DEVELOPMENT AND TESTING OF PHOTOVOLTAIC PAVEMENT FOR HEAT ISLAND MITIGATION

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ABSTRACT

The present article deals with the development and testing of photovoltaic pavement for heat island mitigation. The scope of this study is to evaluate its contribution to the balance of the Urban Heat Island phenomenon. For this reason, we made a photovoltaic pavement for purely experimental reasons (dimensions 3.5x1.3m) that consists of two different voltage polycrystalline photovoltaic panels. On top of them, a triplex security glass with a nonslip silk screen, PVB standard 1.14 mm was placed. We measured their surface temperature, from morning till noon, each and every hour, for several months (summer-autumn-spring). It was proven that, in comparison with other respective asphalt street and ground measurements, it has essentially lower values. In addition, in order to find out the degree witch the photovoltaic pavement contributes to the improvement of the urban microclimate, a simulation took place.

KEYWORDS

Heat island, photovoltaics, simulation, mitigation

1. INTRODUCTION

The growing population in urbanized areas, in 1950 30% of the world population lived in urban areas and this price is expected to rise to 60% in 2030, causes an increase of anthropogenic heat and thus, the center of the cities, in temperate zones, become hotter than their periphery, forming an urban heat island (UHI). (Essa et al., 2013)

In recent decades, the scientific community has shown great interest in both the recording of urban heat island effect and the mitigation techniques of it. The reason behind such intensive monitoring of this effect is its significant energy and environmental impact on the urban environment, which can be considered as the most significant recorded event of what we call climate change. The main energy impact of heat island, is associated to the high energy consumption for cooling in buildings (Giannopoulou et al., 2011), which increases the production of smog, contributes to high production of pollutants from power plants (SO_2, CO, NO_X) and acts as a trap for pollutants, reducing therefore the quality of life and resulting in a social - economic impact on urbanized areas. Moreover reduces the levels of thermal comfort and creates additional health problems and mortality due to high temperatures (Gobakis et al., 2011, Giannaros et al., 2013).

The existence of the phenomenon is perceived by calculating the difference in air temperature between urban and non-urban areas, called intensity of the urban heat island effect and depends on the size, topography and geometry of urban areas, the size of population and industrial growth of the city, the heat balance of the urban area, topography, local climate and weather conditions. This phenomenon is observed both day and night and the spatiotemporal evolution depends on the unique characteristics of each urban area (Gobakis et al., 2011).

The thermal properties of construction materials (cement, asphalt, concrete, glass) play a very important role, namely the high heat capacity and low reflectivity in the sunlight. More particularly, the structured surfaces characterized by sensitivity to heat storage during the day which is retransmitted during the night, produce a positive thermal anomaly over the urban area (Papangelis et al., 2012). Furthermore, help to reduce wind speed by approximately 25% in the cities due to increased roughness and urban geometry. An additional feature of cities that creates - intensify the phenomenon is the reduced latent heat of evaporation or the replacement of natural green areas with dry surfaces and rapid runoff of water from rainfall thereby reducing the storage of rainwater on the surface of the earth. Finally, active role played by air pollution over the city, and the anthropogenic heat released from urban activities (cars, air conditioning, etc.). (Stathopoulou et al., 2007)

It has been found that the average spatial extent of urban heat island in Athens is 55.2 km^2 and the average intensity of 5.6^oC. The effect is less pronounced in the early morning and afternoon hours. The intensity of UCL island follows a typical daily cycle by taking the minimum and maximum values, the early hours (sharp decrease after sunrise) and during the night (increase after sunset), respectively (Giannaros et al., 2013). The maximum values occur during the summer and especially in mid-July for day while on the night there is a shift of the maximum about two weeks. Identified and some extremely hot areas (hot spots) where the temperatures differ on average 4-6^oC (with a maximum of up to 9-10^oC) compared to the surrounding suburban. (Keramitsoglou et al., 2011)

Despite the general picture of the phenomenon, there are variations of intensity in the different areas of the basin due to the existence or not of green areas and uncovered areas with bare ground (mines, dumps, stadiums and extensive pedestrianization), the density of buildings, traffic, industrial activity and thermal properties of materials. Topography plays an important role too, which is evident by the lowest temperatures found near the shoreline, probably due to the phenomenon of the sea breeze, but also from the different heating of the slopes of the mountains (eastern warmer than the west) and the cutoff of summer northern winds (annual) by them. (Livada et al., 2002; Stathopoulou and Cartalis, 2006; Stathopoulou et al., 2009; Giannopoulou et al., 2011; Keramitsoglou et al., 2011; Gobakis et al., 2011; Giannaros et al., 2013)

