thermal performance of different types of pavements. Porous paving blocks, asphalt, grass, and ceramic surfaces were all used as pavements. The maximum surface temperature of the porous paving block was reported to be 54.8 °C during noon, which was comparable to the asphalt's surface temperature. Simultaneously, the ceramic pavement and grass had a surface temperature of 44 °C. Additionally, the materials evaluated had a reflectance of 0.25 for a porous paving block, 0.08 for asphalt, 0.27 for grass, and 0.24 for a ceramic pavement. Finally, it was stated that the porous paving block's surface remained dry throughout the experiment, indicating that there were no evaporation losses.

Yamagata et al. tested the thermal performance of 16 different pavements both experimentally and theoretically. These pavements included conventional, porous and water-collecting, made of asphalt, concrete and perforated blocks, and interlocking materials. Grass and bare soils were also tested for comparison purposes. Grass and standard asphalt had the lowest and highest temperatures, with a maximum temperature gradient of 20 °C and 4 °C throughout the day and night, respectively. For all types of pavements, the reduction in sensible heat flow throughout the day and night was calculated when compared to standard asphalt. The bare soil's daily sensible heat was reduced by 270 W/m^2 and grass by 350 W/m^2. The sensible heat reduction was 280 and 180 W/m^2 for cement and interlocking materials, respectively. In the case of so-called cool pavements, the sensible heat reduction of porous and water-holding concrete was 100 W/m^2 as compared to standard asphalt, while the corresponding reduction in water-holding asphalt was roughly 140 W/m^2 [63].

Karasawa et al. tested experimentally the performance of 15 permeable pavements and water-holding concrete pavements. Among the pavements tested, four were permeable and 11 impermeable. Total experimental tests have shown that there is no correlation between the surface temperature and the permeability of paving blocks made of water-holding concrete. In terms of surface temperature, it was observed that water-retaining concrete paving blocks had a significantly lower surface temperature than dense asphalt pavements. When the asphalt pavement reached 56.1 °C, the surface temperature of the water-holding blocks was between 38.5 and 48.9 °C, a difference of 7.2 to 16.6 °C. Additionally, it was discovered that water-retaining pavements had a cooler surface temperature following the rain, with the temperature being cooler for eight days [74]. Liu et al. compared conventional pavements with permeable pavements experimentally and found that porosity and permeability were high enough for urban rainwater to quickly penetrate the road surface, reducing urban waterlogging [123].

Li et al. studied the thermal performance of permeable pavements. They investigated permeable pavements under dry and wet conditions. They found that, under dry summer conditions, the permeable pavement yielded a higher daytime surface temperature than the asphalt concrete pavement by approximately 5 °C. However, under wet summer conditions after watering, the results showed a lower daytime surface temperature by approximately 5 °C. The maximum ambient air temperature under wet conditions was about 3 °C higher than that under dry conditions [127]. Drainage from the asphalt pavement happened only during the night, but with permeable pavements, it occurred gradually over a 36 h period [128]. Flower et al. studied pervious block pavements and compared them with conventional asphalt pavements and impervious shaded pavements. They found that the permeable pavement reduced the daily surface temperature by 7 °C during the summer (between the hours of 12:00 and 18:00). Pervious concrete and shaded impervious pavements showed similar surface temperatures [129]. Water-holding pavements are mainly used in hot and humid climates where the availability of water is not a problem. The application of these pavements has gained great acceptance in countries such as the US, China, Australia, the UK, and Japan. Northern countries also apply these pavements, particularly in parking areas where the surface temperature of asphalt is slightly higher during summer, while surface temperatures above 20 °C appeared to occur 12% more frequently than on concrete pavements. Most large-scale projects were designed and implemented to resolve rainwater problems as well as mitigating the UHI and resolve the problem of design and restoration of parking areas, roads, and pavements. Unfortunately, most projects have not been tracked, and no performance data are available.

4.3.4. Water Availability on Permeable Pavements

Permeable and water-holding pavements require significant amounts of water for better performance. In hot and humid climates, rainwater is used to enhance evaporation, as shown in Table 1. However, in drier climates, reclaimed water (treated water effluent) or liquid waste are used, if available.

