Quantifying Effects of Urban Heat Islands: State of the Art

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Abstract. Recently, the world has been suffering from the distressing effects of one form of climate change, urban heat island (UHI). It means that urban and suburban areas' air and surface temperatures are hotter than their nearby surrounding rural areas. Pavements and parking lots contributes to about 29% to 45% of the urban areas, and they contribute to the UHI phenomena. During the day, temperature of dark dry surfaces (such as pavements and parking lots) in direct sun can reach up to 88 °C while vegetated surfaces with moist soils might reach only 18 °C under the same conditions. The increase in temperature due to UHI leads to an increase in the peak energy demand using more air conditioners and raising the energy bills. It also leads to an increase in the levels of greenhouse gas emissions (global worming) and air pollution. Increased daytime temperatures, reduced nighttime cooling, and higher air pollution levels related to UHIs affects human health as they lead to general discomfort, respiratory difficulties, heat cramps, and exhaustion. UHI has great and direct effects on the environment, on people and on the human health, on energy consumption and on the economy, and on the pavement performance. The factors that affect the formation and intensity of UHI are versatile in nature. These factors vary between geographic location, time of day and season, synoptic weather, city size, city function and city form. The last two factors are the factors which can be controlled in order to mitigate UHI. Recent studies showed more interest in analyzing and quantifying the UHI phenomenon with more focus on the mitigation techniques. It is abundantly clear that there must be strategies to measure, model and control the phenomenon and achieve one of the Sustainable Development Goals, namely; sustainable cities and communities. The primary focus of this concise, yet comprehensive state of the art paper is to present the different technologies to mitigate the urban heat island. This study presented the different UHI definitions, causes, evaluation methods, and finally compared between the different mitigation techniques and set recommendations and guidelines based on a comprehensive literature review.

Keywords: Albedo · Absorptivity · Emissivity · UHI · UBL · UCL · Cool pavements · UHI mitigation · Cool roofs · Green buildings

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1 Urban Heat Island-Background

In 1954, 30% of the world's population lived in urban areas, while in 2014, this number increased to 54%, and by 2050, 66% of the world's population is projected to be urban, with a much higher fraction (82%) in the more developed countries [1]. One of the results of such high urbanization is that urban areas exhibit the clearest signs of inadvertent climate modification. The term "heat island" or "reverse oasis" describes the phenomena where urban and suburban areas' air and surface temperatures are hotter than their nearby surrounding rural areas [2–9]. This is depicted in Fig. 1. The first documentation of Urban Heat Island (UHI) was by Luke Howard, 1818, when he found an artificial excess of heat in London city compared to the surrounding Country [10]. The phenomenon is well documented in many metropolitan areas around the world [8, 11–28]. The annual mean air temperature of a city with 1 million people or more can be 1.8–5.4 °F (1–3 °C) warmer than its surroundings. In the evening, the difference can be as high as 22 °F (12 °C) [29]. Generally, the differential warmth of the urban atmosphere is a function of the population of the city [12, 28, 30].

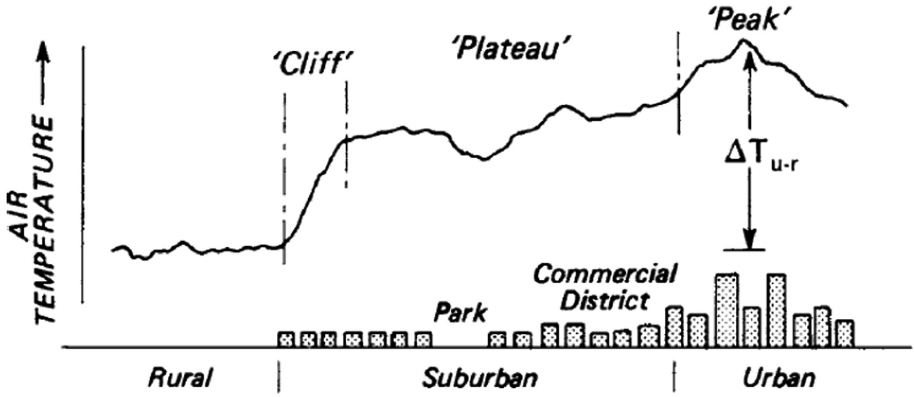

Fig. 1. Generalized cross section of a typical urban heat island [3]

Heat islands are classified into surface heat islands and atmospheric heat islands [31]. They differ in the ways they are formed, the techniques used to identify and measure them, their impacts, and to some degree the mitigation techniques. Table 1 summarizes the basic characteristics of each type of heat island [31].

One has to distinguish between two layers of the atmospheric urban heat island. The first layer termed the ***urban canopy layer*** (UCL) consisting of the air contained between the urban buildings in the layer of air where people live, from the ground to below the tops of trees and roofs. The second layer, situated directly above the first and called the ***urban boundary layer*** (UBL) and it starts from the rooftop and treetop level

Table 1. Basic characteristics of surface and atmospheric urban heat islands [31]

Feature	Surface UHI	Atmospheric UHI
Temporal development	• Present at all times of the day and night • Most intense during the day and in the summer	• May be small or non-existent during the day • Most intense at night or predawn and in the winter
Peak intensity (Most intense UHI conditions)	• More spatial and temporal variation: Day: 18 to 27 °F (10 to 15 °C) Night: 9 to 18 °F (5 to 10 °C)	• Less variation: Day: −1.8 to 5.4 °F (−1 to 3 °C) Night: 12.6 to 21.6 °F (7 to 12 °C)
Typical identification method	• Indirect measurement: Remote sensing	• Direct measurement: Fixed weather stations Mobile traverses
Typical depiction	• Thermal image	• Isotherm map • Temperature graph

and extend up to the point where urban landscapes no longer influence the atmosphere [31, 32]. Canopy thermal climate is governed by the immediate site character (building geometry and materials), and not by the accumulation of thermally modified air from upwind areas [33]. All of the urban heat island layers are illustrated in Fig. 2.