There are many techniques to improve the urban microclimate and mitigation of the heat island phenomenon. Materials play a very important role and determine the thermal balance in the urban environment. The use of materials with high reflectivity to solar radiation and high emissivity in the thermal radiation, called cool materials, both in buildings envelopes and in other urban surfaces, contributes to reduce thermal loads through transport phenomena (convection, radiation). (Santamouris et al., 2011)

Cool materials are characterized by high solar reflectance and infrared emittance values. These two properties result in lower external surface temperatures and reduce heat penetrating into the building and decrease the ambient air temperature.

Sidewalks are a big piece of urban surface and affect strongly the urban climate. Their thermal balance is determined by the amount of the absorbed solar radiation, the emitted infrared radiation, the heat transferred by convection to the atmospheric air, the heat stored in to the mass of the material and the heat conducted to the ground. When latent heat phenomena are present, evaporation or even condensation affect the thermal regime of the pavement surfaces as well, while the effect of rain and icing has to be considered as well. The use of cool pavement surface with lower temperatures and reduced flow sensible heat in the atmosphere is one of the most important solutions proposed (Santamouris, 2013). Cool pavements refer to a range of established and emerging materials that tend to store less heat and may have lower surface temperatures compared to conventional products. Conventional pavements are usually impervious made of concrete and asphalt, with solar reflectance values ranging between approximately 4% and 45%, which can reach peak summertime surface temperatures of 48–67^{o}C. Increasing the solar reflectance of a paved surface keeps it cooler under the sun. Measured data clearly indicate that increasing the pavement's solar reflectance by 0.25 can decrease the pavement temperature by up to 10^{o}C.

Another proposal is to use photovoltaic panels for the mitigation of the phenomenon as mentioned at work of Golden et al., 2006, in which pavement's surface temperatures were measured in three cases: unshaded, shaded by PV canopy and shaded by urban forestry canopy. It was proved that HMA surface shaded by a PV canopy achieves a 55.8^{o}F (13.2^{o}C) surface temperature reduction in comparison to the adjacent fully exposed HMA, while the HMA surface mitigated (covered) by the urban forestry achieves a maximum reduction of 43.2^{o}F (6.2^{o}C) in comparison to the adjacent fully exposed HMA. Photovoltaic panels provide a greater thermal reduction benefit during the diurnal cycle in comparison to urban forestry while also providing the additional benefits of supporting peak energy demand, conserving water resources and utilizing a renewable energy source.

This paper focuses to the use of photovoltaics directly as pavements. Experiments and simulations have been performed to assess the mitigation potential of cool photovoltaic pavements. New technologies for photovoltaic pavements based on the use of PV tiles made with glass integrated over ceramic, enables walking on and placing of furniture. Photovoltaic pavements may provide electricity, save space and in case their surface temperature is appropriate, they could contribute to mitigate heat islands in cities. (Santamouris, 2013)

2. EXPERIMENTAL AND SIMULATION ANALYSIS

To conduct this research an experimental device was developed and built. The device is depicted in the following photos (figure 1, 2). It is a metallic construction, the dimensions and the shape of which are almost similar to those of a conventional pavement, namely 3.5m in length and 1.3m in width. Enough room under the surface of the pavement is provided, appropriate for the storage and safety of the various equipment, (batteries, inverter, etc) required for the operation of the PVs. Two different voltage polycrystalline photovoltaic panels, where their characteristics are given in Table 1, reside at the horizontal surface of the device, able to generate enough electricity for the lighting of the pavement. A triplex security glass with a nonslip silk screen, PVB standard 1.14mm is mounted above the PV panels at a distance of 5cm from the latter and its properties are mentioned in Table 2.

Table 1: Characteristics of PV panels

Panel 1	**Panel 2**
P = 145 W_P	P = 220 W_P
U_{MPP} = 34.1 V	U_{MPP} = 29.3 V
U_{OC} = 42.2 V	U_{OC} = 36.4 V
I_{MPP} = 4.24 A	I_{MPP} = 7.51 A
I_{SC} = 4.69 A	I_{SC} = 8.18 A
V = 840V	V = 1000 V

Table 2: Glass properties

	Luminous factors	**Energy factors**
Nominal thickness = 21.1 mm	Transmittance = 83%	Transmitta nce = 60%
Weight = 51.2 kg/m^2	Outdoor reflectance = 8%	Solar factor g = 0.68%
Normal outdoor	Indoor reflectance = 8%	U_g = 5.3

emissivity = 0.89		W/(m^{2}K)

