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Three decades of urban heat islands and mitigation technologies research

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ABSTRACT

Although the urban heat island (UHI) phenomena phenomenon has was been documented over a century ago, the effect of the urban heat island on urban climate and environment during the summer have only been the focus of research over the last three decades. One main characteristics of the recent research has been to evaluate the summertime effects of UHI on energy use, air pollution, outdoor ambient temperature, and citizen health. The second aspect of the recent research has been the development and evaluation of materials to counter the effects of summertime UHI. This paper provides a selective representation (by topic) review of the research on the development and evaluation of mitigation measures, including: cool roofs, cool pavements, and urban vegetation.

1. Introduction

Urban population is increasing rapidly because increasing birthrate and the migration of the rural population into the cities caused by expectations for a better life, local conflicts and lack of resources in the country areas [1]. According to a United Nations report, in 2011 about four billion people lived in cities; the number of urban dwellers are expected to grow to over 60% of the earth population by 2050 [2]. In addition, the urban areas experience a very significant change of its biophysical attributes, known as urban sprawl, combined with a significant change of land use [3]. Earlier studies have shown that loss of green spaces and application of paving, in combination with a very high increase of the released anthropogenic heat, have affected the urban climate, resulted in a serious environmental degradation and have increased significantly the urban ecological footprint [4,5].

The magnitude of the ambient temperature increase caused by the global climate change is forecasted by the Intergovernmental Panel on Climate Change in its recent report [6,7]. For the period 1990–2005, global temperature is increased between 0.15 K and 0.3 K, while the predictions for the period 1990–2100 indicate that a possible ambient temperature increase ranging between 1.8 K to 4 K. An example for temperature increase trends in Greece for the last forty years is depicted in Fig. 1. This figure illustrates the trends for all four seasons, i.e. for the winter months (December January February—DJF), the spring months (March April May—MAM), the autumn months (September October November—SON) and the summer months (June July August—JJA).

The thermal balance of cities are affected by the increased absorption of solar radiation, the corresponding increase of sensible heat released by urban structures, higher anthropogenic heat, reduced urban vegetation, and higher emission of infrared radiation [10,11]. Additional heat accumulated and released in the urban environment results in a higher urban ambient temperatures compared to the surrounding urban environment, known as 'Urban Heat Island.' Studies of the heat island characteristics are available for most medium and large cities in the world and the reported urban heat island intensities (including urban canyon effects) reach values up to 8–10 K [12].

Urban heat island increases the cooling energy consumption and the peak electricity demand during the summer period, raises the concentration of harmful pollutants like the tropospheric ozone and VOCs, increases the emissions of CO_2 to the atmosphere, deteriorates indoor and outdoor thermal comfort during the warm periods, affects health conditions and increases mortality [13].

To counterbalance the impacts of urban warming, specific mitigation and adaptation technologies are proposed. Two major promising clusters of mitigation technologies have been identified and researched [14]:

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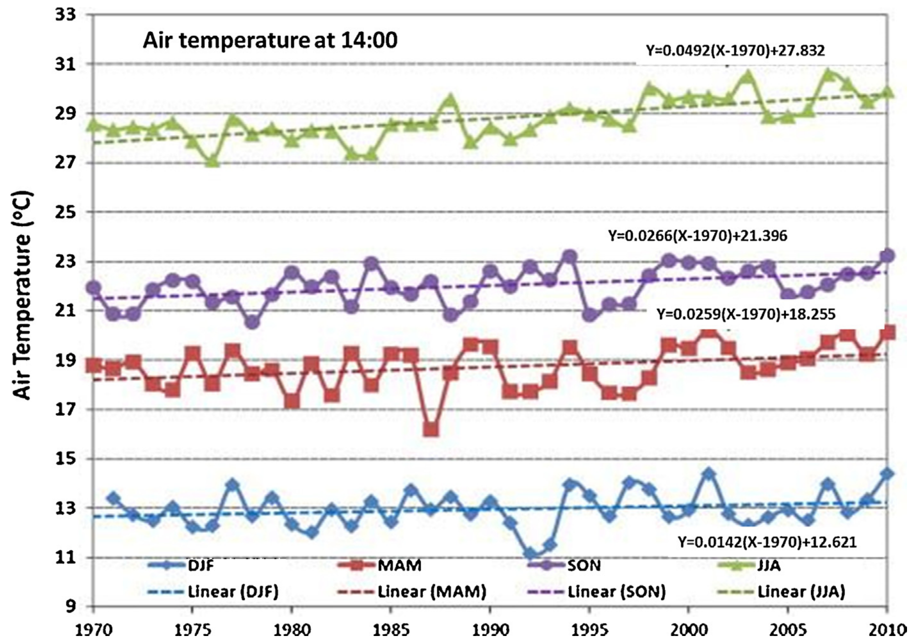

Fig. 1. Trends in air temperature increase at 10 m height above ground, in Greece [8,9]. DIF: Dec, Jan, Feb; MAM: Mar, Apr, May, JJA: Jun, Jul, Aug, SON: Sep, Oct, Nov.