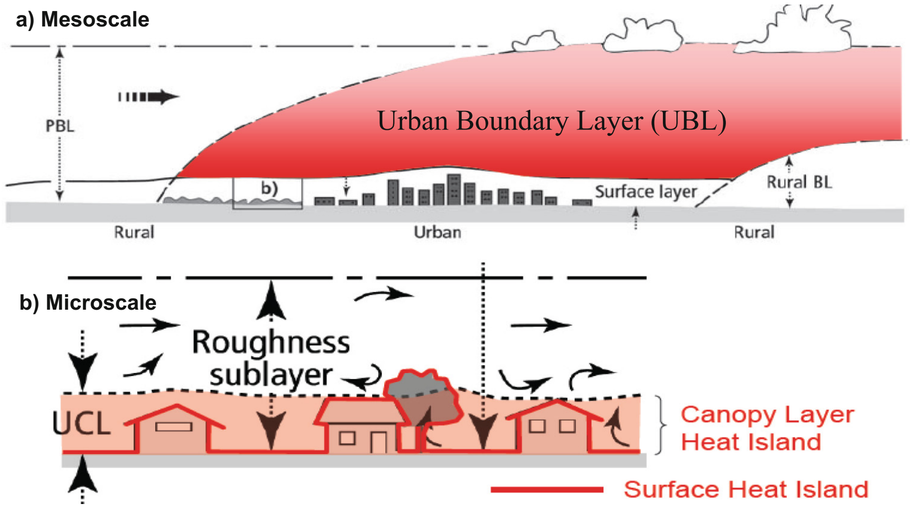

Fig. 2. Schematic representation of surface heat island, the urban canopy and urban boundary layer [34]

2 Urban Heat Island (UHI) Measuring Techniques and Modelling

Urban heat islands may be identified by measuring surface or air temperatures. Surface temperatures have an indirect but significant influence on air temperatures. UHIs have long been studied by ground-based observations taken from fixed thermometer networks or by traverses with thermometers mounted on vehicles. With the advent of thermal remote sensing technology, remote observation of UHIs became possible using satellite and aircraft platforms [32].

Air Temperature Measurements
Air temperature measurements are used to quantify UCL heat island and UBL heat island. Measurement devices could be fixed, traverse, or remote. UCL can be detected by in situ sensors at standard (screen-level) meteorological height or from traverses of vehicle-mounted sensors. The measuring devices could be fixed at weather stations, or traverse using hand-held measurement devices or mounting measurement equipment on cars [32, 34]. Urban Boundary Layer (UBL) heat island observations are made from more specialized sensor platforms such as tall towers, radiosonde or tethered balloon flights, or from aircraft-mounted instruments. These direct in situ measurements require radiation shielding and aspiration to give representative measurements and their setting relative to surrounding features is important [32]. In recent boundary layer studies, remote reading instruments are used to avoid interference with the environment being sensed [3, 35, 36].

Surface Measurements
All surfaces give off thermal energy that is emitted in wavelengths. Instruments on satellites and other forms of remote sensing can identify and measure these wavelengths, providing an indication of temperature. Measurements of surface temperature were used to be done using in situ thermocouple or thermistor thermometry to estimate surface temperatures. An alternative is to use infrared radiometry, where instruments indirectly estimate an apparent surface temperature based upon the radiance received from that area of the surface [37].

Thermal remote sensors observe the surface urban heat island (SUHI), or, more specifically they ‘see’ the spatial patterns of upwelling thermal radiance received by the remote sensor [32]. Figure 3 illustrates the different measuring techniques for each layer. Figure 4 exemplifies remote sensing images of both Phoenix and Washington DC.

The first SUHI observations (from satellite-based sensors) were reported by [38]. Since then, a variety of sensor-platform combinations (satellite, aircraft, ground based) have been used to make remote observations of the SUHI, or of urban surface temperatures that contribute to SUHI over a range of scales [25, 39–52]. However, surface measurements taken by remote sensing have several limitations. First, they do not fully capture radiant emissions from vertical surfaces, such as a building walls, because the equipment mostly observes emissions from horizontal surfaces such as streets, rooftops, and treetops. Second, remotely sensed data represent radiation that has traveled through the atmosphere twice, as wavelengths travel from the sun to the earth as well as from the earth to the atmosphere. Thus, the data must be corrected to accurately estimate surface properties including solar reflectance and temperature [35].

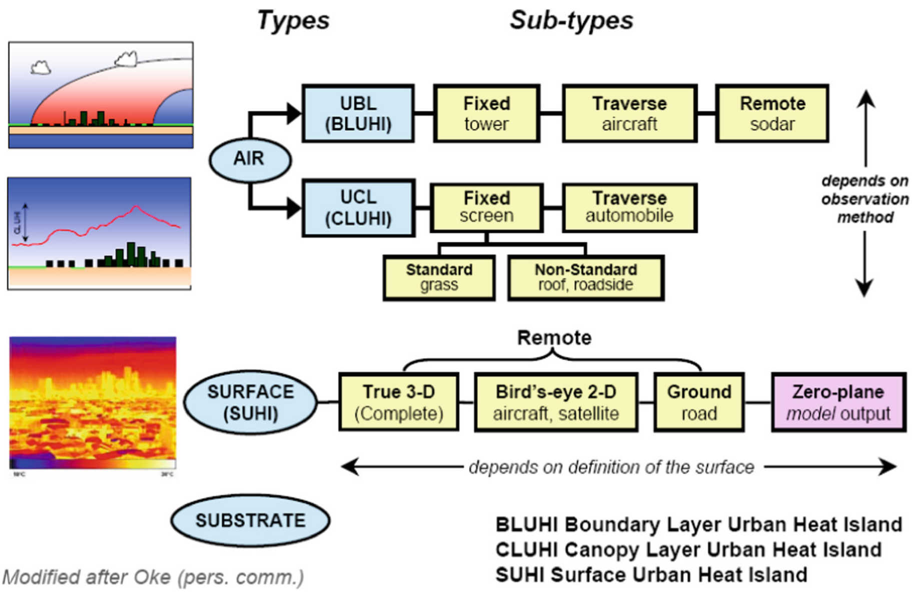

Fig. 3. Urban heat island various measuring techniques [34]