Figure 1: The experimental PV pavement

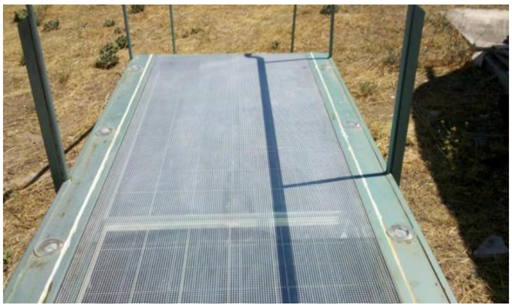


Figure 2: Closer look to the glass above the panels

During the summer of 2013 (June-July) the surface temperatures of asphalt, pv pavement and soil surfaces were measured using a contact thermometer. Thus, as shown in the figure 3, the soil has higher temperature than the other two surfaces in the early hours and a sharp drop immediately after the local noon. The photovoltaic pavement on the other side increases gradually its surface temperature in the morning and performs a delay compared to the soil, about 2 hours, when it starts reducing its temperature in smoother way than the soil. Finally, concerning the asphalt, lower temperature observed in the morning, but increases during the day and remains higher than the other two surfaces during evening hours.

To prove, however, that such an application, beyond the benefits of photovoltaics in energy production without the emission of pollutants, helps in urban heat island mitigation, an appropriate three-dimensional microclimate model (Envimet 3.1) is used to calculate the mitigation potential of pv pavements. The thermal regime in the area was calculated considering a) conventional asphaltic pavements and b) pv pavements. For the simulation of the above mentioned phenomena a main street (Fragoklissias) in Maroussi was selected, the coarse urban formation and the dense planting of which ensures big amounts of insolation during the day time (figure 4).

Figure 4: Image of analysis area as shown in Google earth

This model takes into account all types of solar radiation (direct, diffuse and reflected) and thermal radiation flows from the atmosphere, soil and walls. The calculation of the radiation flow includes shading, absorption and reradiation of plants.

To obtain results an input file feeds the software with the required data, the latter given in a matrix format. Such data include the geometry of the site and neighboring buildings, the selected step of the simulation grid (grid), the atmospheric and climatic conditions, types of plantings, paving materials, and elevations of the perimeter buildings and levels.

A grid was used over the study area, consisting of 220x60x20 nodes (x, y, z) with a resolution of 3.4m x 3.4m. The total simulation time was 24 hours from midnight of one day to midnight the next day, the meteorological start data of the simulation, defined by meteorological data for the region during summer 2013 by the National Observatory of Athens and paving materials of status quo and their characteristics are shown in table 3.

Table 3: Characteristics of conventional paving materials

material	reflectance	Emissivity
asphalt	0.1	0.9
Pavement tiles	0.2	0.9
soil	0.0	0.98