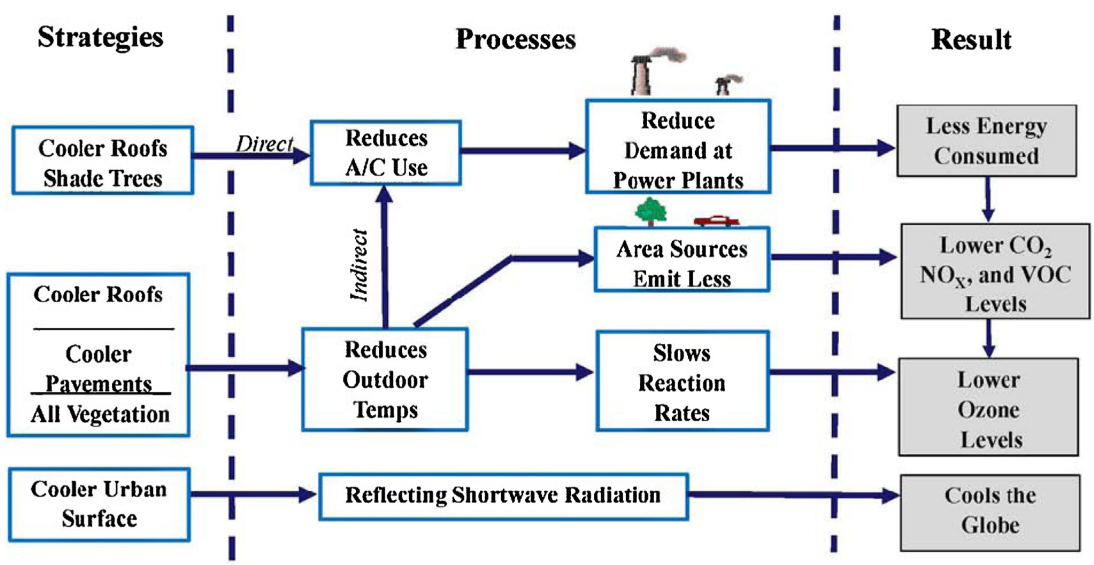

Fig. 2. Effects of heat island countermeasures. Cool roofs and shade trees reduce air conditioning energy use leading to a lower demand for power, lower consumption of fuel, lower air pollutants and lower greenhouse gas emissions. Cool roofs, cool pavement, and urban vegetation cool the city and reduce formation of smog. Cool roofs and cool pavements reflect shortwave radiation back to space and induce a negative radiative forcing.
(Adapted from [17]).

- Increasing solar reflectance: Mitigation technologies to decrease absorption of the solar radiation in the urban environment. This is mainly achieved through the use of materials with high solar reflectance (and high thermal emittance) to keep surfaces cool. These materials, known as cool materials, can be used in the building's facade, roofs, and pavements. Use of cool materials decreases the surface temperature of the urban areas and minimizes the corresponding release of sensible heat to the atmosphere; and
- Increasing evapotranspiration: Technologies aiming to increase evapotranspiration in the urban environment. This may be achieved through the intensive use of urban greenery like urban parks and green roofs and also through the use of water-permeable pavements.

To this end, the aim of the present paper is to analyze the evolution of the urban climate change as well as its mitigation technologies over the last three decades. In this specific period significant effort has been put in understanding and monitoring the urban climate change as well as developing and testing various mitigation technologies.

2. Effects of cool surfaces and urban vegetation on cooling energy use, urban air quality, and cooling the globe

During the summer, unshaded horizontal surfaces in urban areas (e.g., roofs and pavements) absorb significant amount of solar radiation. On a dry surface, almost 50% of this absorbed energy is convected to the air, leading to higher ambient air temperatures

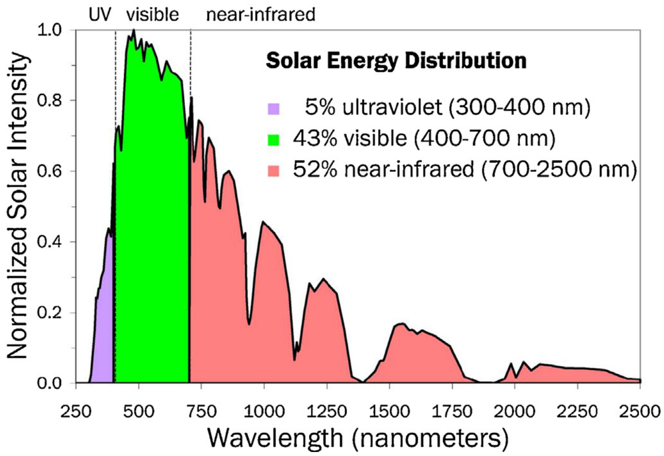

Fig. 3. Spectral solar energy characteristic intensity typical for North America.
Source: Heat Island Group, Lawrence Berkeley National Laboratory, Berkeley, California, USA.

