Experimental testing of cool colored thin layer asphalt and estimation of its potential to improve the urban microclimate

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Afroditi Synnefa
National and Kapodistrian University of Athens

Theoni Karlessi
National and Kapodistrian University of Athens

Niki Gaitani
Norwegian University of Science and Technology

Mat Santamouris
National and Kapodistrian University of Athens

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Afroditi Synnefa [a,*], Theoni Karlessi [a], Niki Gaitani [a], Mat Santamouris [a], D.N. Assimakopoulos [b], C. Papakatsikas [c]

[a] Group Building Environmental Studies, National and Kapodistrian University of Athens, Department of Applied Physics, Physics Department, Building of Physics – 5, University Campus 157 84 Athens, Greece
[b] National and Kapodistrian University of Athens, Department of Applied Physics, Physics Department, Building of Physics – 5, University, Campus 157 84 Athens, Greece
[c] Aktis S.A. Odysseos 13, Thessaloniki 54629, Greece

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ABSTRACT

Urban Heat Island refers to the temperature increase in urban areas compared to rural settings, exacerbating the energy consumption of buildings for cooling. The use of highly reflective materials in buildings and urban structures reduces the absorbed solar radiation and contributes to mitigate heat island. This paper presents the results of a study aiming to measure and analyze the solar spectral properties and the thermal performance of 5 color thin layer asphalt samples in comparison to a sample of conventional black asphalt. Computational fluid dynamics (CFD) simulation is used for evaluating the thermal and energy impact of applying the samples in outdoor spaces (roads). The spectrophotometric measurements showed that the colored thin layer asphalt samples are characterized by higher values of solar reflectance compared to the conventional asphalt, which is mainly due to their high near infrared solar reflectance. From the statistical analysis of the surface temperatures it was found that all the colored thin layer asphalt samples demonstrate lower surface temperatures compared to conventional asphalt. The maximum temperature difference recorded was for the off-white sample and was equal to 12 °C. The CFD simulation results show that surface and air temperatures are decreased when applying the color thin layer sample.

1. Introduction

The urban microclimate is mainly influenced by increased building density with the canyon geometry, the use of materials with inappropriate optical and thermal properties and the lack of green spaces, increased anthropogenic heat and increased air pollution [1,2]. The Urban Heat Island (UHI) effect, with temperatures in urban areas higher by several degrees compared to the surrounding rural areas, has been documented in over 30 cities worldwide [3–10]. The UHI has the effect of increasing the demand (and peak demand) of energy for cooling and energy prices, accelerating the formation of harmful smog, as increasing energy demand generally results in greater emissions of air pollutants from power plants and higher air temperatures also favor the formation of ground-level ozone, and causing human thermal discomfort and health problems by intensifying heat waves over cities [1,2,11–18].

The surface temperature is of prime importance as it modulates the air temperature of the lowest layers of the urban atmosphere, it is central to the energy balance of the surface, helps to determine the internal climates of buildings and has an impact on the energy exchanges that affect the comfort of city dwellers [19]. Pavements (roads, parking spaces etc.) cover an important percentage of a city's surface and their thermal characteristics play a dominant role in the formation of the urban heat island effect. Paved surfaces contribute to sunlight's heating of the air near the surface and they can transfer heat downward to be stored in the pavement subsurface, where it is re-released as heat at night [20–22]. Asaeda [23] found that pavement heat flux in Tokyo is equal to about half the energy consumption rate of the city. Conventional pavements are usually impervious made of concrete and asphalt, with solar reflectance values ranging between approximately 4% and 45% [24,22], which can reach peak summertime surface temperatures of 48–67 °C [2,22,25,26], as reported from several experimental studies for hot summer climatic conditions.

One of the heat island mitigation strategies that has been proposed by researchers and has gained a lot of interest in the last years is the use of materials that present high reflectivity during the summer period [27,28]. Cool materials are characterized by high solar reflectance and infrared emittance values. These two

* Corresponding author. Tel.: +30 2107257533; fax: +30 2107295282.
E-mail address: asynnefa@phys.uoa.gr (A. Synnefa).

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properties result in lower surface temperatures. If the surface is on the building envelope, the heat penetrating into the building will be decreased, if it is any surface of the urban environment it will contribute to decrease the temperature of the ambient air as the heat convection intensity from a cooler surface is lower [29].

Cool roofing products are made of highly reflective and emissive materials, are usually bright white and can remain approximately up to 30 °C cooler than traditional materials during peak summer conditions [30,31]. Researchers and manufacturers, have also been developing cool colored roofing materials for the cases where the use of light colors creates glare problems or when the aesthetics of darker colors is preferred [32–34]. The Cool roofs technology and market is well established with measurement standards related to Cool Roof products (e.g. those by ASTM reported in [20]), organizations rating and promoting cool roof products [3,35–38] and energy codes including them.