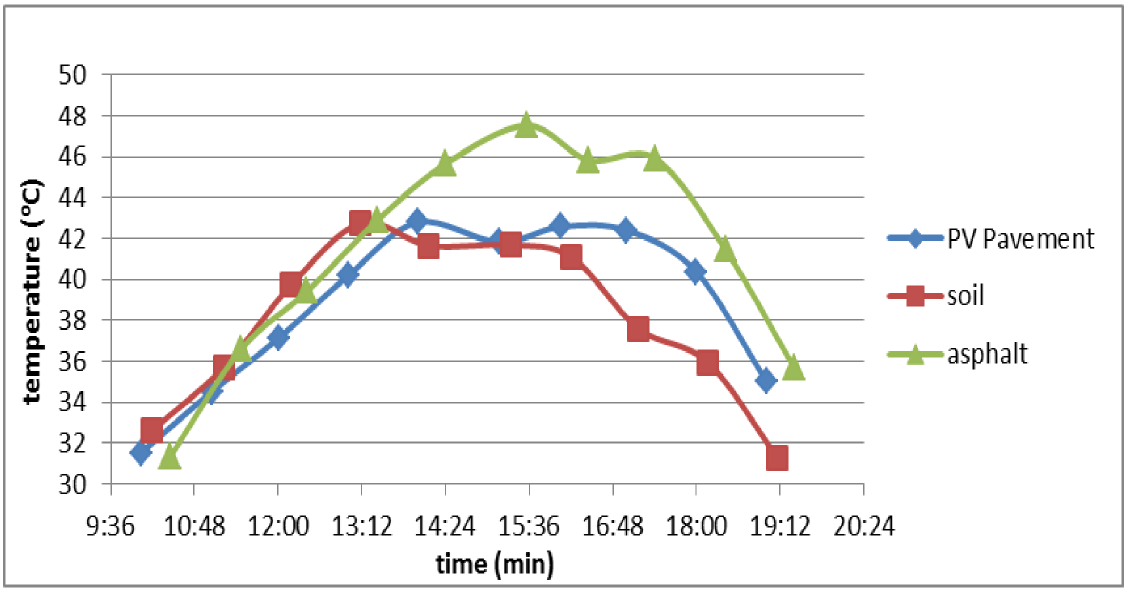
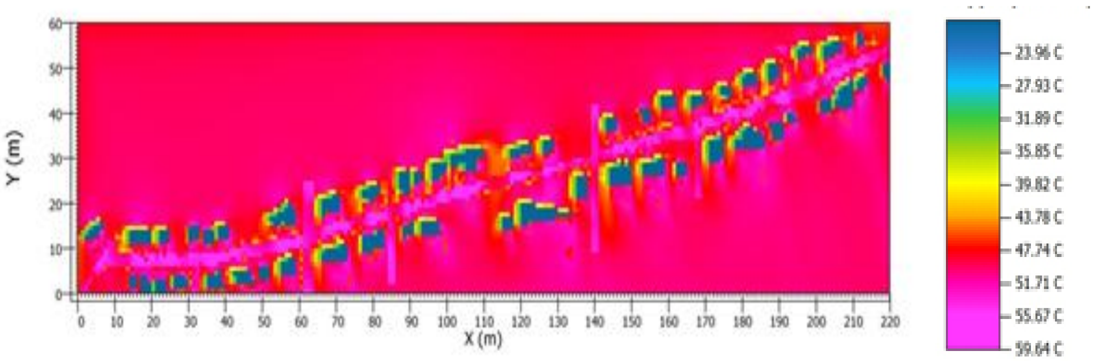
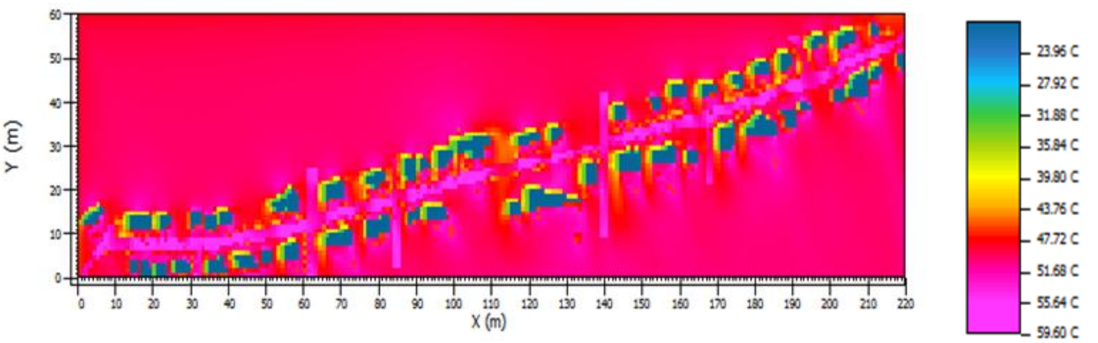


Figure 3: Comparison of daily temperature distribution of three different materials

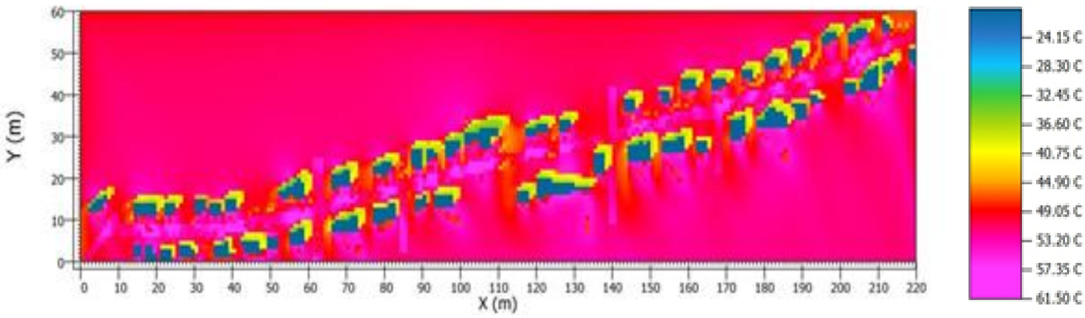
At a first step, the distribution of the surface temperature in the street, on the current situation, has been calculated for a typical summer day with specific boundary conditions (temperature, wind direction and velocity, solar radiation). Secondly, the same calculations have been carried out for the same boundary conditions as the ones used in the initial phase for the new situation. The different optical properties of the materials have been taken into account. For solar radiation values corresponding to 12:00h and 15:00h (Local Time) and for undisturbed ambient temperature and wind speed, the calculated surface temperatures for both situations are shown in the following figures.