[15]. A higher ambient temperature accelerates the photochemical reaction of atmospheric pollutants generating smog, also causes pedestrians discomfort. Part of the solar radiation absorbed by roofs is conducted into the buildings leading to higher cooling load in air-conditioned buildings and occupants discomfort in non-conditioned buildings. In winter and in climate conditions with significant heating requirements, the amount of solar radiation absorbed by horizontal surfaces is only a fraction of that absorbed in the summer time [16].

Changing the horizontal surfaces to the materials that absorb little sun (high solar reflectance) and emit the absorbed part of the solar radiation freely (high thermal emittance) keeps the surface temperature low. A cooler surface convects less heat to the ambient air and conducts less heat into the building. Materials with high solar reflectance and high thermal emittance are referred to as "cool" materials; examples include cool roofs and cool pavement. The effect of cool urban surfaces (roofs and pavements) on cooling energy use, smog, and cooling the earth is shown in Fig. 2.

3. The cool roofing materials and cool pavements evolution

3.1. Cool roofs

The early research in developing cool roofing materials focused on identifying and evaluating the readily available alternative cool roofs. In the U.S., the roofing market for commercial buildings (mostly flat or low sloped) consists of building up roofing (BUR), single ply membrane, modified bitumen, metal, and liquid applied coatings. For residential buildings (mostly sloped roofs), the common roofing materials are fiberglass asphalt shingles, wood shakes, and tiles (clay and concrete). Table 1 summarizes the reflectance of some of the common roofing materials for both readily-available dark and white colored options. The research indicated that for many of common roofing materials there exists cool roof options, typically at no incremental cost. This led to adaption of cool roofing materials in several state and national standards [18].

The research then extended (with collaboration with roofing and coating products manufacturers) to develop a new class of cool-colored roofing materials that reflect the near infrared (NIR) solar radiation. The solar radiation reaching the earth surface consists of three bands of ultraviolet (UV, ~5%), visible (VIS, ~43%), and near-infrared (NIR, ~52%) (cf. Fig. 3). Surfaces absorb the NIR radiation but human eyes are not sensitive to it. Hence, the basic principal behind cool-colored materials is to develop colored pigments with much higher NIR reflectance. An example of such a material is shown in Fig. 4.

An extended and ground-breaking research was carried out to identify and measure the spectral characteristics of 87 pigments [20]. Some of the identified cool pigments were already being used by manufacturers, indicating that they were viable economic options. These technologies quickly found their ways to the market; many manufacturers produce durable white and cool-colored roofing materials available for coating, tiles, painted metals, and fiberglass asphalt shingles [21] (see Fig. 5.)

Cool-colored materials can also be developed through layering applications of coatings. A thin layer of cool-colored coating is fairly transparent to NIR radiation. The radiation that is not absorbed or reflected in a layer will go through the coating and be incident on the under layer. A white and reflective under-layer coating will scatter back (reflect) the NIR radiation, a dark under-layer absorbs the NIR radiation. This layering technique is used to develop cool colored materials [22]. An example of application of layered coating is shown in Fig. 6.

Research was further extended to develop thermochromics roofing materials that become more reflective at higher temperatures [23]. Most known thermochromics materials are organic and they rapidly disintegrate under the sun. Karlessi and Santamouris note that

> "...photo-degradation is a major problem for thermochromics materials when exposed to outdoor environments. Various methods have been tested by applying different UV absorbers with different techniques in the thermochromics coatings, to photostabilize the color-changing effect of the material. The results, however, show that the performance of the thermochromics material was not improved and the degradation problems remain. This indicates that not only the ultraviolet but also other parts of the solar radiation interact with the molecular bonds, having a negative effect on thermochromism."

Significant R&D is needed to develop economically viable thermochromics roofing materials.

Engineered directionally reflective materials (DRM) that are reflective to the sun's ray and look dark from streets are simple durable alternatives to thermochromics roofing materials. DRMs are also more reflective during the summer (when the sun angle is high) and less reflective during the winter (when the sun angle is low). One simple way to produce DRM shingles is to brush a white coating on one direction of colored shingles. Fig. 7 shows examples of recently developed DRMs. Akbari and Touchaei [24] have analyzed the annual performance of DRMs and have developed a model to estimate their summer and winter reflectances.

Retroreflective materials that reflect the light in the direction of the sunlight have become the subject of research in recent years (e.g., [25,26] and references within). Retroreflective materials works best in an urban environment with tall buildings; retroreflective materials applied on wall permit the incident light on walls to be reflected in the direction of the incoming radiation rather than diffusely reflected into the urban canyon. Retroreflective coatings are not widely used currently. This technology can also be used as transparent coatings on windows.