Table 1. Advantages and disadvantages of permeable and reflective cool pavements.

	Permeable (New)	Reflective (Maintenance)
Advantages	Improved air quality	Improved air quality
	Driving safety	Nighttime illumination
	Pollutant reduction	Improved sustainability related to traffic and transport
	Energy conservation	Social safety in dark rural areas
	Water conservation implications	High albedo
	Stormwater implications	Energy conservation
	Runoff reduction	Pavement durability
	Noise reduction of vehicular roadway traffic	Reduction of power plant emissions
Disadvantages	Smaller durability	Difficult installation
	High maintenance cost	Easy reflective cracking
	Limiting factors: climate, locally available materials	Additional time for removal of bitumen skin

The idea of spraying water-retentive pavements with reclaimed water to increase evaporation and reduce surface temperature has been extensively studied in Japan [130,131] and France [131]. In all cases, it was observed that by spraying water on pavements made of water-holding materials, the surface temperature was reduced significantly. Laboratory experiments which measured the evaporation performance of water-holding pavements, have shown that the surface temperature of these materials depends strongly on their water-holding and evaporation performance [132,133]. It was concluded that a water supply system is necessary in order to achieve lower surface temperatures.

Yamagata et al. described an extensive experimental application, where treated water waste was sprayed on water-holding pavements. The experiment was performed in the Shiodome district in Tokyo, Japan. It was reported that the water reduced the road temperature by 8.0 °C during the day, and 3.0 °C during the night. During the day, the surface temperature of the area sprayed with water was 37.8 °C versus 45.8 °C for the non-sprayed area. The corresponding surface temperatures during the night were 28.8 °C and 31.8 °C respectively. When the spraying took place only during the day, it was observed that the water-holding pavement showed a lower surface temperature, even in the next night. Sensible heat losses were also calculated, and water spraying was found to reduce the sensible heat flow by almost 30%. The daytime sensible heat flow was 154 kJ/m^2 in sprayed areas and 456 kJ/m^2 in unsprayed areas. During the night, the corresponding flows were 16 kJ/m^2 and 62 kJ/m^2 [63].

4.4. Technologies of Cool Pavements with New Construction

There exist different strategies that may be used for the construction of new pavements, based either on increasing reflectivity or promoting cooling through evaporation. Such strategies use different materials and techniques than traditional methods. Some of these techniques have environmental benefits, reduce pavement temperature, and use less hazardous binders, resulting in less effluent erosion.

4.4.1. Modified Mixtures of Asphalt and Concrete

a. *Conventional asphalt pavements*. The most frequent type of pavement surface is conventional asphalt. It can be swiftly and readily installed, and it has a wide range of uses, including low-volume parking lots, high-traffic highways, and airport runways. Asphalt pavements can last for many years with correct design and upkeep. Asphalt pavements can also be recycled and processed to create new pavements. However, standard asphalt pavements often have a low albedo due to their black and impermeable surface, making them susceptible to absorbing and storing solar radiation heat. As a result, the asphalt's maximum surface temperature can reach 120 to 150 °C [81]. They are made up of an asphalt binder and aggregate that can be amended with high-reflectivity materials. For decades, this material has been employed in a variety of parking lots and highways [32,40]. Due to oxidation of the binder, traditional asphalt pavement will often fade in color as it ages. Asphalt concrete has an albedo of around 0.05 to 0.10 when it is first installed, and it rises to about 0.12 to 0.18 after six years [32]. Asphalt pavements can be built using high albedo materials or built traditionally and then improved with a surface treatment or coating to increase surface reflection. Light colored aggregate, paint pigments, sealants, and other high albedo materials can be utilized in the main construction. In a recently laid pavement, the use of light-colored materials was able to improve albedo by 0.15 to 0.20 [40]. Chip and sand sealing with light-colored aggregates, surface coating, and grinding (if light-colored aggregates are used) are all treatments that can be used after installation as a preventive maintenance activity while also enhancing solar reflectivity [81].