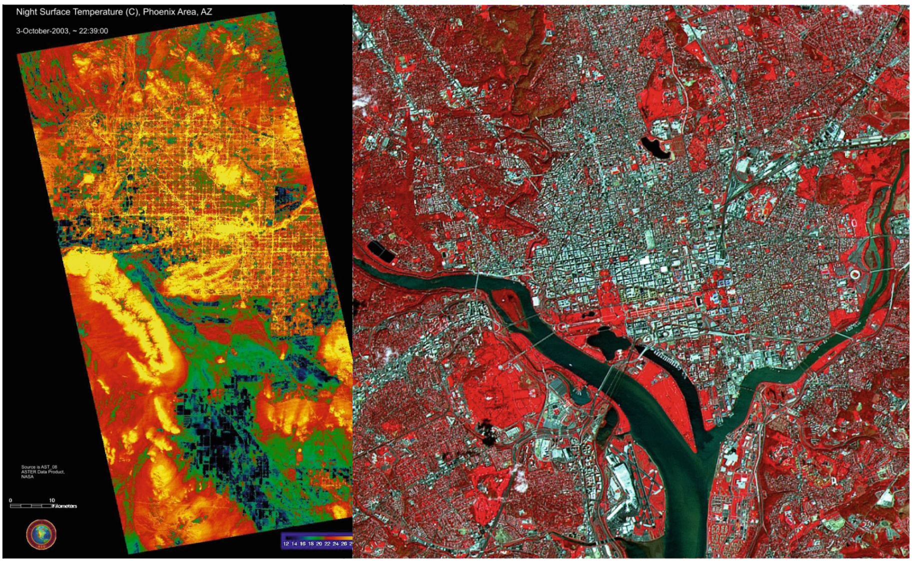

Fig. 4. Remote sensing Image of (1) Phoenix, Arizona, 3 October 2003 11:00 pm to the left, (2) Washington D.C 1 June 2000 to the right via NASA [53, 54]

3 Urban Heat Island-Causes

3.1 Thermal Properties of Urban Materials

In order to understand the causes of Urban Heat Island (UHI) and its mitigation techniques, it is important to study the thermal behavior of urban materials. This requires understanding of the key thermophysical properties of matter that govern thermal phenomenon. These properties can be divided into two distinct categories: (a) heat transfer through a system, (b) thermodynamic or equilibrium state of a system [55]. Heat transfer, can occur by means of radiation, conduction and convection. Heat transfer properties of materials relating to radiation include absorptivity (α_{abs}), albedo (β) and emissivity (ε).

Solar Energy and Absorptivity

About 45% of the solar energy radiates at wavelengths in the visible spectrum, (nominally between 0.3 and 0.7 μm). Also, note that only a little more than 1% of the sun energy at shorter wavelengths (UV and X-solar radiation) and the rest (54%) is in the infrared (IR) region [56]. Radiation energy from sun is either reflected or absorbed. Absorbed energy is then conducted deeper, emitted as radiation, or transferred to air near the surface by convection [57]. Solar energy is a major contributor to the formation of the UHIs. Pavement surfaces will absorb portion of the sun's solar radiation. Thus an increase in the thermal energy occurs. The rate at which radiant energy is absorbed per unit of surface area is dependent on the absorptivity (α_{abs}), *where* $0 \leq \alpha \leq 1$.

Solar Reflectance (Albedo, β)

The rate at which energy is reflected by the surface is known as the albedo (β) of the surface. Albedo is simply ($1 - \alpha_{abs}$) where α_{abs} is the absorptivity of the surface. It takes into account the full spectrum of solar radiation and not just those in the visible range [58, 59]. The albedo of pavement surfaces differs greatly by the materials used in construction. Its values range between zero (complete absorption) and one (complete reflectance). From a climate change perspective, albedo is the first line of defense a surface has against incoming solar radiation. It is regarded as the most important factor in the mitigation of the UHI effect [60]. Reasonable increases in urban albedo can

Table 2. Comparison of the albedo of different surfaces [62–64]

Material type	Albedo
Asphalt	0.05–0.10 (new)- 0.10–0.15 (weathered)
Gray portland cement concrete	0.35–0.40 (new)- 0.20–0.30 (weathered)
White portland cement concrete	0.70–0.80 (new)- 0.40–0.60 (weathered)
Green grace	0.25
Black soil	0.13
Bare soil (Land)	0.17
Desert sand	0.40
Cool pavement coatings	+0.50

achieve a decrease of up to 2 °C to 4 °C in air temperature [61]. Table 2 compares the typical ranges of the albedo for different pavement surfaces [62, 63].

A comparison of the Albedo values of different materials that can be found in the downtown of an urban area is shown in Fig. 5.

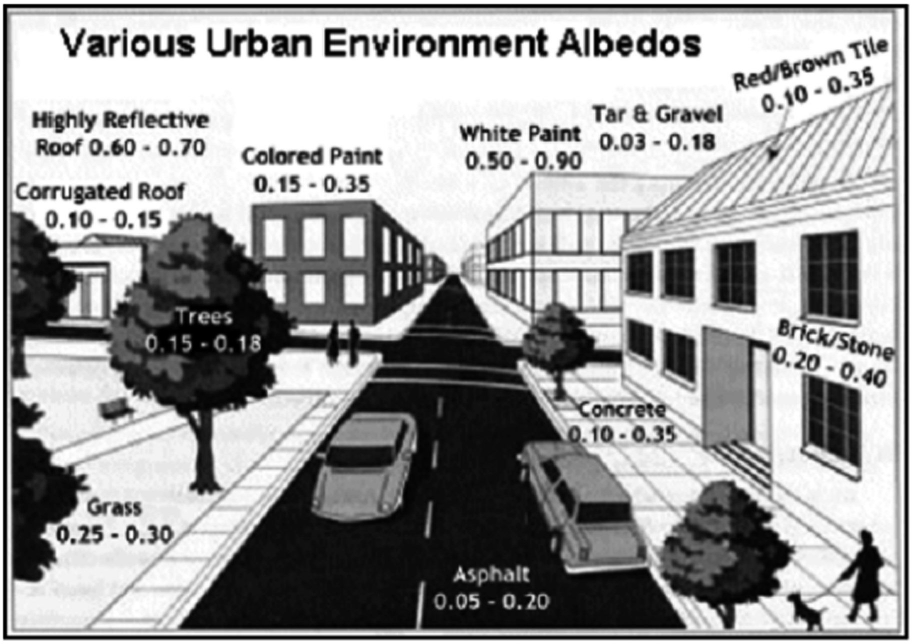

Fig. 5. Albedo of different materials in downtown an urban area [60]