Most cool roofing materials lose a fraction of their initial reflectance by weathering and aging. To have a realistic potential of cool roofing materials savings, standard bodies prescribe solar reflectance and thermal emittance of aged materials [18] and references within). Sleiman et al. [27] analyzed the solar reflectance of over 100 roofing materials after three years of aging in three weathering farms in Ohio, Florida, and Arizona and have documented a reduction in the weathered materials' solar reflectance from their initial value on the average of up to 0.15 from their initial

Table 1
Warmer and cooler options for low- and steep-sloped roofs. Shown are ranges of typical values for initial solar reflectance and initial thermal emittance.

Warmer Roof Options			Cooler Roof Options		
Roof Type	*Reflectance*	*Emittance*	*Roof Type*	*Reflectance*	*Emittance*
Built-up Roof			Built-up Roof		
with dark gravel	0.08–0.15	0.80–0.90	with white gravel	0.30–0.50	0.80–0.90
with smooth asphalt surface	0.04–0.05	0.80–0.90	with gravel and cementitious coating	0.50–0.70	0.80–0.90
with aluminum coating	0.25–0.60	0.20–0.50	smooth surface with white roof coating	0.75–0.85	0.80–0.90
Single-Ply Membrane			Single-Ply Membrane		
black (PVC)	0.04–0.05	0.80–0.90	white (PVC)	0.70–0.78	0.80–0.90
			color with cool pigments	0.40–0.60	0.80–0.90
Modified Bitumen			Modified Bitumen		
with mineral surface capsheet (SBS, APP)	0.10–0.20	0.80–0.90	white coating over a mineral surface (SBS, APP)	0.60–0.75	0.80–0.90
Metal Roof			Metal Roof		
unpainted, corrugated	0.30–0.50	0.05–0.30	white painted	0.60–0.70	0.80–0.90
dark-painted, corrugated	0.05–0.08	0.80–0.90			
Asphalt Shingle			Asphalt Shingle		
black or dark brown with conventional pigments	0.04–0.15	0.80–0.90	“white” (actually light gray)	0.25–0.27	0.80–0.90
Liquid Applied Coating			Liquid Applied Coating		
smooth black	0.04–0.05	0.80–0.90	smooth white	0.70–0.85	0.80–0.90
			smooth off-white	0.40–0.60	0.80–0.90
			rough white	0.50–0.60	0.80–0.90
Concrete Tile			Concrete Tile		
dark color with conventional pigments	0.05–0.35	0.80–0.90	white	0.70	0.80–0.90
Clay Tile			Clay Tile		
dark color with conventional pigments	0.20	0.80–0.90	terracotta (unglazed red tile)	0.40	0.80–0.90
			white	0.70	0.80–0.90
Wood Shake			Wood Shake		
painted dark color with conventional pigments	0.05–0.35	0.80–0.90	bare	0.40–0.55	0.80–0.90

Source: [19].

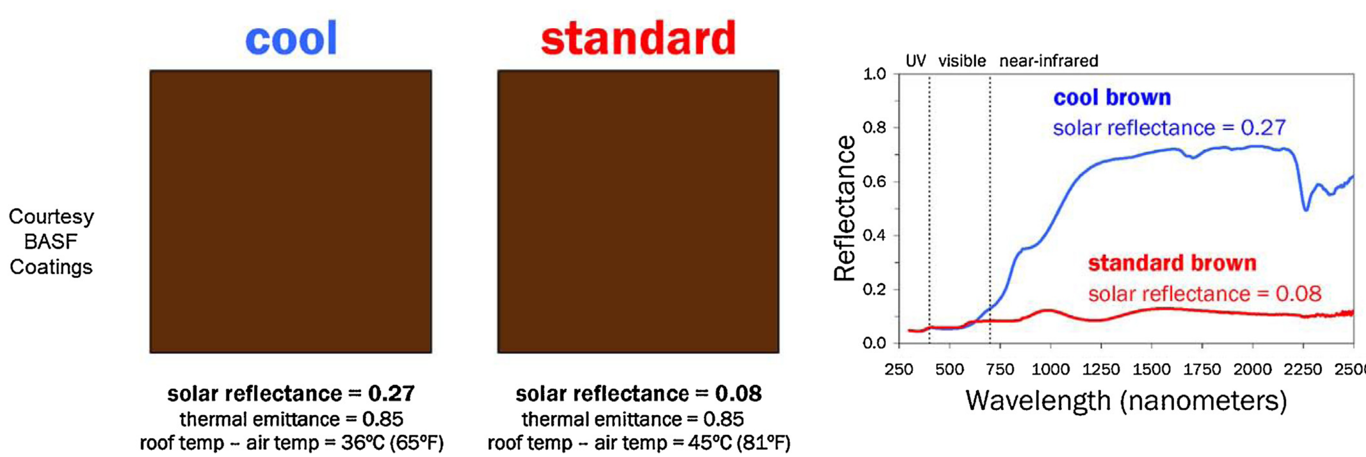

Fig. 4. A cool brown and a standard color brown. Note the UV, VIS, and NIR characteristics of the pigments.
Source: Heat Island Group, Lawrence Berkeley National Laboratory, Berkeley, California, USA.

values, depending on the material and its initial solar reflectance. Most reduction in the solar reflectance is caused by accumulation of soot particles [28]. Further reductions in solar reflectance caused by growth of algae on some materials were observed [27]. Sleiman et al. [29,30] developed a laboratory method to simulate the three-year aged of the roofing products weathered in the three weathering farms in Ohio, Florida, and Arizona. This practice assists manufacturers to develop and test products that can maintain their initial reflectance over time.