a)





b)



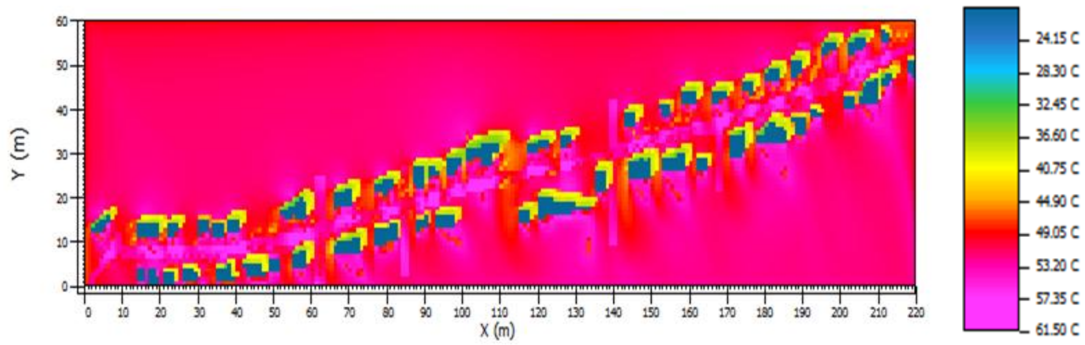
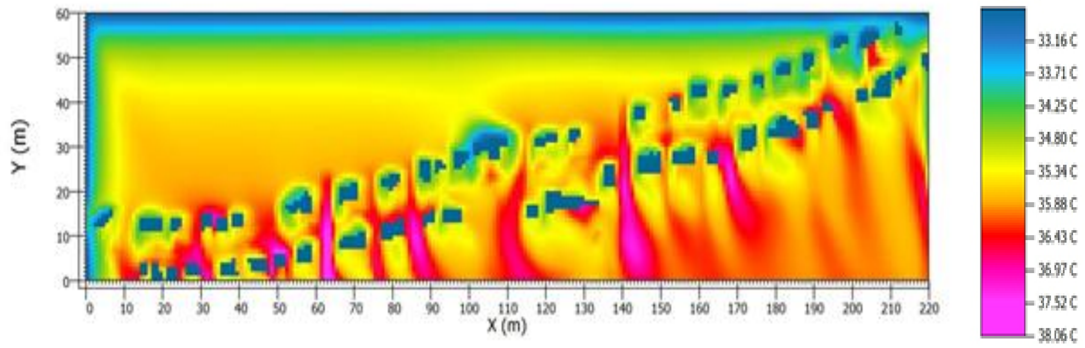
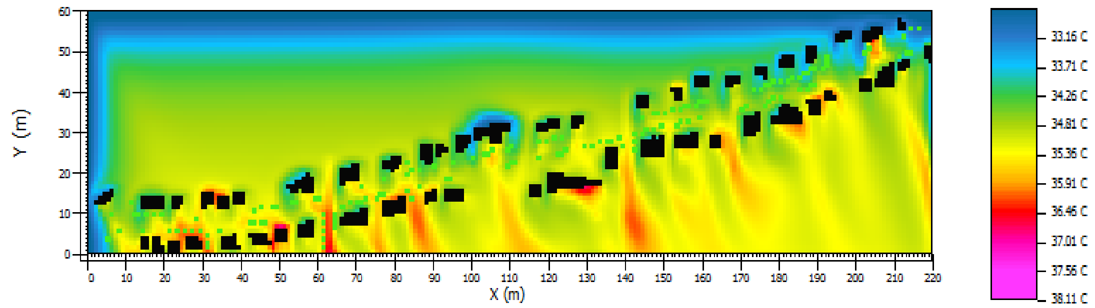


Figure 5: surface temperature before and after the application of pv pavements respectively at a) 12:00h, b) 15:00h