A recent study conducted at Lawrence Berkeley National Laboratory, showed that a 0.1 increase in albedo reduces the pavement temperature by about 4 °C ± 1 °C while a 0.25 increase in the pavement albedo will cause a significant decrease in the pavement temperature by about 10 °C [65].

Emissivity (ε)

Emissivity (ε) is a radiative property of the surface *w*ith values in the range $0 \leq \varepsilon \leq 1$. This property provides a measure of how efficiently a surface emits energy relative to a blackbody. It depends strongly on the surface material and finish [55, 65]. Most pavement materials have high emittance values which contributes to the UHI [66].

Representative values of construction materials emissivity as reported in published articles and their validated field measurement values are illustrated in Table 3, [67].

Table 3. Field validation of emissivity [67]

Material	Published emissivity emissivity	Field trial results
Asphalt paving	0.967–0.970	0.95–0.971
Concrete	0.93–0.97	0.90–0.98
Brick	0.93	0.94

The absorptivity and emissivity of a surface are independent of each other as illustrated in Fig. 6 [57].

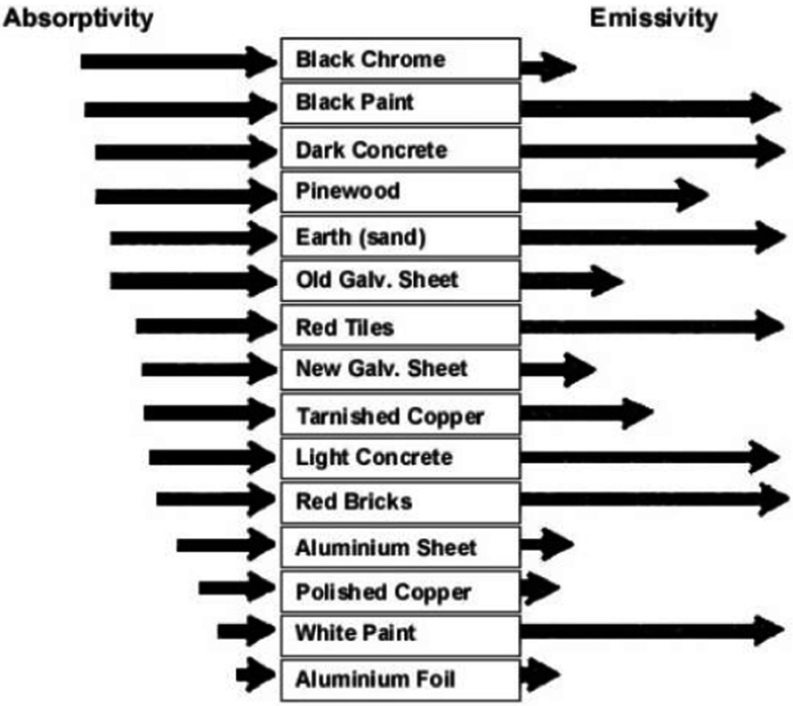

Fig. 6. A visual representation of the magnitudes of absorptivity and emissivity for common building materials [57].

Heat Capacity

Heat capacity or (thermal capacity) specifies the amount of heat energy required to change the temperature of an object by a given amount. It can be calculated as follows [68]:

$$C = \frac{\Delta Q}{\Delta T}$$

Where:

C = heat capacity, in joules per kelvin (J/k)
ΔQ = change in the amount of heat in joules
ΔT = change in temperature in kelvins.

It is more common to report the heat capacity as function of a unit mass such as joules per gram per kelvin (j/g.k). This is called the specific heat capacity (Cp) which is widely used in thermal analysis. Unlike natural materials such as soils and sand, pavements can store more heat. The high heat capacity of the pavement materials contributes to UHIs at night when they resale the stored heat. A comparison of the specific heat capacity values of different materials and natural soil is represented in Table 4 [69].

Table 4. Typical values of specific heat capacity of different materials [69]

Material	Specific heat capacity (j/g.k)
Asphalt	0.92
Concrete	0.88
Granite	0.79
Sand	0.835
Soil	0.80

Thickness

The thickness of a pavement is an important factor affecting how much heat the pavement will store. Of course, thicker pavements store more heat. Thinner pavements will heat faster in the day while cool more quickly at night. A recent study showed that there exists a critical layer thickness at which the maximum surface temperature is optimized (i.e. the maximum surface temperature reaches its lowest point). Pavement thickness greater than this optimum will lead to higher maximum and minimum surface temperatures [70].

3.2 Heat Transfer Models of Pavement Materials: Basics and Principles

Selecting the appropriate paving materials not only ensure stability and safety for road users, but also the ability to mitigate heat absorption and high surface temperatures contributing to the UHI effect and human comfort. In order to select the optimum pavement materials for UHI mitigation, it is also important to understand, study, and develop accurate models for the heat transfer through pavement materials. Literature search has shown that there are several models available [58, 71–79]. In general, heat transfer models predict the surface temperature as well as the temperature profile of the pavement as a function of the climatic data such as (air temperature, wind speed, relative humidity, solar radiation) and material properties such as (albedo, emissivity, aerodynamic roughness, thermal diffusivity, and specific heat of the pavement layer, and thermal diffusivity of the sub-grade and base layers.