3.2. Cool pavements

Pavements constitute over 30% of typical urban areas in the U.S. This fraction may be larger in cities with much higher population density. Paved surfaces include roads, streets, driveways, sidewalks, parking lots, runways, plazas, and playgrounds. Most these surfaces are either paved with asphalt concrete (typically referred to as “asphalt”) or cement concrete (typically referred to as “concrete”). Pomerantz et al. [31–34] have characterized many paving materials and paving surface technologies such as cool coatings, chip seals, whitetopping (use of a thin layer of light-colored concrete on asphalt), colored concrete, light-colored concrete, grasscrete (cellular grassed paving in concrete or plastic), and permeable pavements. Levinson and Akbari [35] have studied methods to develop concrete with high solar reflectance. Some of these cool paving technologies are currently used in several municipalities in the U.S (e.g., use of chip seals for resurfacing pavements in San Jose, California). Grasscrete and porous pavements are used

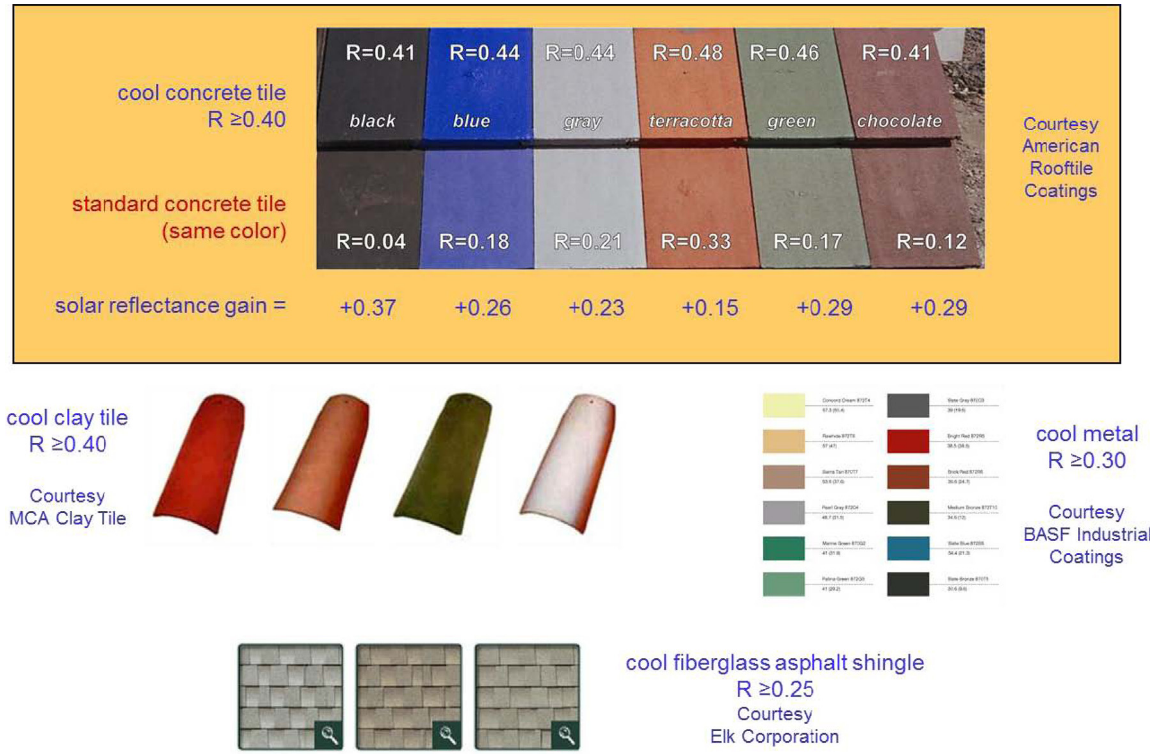

Fig. 5. Examples of cool-colored roofing materials in the market. R is solar reflectance.
Source: Heat Island Group, Lawrence Berkeley National Laboratory, Berkeley, California, USA.

in many cities as a flood control measure (e.g. Singapore, Osaka Japan).