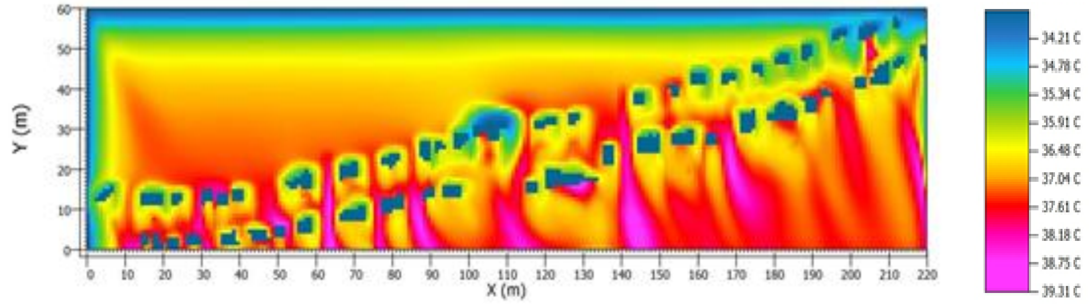
Simulations of the ambient temperature, in height of 1.80m, have been carried out for the same climatic boundary conditions as used previously in order to be able to quantify the possible microclimatic improvements. In particular, simulations have been carried out for an undisturbed ambient temperature and wind speed taking into account the considered improvements. The calculated distribution of the surface temperature has been introduced to the computerized tool as a new boundary. The results of this simulation both with and without the interventions, at 12:00h and 15:00h o clock as before, are given in figures below.

a)





b)



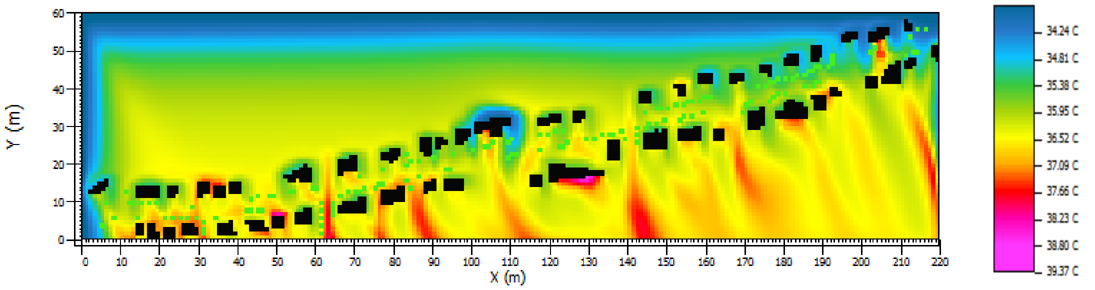


Figure 6: air temperature (1.80m) before and after the application of pv pavements respectively at a) 12:00h, b) 15:00h

Obviously, replacing conventional pavements with PV ones results in a drop of both surface and air temperature, whereas these temperature differences are with time, which is well validated against the above obtained experimental data. More specifically there is a maximum decrease of the surface temperature close to 4^{o}K and to the ambient air close to 2^{o}K. Speaking for the surface temperatures, they have been substantially decreased because of the different thermal properties of pv pavements against the conventional ones. Concerning the ambient air temperatures, there is a remarkable drop due to lower surface temperatures of pv pavements, which cause a reduction in heat exchange.

3. CONCLUSIONS

Heat island increases temperature in urban areas, increases the energy consumption for cooling purposes and affects the global environmental quality of cities. The use of advanced mitigation techniques highly contributes to decrease temperatures and improve comfort in open urban areas. (Santamouris et al., 2012)

New materials, systems and technologies have been developed and proposed in order to decrease the sensible heat flux to the atmosphere from different urban structures like buildings and paved surfaces. Business around pavements present an extreme commercial importance and employ hundreds thousands of workers, engineers and administrators. It is during the very recent years that researcher working on pavement technologies started to look on their optical and thermal properties and the possible impact on urban climate.

Photovoltaics were only known about their use in energy production. The present paper presents a mitigation technique for urban heat island phenomenon with the use of photovoltaics and in particular the application of photovoltaics directly in pavements. This technique has direct and indirect effects on the microclimate. The analysis of the results obtained through the monitoring and the detailed simulations have shown that the considered microclimatic improvement technique have helped to decrease substantially both the surface and ambient temperatures up to 5^{o}K and to 2^{o}K respectively against the conventional pavements. Also the power generated from the PV will depend on the rating of the system and the available electricity generating potential hours. PV pavements can be used to provide supplemental base load and peak power electricity for urban open areas.

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