3.3 Causes of Urban Heat Island

Several factors contribute to the creation of UHIs. Among these factors reduction of vegetation in urban areas and the solar reflectivity of urban materials are the two primary key factors affecting the formation of UHIs. These two factors are given more attention because unlike other UHI factors, the technology to mitigate them is available via cool roofs and cool pavements. Other factors to consider in the formation of UHIs are heat trapping (heat stored and re-radiated) by urban geometry, the properties of urban surfaces, weather, and geographical location, human-caused (anthropogenic) heat input from transportation and industrial processes [2, 22, 80]. These factors could be classified as controllable and non-controllable factors as illustrated in Fig. 7 [80].

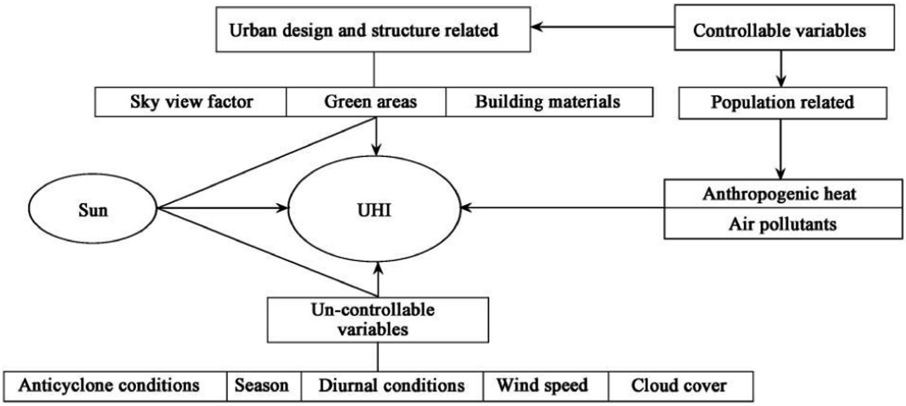

Fig. 7. Generation of urban heat island (UHI) [80].

The UBL can be heated from below as a result of anthropogenic heat input and the formation of UHI in the urban boundary layer (upper part of the UHI) could be due to:

- The slow decline of turbulent sensible heat flux in the late afternoon and evening, and its failure to turn negative at night (unlike rural areas).
- The large release of sensible heat from storage in the urban system in the late afternoon and evening.

There are some features or properties in the Urban Canopy Layer (UCL) and the Urban Boundary Layer (UBL) that could cause positive thermal anomaly due to energy alteration, some of these properties and their consequences are illustrated in Table 5 [81].

Table 5. Suggested "Causes" for the canopy layer and urban boundary layer heat islands (not in rank order) [81]

Altered energy terms giving a positive thermal anomaly	Urban properties underlying energy balance changes
Urban Canopy Layer (UCL)	
1. Increased solar absorption 2. Increased long-wave radiation from the sky 3. Decreased net long-wave radiation loss 4. Anthropogenic heat 5. Increased storage of sensible heat 6. Decreased evapotranspiration 7. Decreased total turbulent heat transport	Canyon geometry - greater surface area and 'trapping' by multiple reflection Air pollution - greater infra-red absorption and reemission Canyon geometry - smaller sky view factor Buildings and traffic - heat output Building/paving materials and larger surface area - greater thermal admittance Building and paving materials - surface 'waterproofing' Canyon geometry - increased wind shelter
Urban Boundary layer (UBL)	
1. Increased absorption of short-wave radiation 2. Anthropogenic heat 3. Increased sensible heat flux from below 4. Increased sensible heat from above	Air pollution - increased absorption by aerosol and gases Chimneys and stacks - heat output UCL heat island - greater heat flux from roofs and street canyons if warmer than UBL air Rough, warm city - increased entrainment from capping inversion

3.4 Modeling of Urban Heat Island Phenomenon in Relation to Pavements

Several attempts have been made to model the phenomenon of Urban Heat Island. Different modeling techniques have been used to model this phenomenon by predicting the asphalt pavement temperature profile. Table 6 shows some examples of these attempts.

4 Urban Heat Island (UHI) Negative Effects

The field of UHI has become highly interesting for scientists and engineers due to its adverse environmental and economic impacts on the society and promising benefits associated with mitigating high heat intensity [80]. Warmer air temperatures due to UHI lead to several adverse effects on people, environment, economy, and even on flexible pavements.

4.1 Negative Effects on the Environment

UHI negative environmental effects in summer are becoming increasingly undebatable, such as the deterioration of the pedestrian-level thermal comfort and the acceleration of

Table 6. Urban heat island modeling techniques

Model type	Output	Case study (Place)	Duration	Inputs	Ref.
3D finite element model	Asphalt pavement temperature	Northeast Portugal	4 months (December 2003 to April 2004)	1. Hourly solar radiation 2. Air temperature 3. Mean daily wind speed	[72]
One dimensional mathematical model	Asphalt pavement temp. profile	Various regions in US&Canada	–	1. Max. air temperature 2. Hourly solar radiation	[75]
One-dimensional mathematical model	Asphalt pavement near surface temperatures	Phoenix, Arizona	3 days	1. Hourly measured solar radiation 2. Air temperature 3. Dew-point temperature 4. Wind velocity data	[58]
Two-dimensional finite-difference model	Asphalt pavement temp. fluctuations	239 stations validated by field data of Alabama	12 month of Data files of 30 Years from 1961 to 1990	1. Climate conditions 2. Thermal and radiative properties of asphalt mixes 3. Surface convective conditions and geometry 4. Solar irradiation	[78]
One-dimensional finite-difference model	Surface temperature, time of wetness, time of freezing events of concrete Pavement	12 representative geographical locations of USA	Typical meteorological one year data files of Weather data from National Renewable Energy Laboratory (NREL)	1. Ambient temperature 2. Dew-point temperature 3. Ambient relative humidity 4. Wind sped 5. Precipitation 6. Cloud cover 7. Incident global horizontal radiation	[82]
One-dimensional model	Pavement temperature of porous asphalt, dense graded asphalt and Portland cement concrete pavements	Phoenix, Arizona	3 days from 12–14 August 2010	1. Pavement thickness 2. Pavement structure 3. Material type 4. Albedo	[83]
One-dimensional mathematical model	Pavement near-surface temperatures	Phoenix, Arizona	Three year from 2004 to 2007	1. Hourly measured solar radiation 2. air temperature 3. Dew-point temperature 4. Wind velocity data	[57]
One dimensional mathematical model	Temperatures of asphalt concrete during summer	Köping, outside Stockholm	Summer 1997 and validated by one day data in July 1998	Hourly values of 1. Solar radiation 2. Air temperature 3. Wind velocity	[73]