Pavements with high solar reflectance can potentially have a higher service life. Fig. 8 shows an example of how a cooler pavement can have a longer life in a laboratory testing of pavement rut. Also light-colored pavements may save nighttime lighting energy use for having the same illuminance. Stark [36] has documented that a road with asphalt (dark) pavement was found to need 24 light fixtures per kilometer to meet recommended nighttime lighting levels, but when the same road was repaved with a more reflective concrete, only 17 light fixtures were required per kilometer (a ~30% decrease).

Cool pavements only affect the cooling energy use in buildings by cooling the urban temperature (the reflected radiation can potentially be incident on building walls and windows). In evaluating implementation policies and practices for installation of cool pavements many factors shall be considered. Gilbert et al. [37] have developed a model for a life-cycle cost performance analysis of cool pavements.

4. The role of greenery as an urban climate mitigation technology

Various forms of greenery exist in the city areas, such as nature reserves, parks, rooftop gardens, vertical greeneries. They are mainly categorized into two major categories: natural and man-made. In the last decades, green infrastructure has gained popularity as an effort to increase green areas in cities. This greenery appears in the form of green roofs, green facades [38,39,40], urban parks, and other green zones [41,42]. The role of green vegetation in urban climate and mitigation of urban overheating for the period under study was pinpointed by Hoyano [43] and Wilmers [44] showing the effect of diminishing the difference of temperature between the areas covered with vegetation and their surroundings. Since then there is a significant effort for the analysis of the green infrastructure's impact on the built environment. The various aspects of green infrastructure in the urban context are presented below.

4.1. Greek parks and green zones

The role of trees and green spaces to the improvement of the urban climate has been studied in detail the last decades. An urban forest of 100,000 trees can save US$1.5 million on annual basis because the shade provided reduces electricity consumption and saves water [45].

Numerous studies have been performed for the quantification of the urban parks' influence in cooling the surrounding areas and mitigating the urban heat [46,47]. Most studies show that the influence of the park is extended several hundred meters beyond the park borders [48]. Some examples include the study of [49] for a park in Montreal as well as the study of [50] for a small park of 0.6 km^2 in Japan showing that the park's climatic influence at midday may be extended up to 1000 m beyond its borders. Wattkins et al. [51] estimated that the impact of parks in London is extended to a distance between 200 and 400 m. Similar results are reported by Wong [52] for Singapore, Hamada and Ohta [53] for Japan, and Skoulika et al. [54] for Athens.

An important aspect of the research concerning urban parks is the quantification of cool island intensity, i.e. the difference between the parks and the surrounding urban areas. Bowler et al. [55] performed a review of the various studies showing that the average nocturnal temperature difference between parks and urban areas is close to −1.15 K while during day this difference is close to 0.94 K (i.e. parks are cooler during the day and warmer during the night than the surrounding urban areas). Data from four experiments in cities characterized by an oceanic climate show that the intensity of the cool island varied between −0.5 and −2.5 K [56,57]. Finally, there is one experiment concerning hot desert climate; Bencheikh and Rchid [58] reporting a cool island intensity