b. *Roller Compacted Concrete (RCC)*. RCC is a mixture specially shaped and positioned using a specific method. It contains a very hard mixture placed with the techniques and equipment used for asphalt pavements. The result is a strong pavement, with a smoother surface than conventional concrete pavement. It is used for heavy-load trucks and high-speed motorways, large-volume storage areas, automotive and military installations, and warehouse floors. Although some of its surface parts may become eroded over time, RCC is economical, with an initial cost lower than ordinary concrete [32] and in many markets competitive with asphalt concrete. RCC generates a natural-looking pavement by absorbing the color of the added gravel or sand. A lighter-colored RCC, like conventional concrete, has a high albedo [81].

c. *Conventional Portland Cement Concrete (PCC)*. These pavements are made of blending Portland cement with water and aggregates and may be used in a wide range of applications, including pavements and parking areas. Conventional PCC pavement has been proposed as a cool pavement because of its light color and reflection. It is used in new constructions and reconstructions [32]. Recyclable materials, such as fly ash and metal extracts [45], are used mixed with concrete in order to improve the reflectivity. The degree of surface reflection is affected both by the color of the cement and by the type and color of the aggregate, particularly because the cement surface is damaged, and the aggregate is exposed [32]. However, some satellite photographs of various types of pavements in a metropolitan area show promising results in terms of being used as cool pavements.

d. *Light gravel on pavement of asphalt concrete (ACP)*. ACP reflectivity may be reduced by using a light aggregate, such as limestone. This type of aggregate is available as a natural resource in countries such as the US (e.g., Houston and Florida) and it is used in the construction and reconstruction of conventional pavements, with a zero incremental cost. Elsewhere, however, the transportation cost of this aggregate is very high, and this method is perhaps not economically advantageous [32].

e. *White cement* is similar to the gray cement used in conventional concrete except that it is lighter in color. This is generally accomplished by reducing the iron content of the raw materials used to make cement. Because iron is a fluxing material, changing it raises the temperature at which cement must be processed, increasing both the cost of production and the emissions connected with it. The only significant difference is that white cement is more expensive than gray cement, despite the fact that the cement's strength and behavior, as well as the time it takes to set and acquire strength, are all similar. White cement concrete has, on average, substantially higher reflectivity than gray cement concrete. Depending on the phase of exposure, the albedo of the most reflective white-cement concrete was 0.18 to 0.39 higher than that of the most reflective gray cement concrete [40,81].

f. *Texturing/grouting of open-graded course with cementitious materials*. Texturing is the process of laying asphalt, compacting it into a pattern, and then covering it with a polymerized cement coating. Salviacim and Densiphalt+D99 are semi-rigid procedures that *combine* open-graded asphalt concrete with a high-strength cementitious grout to fill gaps of between 20% and 25%. The grouted surface should have a comparable reflectivity to concrete. Additionally, densiphalt is beneficial for avoiding gasoline leaks and improving abrasion and rutting resistance [41,81].

g. *Gritting with light-colored aggregates*. Surface gritting entails strewing light-colored particles *over* freshly poured hot mix asphalt (HMA) and rolling it down. Surface gritting can improve surface friction while also lightening the color of asphalt (thus skid resistance). Grit may be kicked up off the road by vehicle traffic after gritting an existing asphalt pavement, creating danger. While surface gritting may be a viable method, more research is needed to determine whether the construction process results in uncoated lightly colored aggregate adhering sufficiently to the asphalt surface [41,81,134].

h. A clear tree resin replaces the traditional black petroleum-derived asphalt binder in *resin-based* pavements. Pure resin forms an inert aggregate when it bonds with a petroleum chemical element (C_2I_{2n}) on any part of the coating [43]. As a result, the pavement can take on the natural appearance of the various materials that were used in the mix. Resin-based pavements can be brighter and have higher solar reflectance than typical asphalt pavements because the pavement takes on the color of the particles (if light colored aggregates are used). Hiking and bicycle trails have traditionally employed resin-based pavements. Aside from resin-based pavement, light-colored aggregates can be bound with a variety of colorless and reflecting synthetic binders. These are commonly utilized as surface courses in sports and leisure activities [41,81].