photochemical air pollution [84]. The adverse effects of UHI on the environment include the deterioration of living environment [85], elevation in ground-level (tropospheric) ozone concentrations [60, 86–88], increase of pollution levels, and modification of precipitation patterns which may lead to floods [89–91]. Urbanization leads to production of distinctive negative environmental effects, namely CO^2 emission [89, 92–95]. In parallel, several studies have concluded that urban heat island is responsible for higher pollutant concentration over the cities like Tokyo and Paris [96, 97].

Furthermore, UHI has an evident impact on outdoor and indoor thermal comfort. Many studies conclude that higher urban temperatures lower substantially the specific comfort levels [93, 98–106], and the problem is magnified in low income households which suffer from energy poverty [107]. Most of the studies that investigated the impact on the indoor environmental conditions of low income households have shown that indoor temperatures exceeded comfort temperature thresholds while in many cases exceed the maximum allowed indoor temperatures for health reasons [108–120].

4.2 Negative Effects on People and Human Health

UHI has a serious impact on the health conditions of the vulnerable urban population [93]. The World Health Organization, and other national institutions [111–115, 121], recognize that the exposure to high temperatures may cause important cerebrovascular disorders, cardiovascular stress, thermal exhaustion, heart stroke and cardiorespiratory diseases, decrease the viscosity of blood and increase the risk of thrombosis, thermo regulation and impaired kidney function [88, 122–128]. UHI effect exacerbates hot weather events or periods, intensifies the impact of extreme heat events and cause higher fatalities especially in vulnerable populations such as the elderly [129, 130].

There is a strong evidence that during heat waves, hospital admissions and mortality rate related to high ambient temperature increased - in France, Mediterranean, Northern Europe, Spain, Milan, Italy, Budapest, London, Southern Ontario in Canada, Asian cities like Bangkok, Thailand, Delhi, India, urban areas of Bangladesh and Hong Kong [128, 131–143]. According to Centers for Disease Control and Prevention (CDC), excessive heat claims more lives in the United States each year than hurricanes, lightning, tornadoes, floods, and earthquakes combined [144–146]. In Shanghai, as the urban heat island has grown, heat-related mortality rates have increased [147].

Higher urban temperatures are found to have an important impact on mental health [144]. During the heat waves periods in Australia, hospital admissions for mental and behavior disorders increased for ambient temperatures above 27 $^{\circ}$C [148]. In parallel, urban warming seems to have an important impact on social behavior increasing the crime rates. It has been demonstrated that, during hot weather and above 32.2 °C, the correlation between the ambient temperature and the probability of collective and assault and domestic crimes are positive and linear [149].

4.3 Negative Effects on Energy Consumption and Economy

UHI has a serious impact on the quality of life of urban citizens. It increases the energy consumption for cooling purposes, and increases the peak electricity demand during the summer period [85, 87, 90, 95, 150–160]. The hourly, daily or monthly electricity consumption increases between 0.5% and 8.5% per degree of temperature rise [161]. The average additional annual cooling energy penalty due to UHI effect was found to be close to 13.1% [159, 162]. Several studies have produced estimates of UHI economic impact, most of these studies conclude that higher ambient temperatures may have a negative relationship to the Gross National Product (GNP) of the countries. However, the results are country specific and vary considerably as a function of the local conditions. For example, the Garnaut Review on Climate change carried out in Australia [163], concluded that a 5 °C temperature increase may result in a reduction of the Australian GNP by 1.3% by 2030. Another study analyzing the relevant data from the last half of the previous century, concluded that higher temperatures reduce economic growth in poor countries but not of the developed ones [164].

4.4 Negative Effects on Flexible Pavement Performance

The increased temperature due to UHI also affects pavement performance. As the air temperature increases, the asphalt is softer at its early ages (usually 3 to 5 years after opening it to traffic) leading to premature permanent deformation (rutting) in the asphalt layer. Over time, as the pavement is exposed to prolonged periods of elevated temperatures it ages and the pavement cracks. A study on the field data of forty-eight street segments paired into 24 high-and low-shade pairs in Modesto, California, U.S. indicated that tree shade was partially responsible for reduced pavement fatigue cracking, rutting, shoving, and other distress. Shaded street was projected to save \$7.13/m^2 (\$0.66/ft^2) over the 30-year period compared to the unshaded street [165].

Another study investigated how solar radiation affects asphalt pavement performance under the influence of traffic loading by a software simulation model and building a model of pavement with its real physical properties. With a controlled trail, the result showed that pavement stresses are obviously influenced by solar radiations, surface temperature changes, and wheel pressures. Under the same traffic loading, higher surface temperature led to larger stress. This conclusion matched two major reasons of pavement cracking: thermal cracking and fatigue [166].

5 Pavement Share in Urban Areas in and Outside US

Pavements can absorb and store much of the sun's energy contributing to the urban heat island effect. In large urban cities in the U.S., about 29% to 45% of the city's land is covered with pavements [167]. Figure 8 represents the percentage of paved areas in different cities of the United States and the world after [168, 169].