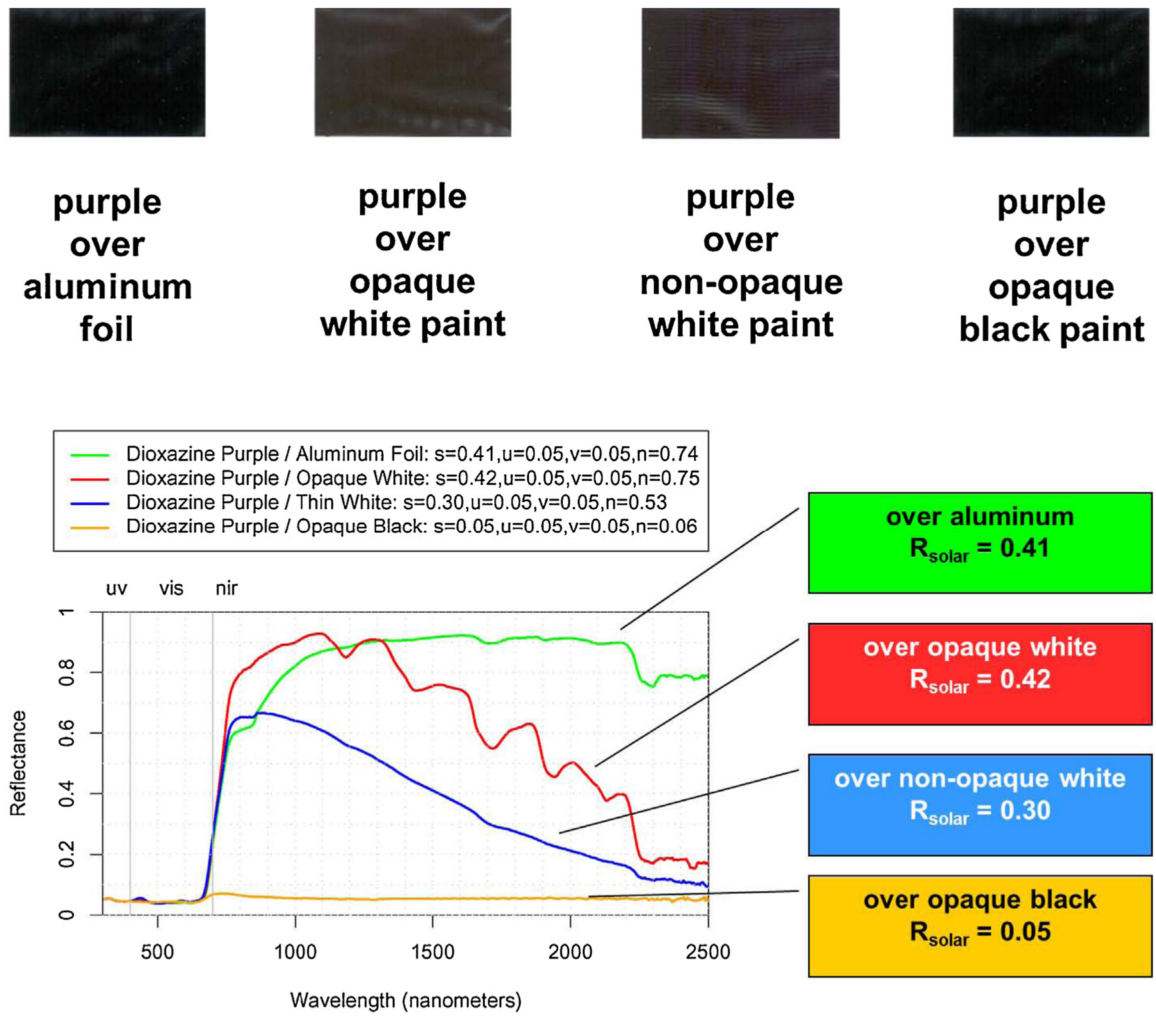

Fig. 6. Spectral reflectance of dioxazine purple on aluminum, opaque white, non-opaque white, and opaque black sublayer. Dioxazine purple is a dye that could be used to make black coatings.
Source: Heat Island Group, Lawrence Berkeley National Laboratory, Berkeley, California, USA.

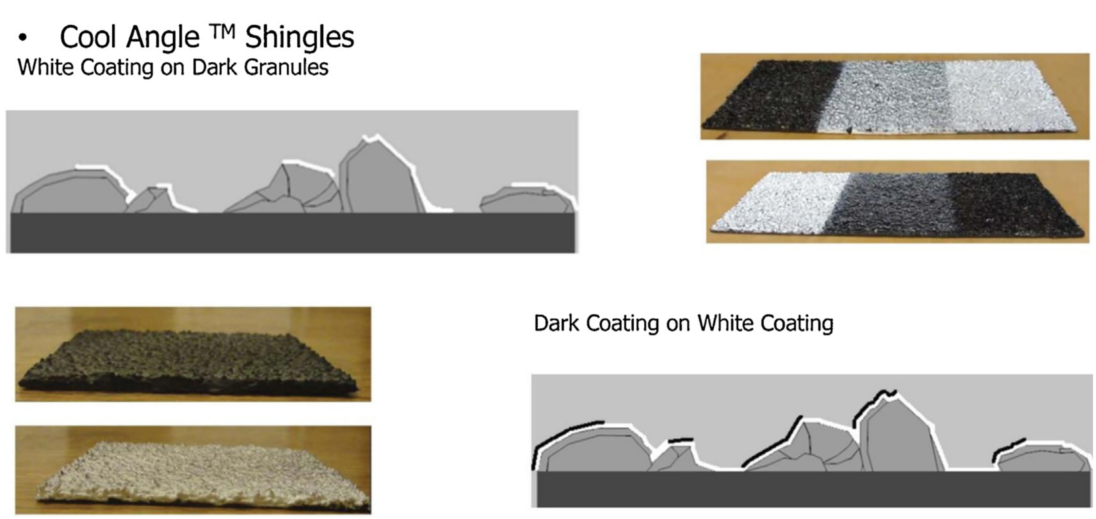

Fig. 7. Directionally reflective materials. Photos courtesy of Cool Angle LLC, Brigham City, Utah. USA.

(CII) of −4.5 K in Ghardaia. Algeria, while Jansson et al. [59] reported that the CII in Stockholm, Sweden under continental climatic conditions, ranges between −0.5 and −2.0 K.