i. *Titanium dioxide* (TiO_2) in certain forms can act as a photocatalyst. Ballari et al. conducted a study in which they used it on a concrete paving stone in order to reduce nitrogen oxide (NO_x) pollutants. A heterogeneous kinetic expression was suggested for the degradation of nitrogen monoxide, and for the appearance or disappearance of nitrogen dioxide [135]. Lee et al. conducted an experiment in order to eliminate NO_x air pollutants. The photocatalytic reaction of titanium dioxide is a mechanism by which the elimination of NO_x air pollutants may be achieved, and it is necessary to use ultraviolet (UV) rays and TiO_2 in the concrete. Titanium dioxide may be applied to existing roads made from concrete blocks, to reduce NO_x. The study showed that concrete pavements containing titanium dioxide with surface penetration agents at an uptake of 500 g/m^2 reduce airborne NO_x by 50% for an L-type side ditch and interlocking blocks of concrete [136]. Investigations into the runoff from photocatalytic surfaces are currently underway [80].

4.4.2. Use of Solar Pavements

Recent research has examined the use of photovoltaics on pavements. Photovoltaic coatings integrated in a ceramic substance that allows for walking are among the new pavement innovations. If their surface temperature is adequate, photovoltaic pavements can generate power, save space, and aid in mitigating the effects of UHI. Preliminary studies from the summer of 2012 in Athens (Greece) indicate that photovoltaic pavements may have a surface temperature 3 to 5 °C lower than traditional concrete pavements [37,43]. Photovoltaic pavements can be used to charge electric automobiles on the road or to supplement the electricity provided by the vehicle while driving, resulting in smaller and lighter batteries.

5. Conclusions and Policy Considerations

Along with other advancements in the transportation sector that have led to reduced vehicle energy consumption [137], the primary reasons that energy efficient pavements are welcomed are to minimize energy consumption and increase road safety. The European Union's policymakers are currently very interested in energy-efficient pavements and the role they can play in the development of sustainable cities. The energy intensity of passenger cars has decreased significantly in some countries (such as Greece), from 1.9 MJ per passenger-kilometer (pkm) in 2000 to 1.1 MJ/pkm in 2014 [137].

On the other hand, the business community is keenly interested in comparing and monitoring different types of pavements. Competition among pavement manufacturers is welcomed by EU member states, as it has the potential to save millions of euros in public funds. Despite this interest and benefit, public road authorities have resisted specifying specific pavement types. This is a result of tradition, a lack of experience, and a lack of willingness to change. Nonetheless, stimulating competition in the market for cool pavements should not be difficult. Public procurements, cool pavement performance evaluations, and the life cycle assessment can all be used to determine the best pavement for a given application. This would make efficient use of taxpayer funds (thereby increasing public spending efficiency) and contribute to the reduction of millions of tons of carbon dioxide, meeting the EU's greenhouse gas reduction targets for roads.

Asia is the current urbanization hotspot, having surpassed the industrial era of North American cities, with China and India having the largest urban expansion areas [138]. China in particular is the global leader and dominates urbanization trends [139]. In China, urban land and urbanization rates have risen rapidly, fueled by periods of real estate boom and prompted by regional development policies, urbanization guidelines, and national reform and opening-up policies. Over the next 30 years, China is likely to experience massive urbanization. Six of the world's thirty-six megacities (16.7%) with populations over 8.9 million people are already located in China [140], typifying new urbanization patterns [138].

The twenty-first century has emphasized the sustainability of urban development [139]. Sustaining socioeconomic development and promoting environmental quality are viewed as critical components of China's future urban development. The goal is to achieve a win–win situation by promoting economic development and improving urban environments [139]. In this spirit, China has been transitioning to a more environmentally friendly mode of development in order to meet the United Nations' 2030 development goals for sustainable cities and communities. There is concern that, like many urban areas, Chinese cities are plagued by uneven development and environmental is-sues. As urbanization increases the imperviousness of surfaces, hydrological processes and energy exchanges with the atmosphere are altered, exacerbating UHI and flood disasters [138]. Geopolitical concerns are related to urbanization and how it may even jeopardize food security by encroaching on prime cropland, resulting in habitat and biodiversity loss [138]. Additionally, the Belt and Road initiative is likely to reshape urban land in countries along its land and sea routes [139].