6 Urban Heat Island Mitigation Strategies

The factors that affect the formation and intensity of UHI are versatile in nature. These factors vary between geographic location, time of day and season, synoptic weather, city size, city function and city form. The last two factors are the factors which can be controlled in order to mitigate UHI. Most of the studies investigated the influence of changing city form in terms of materials, geometry or design and green spaces on UHI.

The US Environmental Protection Agency (EPA) calls for three techniques to help mitigate the extreme temperature increases experienced in and around cities:

1. Design and material selection for pavement surfaces (Cool Pavements).
2. Design and material selection for roof structures and surfaces (Cool Roofs).
3. The incorporation of more trees, planting and landscaping elements in urban cities (City Form) [57].

On view of the impacts of UHI, a number of federal, state and local programs aimed at mitigating the UHI effect and its impacts were developed in the 1990s. The Heat Island Reduction Initiative (HIRI), a federal program that includes representatives from NASA, the US Department of Energy, and the US EPA, was initiated in 1997 to mitigate UHI. Since the inception of the project, Lawrence Berkeley National Laboratory (LBNL) has conducted detailed studies to the impact investigate of HIR strategies on heating and cooling energy use of three selected pilot cities [170]. The EPA initiated the implementation of some sustainable practices that would help in mitigating the UHI effect. City planners also should be engaged with global climate scientists to devise contextually relevant strategies to address the urban heat island effect [171]. In this approach, Million Cool Roofs Challenge, a global challenge initiated by a large number of foundations and stake holders to accelerate access to affordable, sustainable cooling through rapid deployment of cool roof materials. The global competition will provide US$2 million in grants to applicants with the most promising ideas and demonstrated success bringing cool roof innovations to scale [172].

Furthermore, due to the important role pavements play in the formation of urban heat island, the Transportation Research Board (TRB) Design and Construction Group has established a "Paving Materials and the Urban Climate" Subcommittee to address the influence of pavements in the formation and mitigation of the UHI and to examine the relationship of pavements to broader climate concerns. The subcommittee's scope includes modeling, design practices, testing, standards development, and planning and policy considerations. The subcommittee inaugurated its activities at the 2008 TRB Annual Meeting [173]. In the following section, the authors will review mitigation strategies and their effects.

6.1 Cool Pavements

Since paved areas represent nearly 30 to 45% of land cover in urban cities, they can absorb and store much of the sun's energy contributing to the urban heat island effect [167]. Some cool pavement efforts were aimed towards reducing the need to pave, particularly over vegetated areas that provide many benefits, including lowering surface and air temperatures. However, this technique is impractical for busy urban areas. Hence, emerged the need for increasing the pavement ability to cool through three different mechanisms to reduce pavement's contribution to the urban heat island: (1) by providing a surface that reflects a greater amount of solar radiation, (2) by increasing

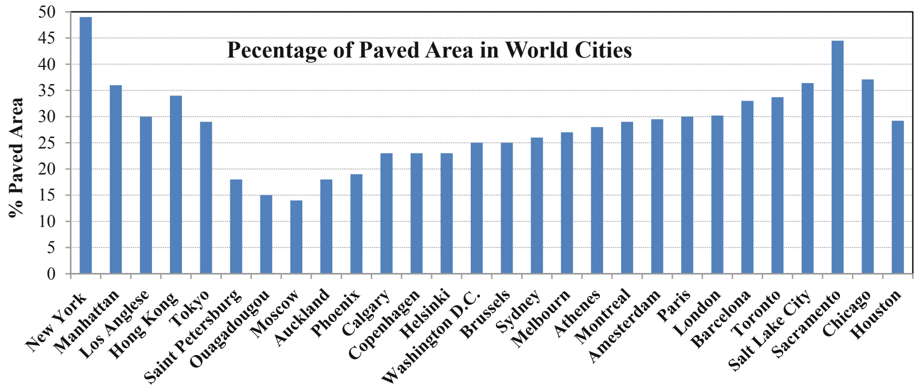

Fig. 8. Percentage of paved area in different world cities

the ability of the pavement to cool at night; and (3) by allowing a pavement to cool through evaporation by designing and building it as a porous structure [174].

Increasing Reflectance of Pavement Surfaces

Although concrete surfaces are already more reflective than asphalt surfaces [175], they can be made even more reflective with the use of white cement and lighter coarse and fine aggregates [59]. However, hence Asphalt pavements account for nearly 94% of pavement in the United States [176], there are several techniques to increase the solar reflectance of asphalt pavements [177] as follows:

1. Surface Gritting with Light-Colored Aggregate
2. Chip Seals with Light-Colored Aggregate
3. Sand Seals with Light-Colored Aggregate
4. Sand- or Shot-Blasting and Abraded Binder Surface
5. Colorless and Reflective Synthetic Binders with Light-Colored Aggregate
6. Surface Painting with Light-Colored Paint
7. Microsurfacing with Light-Colored Materials
8. Grouting of Open-Graded Course with Cementitious Materials.

Increasing the Ability of the Pavement to Cool at Night

A key aspect of urban heat island is the nighttime temperature (the time after sunset and before sunrise). The heat stored in the materials during the day returns back into the air, causing an increase in the air temperature during the night [178]. A study conducted in Arizona studied the influence of pavement materials in lab. And in the field on the near surface pavement temperature and the extent at which the surrounding air temperature will be affected. The materials investigated were; dense graded HMA, porous HMA, conventional Portland Cement Concrete (PCC), and pervious PCC. Based on the observed trends, the section that shows a higher surface temperature during the day tends to have a cooler surface temperature at night, hence less capacity to store heat. Therefore, such materials have less negative contribution to UHI effect [178]. Findings from another study suggested that pervious concrete pavements can provide night time minimum surface temperatures that are lower than conventional impermeable pavements [179].

Allowing a Pavement to Cool Through Evaporation
Results for analysis of heat gain of a Portland Cement Pervious Concrete (PCPC) system compared with a Portland Cement Concrete (PCC) system showed that stored rain water in the pervious concrete layer had a significant impact on the heat gain in the pervious concrete system, but this rain would then evaporate, improving the heat mitigation by evaporative cooling [180].