4.2. Green roofs

The technique of green roofs, public or private, has gained ground during the last decades, as it reduces the energy consump-

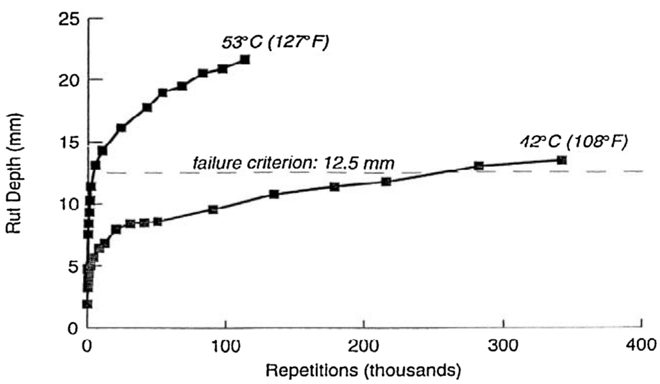

Fig. 8. Depth of rutting *vs.* number of repetitions of a standard axle load, wide-base, single tire at pavement surface temperatures of 42 °C and 53 °C.
Source: [33].

tion of the buildings while improving the microclimate of the wider urban space where the building is situated. Green roofs are roofs that are fully or partially covered with vegetation. Green roofs have been categorized into two major types of intensive roofs (which may include small trees and shrubs) and extensive roofs (which are covered by a thin layer of vegetation). There are several advantages associated to green roofs like decreased energy consumption, better outdoor air quality and noise reduction, and increased durability of the roof materials [60,61,62,63].

Numerous studies have analyzed the performance of green roofs showing their important energy benefits as well as their contribution to urban heat mitigation potential (e.g., [64,65,39]). Several studies have investigated the performance of green roofs in some specific localities. These include work performed by Rosenzweig et al. [66] for New York city; work of Wong et al. [67] that studied the effect of an intensive rooftop garden system in Singapore; the analysis of mitigation potential in different European cities performed by Kolokotsa et al. [68], and the work of Sun [69] for the contribution of green roofs in Taipei. A discussion of the main parameters affecting the performance of the green roofs is given in [68].

Green roofs increase the total water-permeable city surface, helping water to be retained in the soil and allowing larger quantities to be available for evapotranspiration [70]. Also, according to the United States Environmental Protection Agency, "On hot summer days, the surface temperature of a green roof can be cooler than the air temperature, whereas the surface of a conventional rooftop can be up to 50 °C warmer" [71].

4.3. Green facades and green walls

Green walls and green facades existed for quite a long time as climbing or trailing plants. Nowadays green walls and facades are considered very important aspect of green infrastructure and nature based solutions for climate change mitigation in the urban environment [72,73]. According to the Growing Green Guide of Australia [74]

> "a green wall is comprised of plants grown in supported vertical systems that are generally attached to an internal or external wall, although in some cases can be freestanding. Green walls differ from green facades in that they incorporate multiple 'containerised' plantings to create the vegetation cover rather than being reliant on fewer numbers of plants that climb and spread to provide cover".

Greenery in walls and facades can be divided into three types: wall-climbing, hanging-down and modular type. The wall-climbing type is a very traditional way of vertical climbing method. The plants can either cover the wall of buildings naturally or grow upwards with the help of a supporting system. The hanging-down type is also a popular method of vertical landscaping, which can form a vertical green belt in multi-storey buildings. The modular type is the latest vertical greenery system that requires a proper design irrigation system, structure growing media and selection of plants [75,76].

Significant efforts have been spent for the quantification of the impact of green walls and facades as climate change mitigation strategies. These include the study of vertical systems in Singapore with a maximum temperature reduction of almost 10 K [77], and the study of vertical greenery in Hong Kong with a temperature decrease of 8.4 K [78]. In Chicago the impact of a plant layer on brick wall is studied by [79] showing a surface temperature decrease that ranged between 0.7 to 13 K. The research on building green walls and facades is continuously upgraded with new case studies and more advanced technologies for plants incorporation, irrigation and maintenance.

5. Conclusions and prospects

The last three decades has witnessed significant progress towards characterization of summertime urban heat islands; their effects on cooling energy use, indoor and outdoor ambient comfort, and urban air quality; and analysis and development of various mitigation technologies. With the advent of global warming, the urban dwellers have to deal with the effects of urban heat islands combined with the increase in global temperature. Following business-as-usual practices will lead to significant increase in energy use, citizen discomfort, and potential loss of life (i.e., heat stress related mortality). Many cities and their political leaders have already concluded that the current practice in urbanization is not sustainable.

Fortunately, urban areas are in constant and dynamic change which allows to adjust the current trends. A vision for an energy-efficient and environmentally positive (not just benign) community will lead the cities to a *change* for better. Buildings are constantly re-roofed; they can use cool roofs. Pavements are constantly resurfaced; they can be re-surfaced with cool pavements. A "masterplan" developed by the cities and their leadership will lead us towards the communities and cities of future. The political leadership of the cities should recognize that cities are responsible for over 90% of all energy use (and hence, environmental impacts) in the world. This recognition comes with significant responsibilities. The time is now to take this responsibility seriously.

One of the major characteristics of the urban heat island and mitigation technologies research over the last three decades has been it applied focus in developing materials, methods, and policies to change the urban fabric and landscape. Many of the mitigation technologies developed are currently used in the field. The scientists are well-advised to keep this focus and even make it sharper.

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