Countries such as the United States of America, Canada, the Netherlands, and Poland have already implemented Market Pull (MP) and Policy Push (PP) tools, such as appropriate legislation, alternative bid contracts, and appropriate decision support tools. These allow for the consideration of costs, environmental impacts, and other factors in advance, leading to the formation of public–private partnerships (PPPs) that foster healthy competition. Additionally, EU policymakers and business stakeholders are currently very interested in the use of cool pavements for a variety of reasons, including road safety and energy efficiency. On the other hand, Urban land change knowledge gaps exist in low-income countries, particularly in the Global South [141].

Significant research has been conducted on novel technologies, materials, and systems with the goal of mitigating adverse conditions, such as the UHI effect. Among other strategies for mitigating the UHI effect, targeting urban structures, such as buildings and pavement surfaces, has been suggested. According to Akbari and Matthews, increasing the albedo of urban roofs and paved surfaces on a global scale will result in a negative radiative forcing equal to 44 Gt of carbon dioxide emissions [47]. By significantly lowering urban air temperature, cool surfaces (roofs and pavements) and urban trees can help reduce cooling load and pollution. Around 20% of cooling demand could be saved by implementing UHI mitigation strategies on a large scale. This translates into annual cooling electricity savings of 40 TWh, or more than $4 billion by 2015 [32].

While cool pavements help to cool the surface air, increased radiation may have a negative effect on thermal comfort and building cooling loads. The absence of detailed re-search results demonstrates the importance of conducting local, unique case simulations and analyses, as well as accounting for factors, such as building geometry, albedo materials, and vegetation. Recent years have seen researchers investigating pavement technologies' optical and thermal properties, as well as their potential impact on urban climate.

There are three key outcomes that could be discussed in the future: (i) pavements are complex, with numerous parameters affecting their reflectivity and heat retention; (ii) un-like cool roofs, cool pavements are affected by both optical and thermal properties; and (iii) pavements with a variety of design specifications and materials serve a variety of purposes. Current research focuses on the use of high-reflective white coatings; infrared reflective dyes to increase the albedo of the pavement surface; reflective colors to increase the reflectivity of pavement components; and dye-changing to achieve better year-round thermal performance in the development of highly reflective pavements. The albedo achieved in laboratory testing can be very high, while the surface temperature of the coating materials can be reduced by up to 20 K.

Numerous evaluations of newly discovered reflective materials and processes have been conducted. Regrettably, only a few of these projects are being closely monitored to accurately document the anticipated benefits of widespread use of reflective pavements. It is critical that various large-scale initiatives evaluate and test all aspects of altering the local microclimate, as well as potential consequences for thermal comfort and energy consumption. Permeable pavements are better suited to wet and rainy areas.

Current research objectives are primarily concerned with the incorporation of materials into the mass of road surfaces (such as steel biofuel, blast furnace powder, fly ash, and industrial waste). Additionally, research aims to improve the capillary capacity of pavements in order to increase water content and material evaporation.

Cool pavements can make a significant contribution to ambient temperature reduction in the urban environment. Experimental evidence indicates that the new generation of permeable pavements has a significantly lower surface temperature than conventional permeable materials. However, the thermal performance of water permeable and water-retentive pavements is largely dependent on the availability of water.

Applications of permeable and water-retentive pavements are characterized by limited scientific information on their thermal performance. While the research results re-viewed in this work indicate that significant advances have been made in the laboratory for cool pavements, it is also widely accepted that the implementation of cool pavements in urban areas with UHI must be expedited. Additionally, it is noted that the development of new cool pavements has remained stagnant in comparison to the maintenance and replacement of existing ones. This is primarily due to public authorities' reluctance to adopt innovative cool pavements.

If a technological revolution aimed at achieving sustainability through innovation is viewed as a feasible and advantageous path out of economic and systemic crises, it should be pursued not only technologically and economically, but also in terms of governance and culture [141,142]. The application of processes and tools, such as public procurement, cool pavement life cycle analysis, and performance monitoring, could all contribute to a more complete picture of new pavements as an appealing solution, particularly among public adopters and the growing cool pavements market.

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