A study conducted in Los Angeles (LA) compared between the impact of four mitigation strategies; green roof, cool roof, additional trees, and cool pavement. Comparing the effect of each heat mitigation strategy shows that adoption of additional trees and cool pavements led to the largest spatial-maximum air temperature reductions at 14:00 h (1.0 and 2.0 °C, respectively) [181].

6.2 Cool Roofs

Since 20% of the urban surface is roofed, the widespread use of solar-reflective roofing materials and the use of vegetative – green roofs can save energy, mitigate urban heat islands and slow global warming by cooling roofs [182, 183]. In Australia, the interest to use green roofs is extensively increasing to make buildings more sustainable and provide ecological, and thermal benefits to cities [184]. Many studies combined between different strategies in UHI mitigation [185].

6.3 City Form

Cool city strategies offer energy efficiency improvements [186]. The main strategies related to city form are; cool coatings and vegetation. Although cool roofs are more popular research wise, cool coatings have recently attracted research efforts [187]. Some research results have shown that solutions involving the increase of the global albedo of the city demonstrate the highest benefits, achieving a reduction of peak ambient temperature of up to 3 °C and of peak cooling demand of residential buildings of up to 20% [188]. Three-dimensional greening of buildings is one of the strategies used to change the city form in order to mitigate the effects of UHI. This happens when city planners combine the building roof, wall, balcony, window and other special space with greening design according to the characteristics of different plants [189].

6.4 Case Studies and Regulations in Practice to Control the Phenomenon

Many legislations and regulations in practice are set in different countries to control or mitigate the phenomenon of UHI. At a national level, the Green Building Council of Australia has included green roofs as a ‘creditable feature’ in the ‘Green Star – Design and As Built’ rating system, the voluntary sustainability certification for new buildings in Australia [184]. Table 7 shows some of the mitigation techniques and case studies where researchers and city planners have done efforts towards controlling the phenomenon.

7 Summary, Conclusions, and Recommendations

This research extends the knowledge of UHI, and factors affecting its formation, intensity, its adverse effects on the environment, human health, energy consumption, the economy, and on pavement performance. This study also set out to emphasize the UHI measurements and modelling techniques besides mitigation strategies. From the review of the existing body of research about the UHI, the following conclusions can be drawn:

1. UHI causes are versatile, they include geographic location, time of day and season, synoptic weather, city size, city function and city form. However, only two factors affecting UHI formation and intensity are controllable in order to mitigate UHI, namely; city function and city form.
2. There are several forms of measurements and modelling techniques that tried to quantify and describe the UHI phenomenon.
3. The adverse effects of UHI on the environment include: deterioration of living environment, elevation in ground-level (tropospheric) ozone concentrations, raise of pollution levels, modification of precipitation patterns and may lead to floods.
4. It is evident that, when urban heat island grows, heat-related mortality rate increases especially in the vulnerable people like the elderly and the effects of heat waves on human and mental health magnifies.
5. Urban heat island has a serious impact on the quality of life of urban citizens. It increases the energy consumption for cooling purposes, increases the peak electricity demand during the summer period, and can reduce economic growth and GNP of some countries.
6. There is an evident correlation between UHI, and pavement performance. As the air temperature increases the asphalt is softer at its early ages leading to premature rutting in the asphalt layer. Over time, as the pavement is exposed to prolonged periods of elevated temperatures it ages and the pavement cracks.
7. As pavements contribute nearly 29–45% and sometimes up to 49%, one of the most prominent UHI mitigation strategies is cool pavements.
8. Each mitigation technique can contribute to the decrease of elevated temperature. However, combining more than one mitigation strategy helped more to reduce the effects of UHI.

From the comprehensive review of the formation, effects, and mitigation techniques of UHI, the following recommendations could be made:

1. Advanced UHI measuring, quantifying and modelling techniques should be adopted.
2. Combining several UHI mitigation techniques is recommended to enlarge the effectiveness of mitigation.

Table 7. Techniques and case studies of UHI mitigation

Mitigation technique	Temp reduction	Energy saving	Case study	Ref.
Porous asphalt pavement	Nighttime 3.1 °C	N/A	Lab. Arizona	[83]
Pavement thermal properties & albedo	14 °C	Lighting demand 41–57%	Lab and field Arizona	[57]
Unidirectional heat-transfer	6.2 °C (day) and 1.3 °C (night)	N/A	Lab and field China	[190]
Increasing the albedo	2 k	N/A	Simulation time series	[191]
1. Additional trees (Increasing greenery) 2. Cool pavements	1.0 °C at 14:00 2.0 °C at 14:00	N/A	Elmonte, Los Angeles	[181]
1. Water mitigation 2. Cool roofs 3. Cool pavements 4. Increasing greenery	6.0 °C 0.5 °C 2.0 °C 1.5 °C	Cooling demand 50%	Darwin City, Australia	[192]
Combined cool roofs with water technology	1.5 °C, local 10 °C near water technologies	Cooling Demand 39% houses 32% offices	Western Sydney, Australia	[192]
Tree canopy shading plan	Localized 2.5 °C	N/A	Green Square, Australia	[192]
Cool roofs	NM	N/A	LBNL, Berkeley, CA, USA	[182]
Permeable pavements watering	15–35 °C Surface temp.	N/A	Davis, California	[193]
1. Increasing Albedo of roofs 2. Green roofs	1.0.9 K. peak ambient Temp. 2.0.3–3 K Avg. ambient Temp.	N/A	N/A	[183]
Green roofs	0.5 °C at morning 0.3 °C at night	2% per building	Rome	[194]
Green roofs	1.24 °C during Day time	2.5–6%	Constantine, Algeria	[195]
Cool roofs and cool pavements	10 K surface Temp.	17% Cooling Demand	Acharnes Greece	[185]
Small green spaces between buildings	1–4 °C Air Temp.	N/A	Seoul, South Korea	[196]
1. Cool Roofs 2. Green Roofs	Reduce heat gain by 37%, 31%	N/A	Singapore	[197]

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