Unlike cool roofing materials, cool paving materials technology is still under development, no official standards or definitions exist and more research in this field is required [15]. Cool pavements refer to a range of established and emerging materials that tend to store less heat and may have lower surface temperatures compared with conventional products [22]. As reported in [39], possible mechanisms for creating a cool pavement that have been studied to date are a) increased surface reflectance, which reduces the solar radiation absorbed by the pavement; b) increased permeability, which cools the pavement through evaporation of water; and c) a composite structure for noise reduction, which also has been found to emit lower levels of heat at night. This paper focuses on the first mechanism.

Increasing the solar reflectance of a paved surface keeps it cooler under the sun, reducing convection of heat from pavement to air and also thereby decreasing the ambient air temperature. Lower air temperatures decrease demand for cooling energy and slow the formation of urban smog. Measured data reported by [40], clearly indicate that increasing the pavements' solar reflectance by 0.25 causes significant decrease of the pavement temperature by 10 °C. Simulations of the influence of pavement albedo on air temperature in Los Angeles predict that increasing the albedo of 1250 km^2 of pavement by 0.25 could potentially reduce air temperature by 0.6 °C, which would result in significant benefits in terms of lower energy use and reduced ozone levels. More specifically, it would result in cooling energy savings worth $15 million per year, and smog-related medical and lost-work expenses reduction by $76 million $year^{-1}$ [41,42]. Many studies report the combined effect of increasing the albedo of both roofs and pavements, which can reduce the summertime urban temperature and improve the urban air quality [40,41,43–45]. In addition, increasing urban albedo can result in less absorption of incoming solar radiation by the surface-troposphere system, countering to some extent the global scale effects of increasing greenhouse gas concentrations. It has been estimated that increasing pavement albedo in cities worldwide by 0.15, could achieve reductions in global carbon dioxide (CO_2) emissions equivalent to 20 Gt, worth about $500 billion [46].

In addition to reduced air temperatures, energy use and air quality benefits, it has been shown, that reduced pavement surface temperatures can result in increasing the useful life (durability) of pavements and reduce waste from maintenance. Furthermore, reflective pavements can enhance visibility at night, potentially reducing lighting requirements and saving money and energy [47].

A potential drawback from raising the solar reflectance of pavements is that it could create glare problems, when driving for example, reducing also visibility of the white line; or it may not be appropriate in places where people will be uncomfortably exposed to the reflected radiation for long periods, as in a children's playground. In order to avoid these problems, Kinouchi et al. [48] have developed a new type of pavement that satisfies both high albedo and low brightness based on the application of an innovative paint coating on conventional asphalt pavement. The pigments and coating structure used are effective in achieving low reflectivity in the visible part of the spectrum (23%) and high near-infrared reflectivity (86%). Field measurements show that the maximum surface temperature of the paint-coated asphalt pavement is about 15 °C lower than that of the conventional asphalt pavement.

In this paper we report our work on five different colored thin layer asphalt samples that we developed and can be applied over new or existing asphalt pavements in good condition, in order to increase solar reflectance but maintaining a dark color. This study reports the results of the spectral analysis based on the measured optical properties of the samples, the analysis of the thermal performance of the samples under summer weather conditions and the evaluation of the impact of applying the samples in outdoor spaces using a computational fluid dynamics model.

2. Experimental procedure

In the framework of this study five (green, red, yellow, beige and off-white) color thin layer asphalt samples have been developed by an industrial partner of the University of Athens and were submitted for testing. The color thin layer asphalt samples were developed by mixing an elastomeric asphalt binder (colorless) and adding special pigments and aggregates of special sizes and colors. The tested samples are shown in Fig. 1. In addition, a sample of conventional black asphalt was also tested and used as reference. For the testing, the asphalt samples have been applied on asphalt membranes at a thickness of 0.5 cm. The dimensions of the samples were 33 × 33 cm for the temperature measurements.

In order to study the optical properties and the thermal performance of the coatings the following parameters were measured:

(a) The spectral reflectances of the samples. These were measured in the lab using a UV/VIS/NIR spectrophotometer (Varian Carry 5000) fitted with a 150 mm diameter, integrating sphere (Labsphere DRA 2500) that collects both specular and diffuse radiation. The reference standard reflectance material used for the measurement was a PTFE plate (Labsphere). Spectral reflectance measurements were performed according to ASTM E903-96: Standard Test

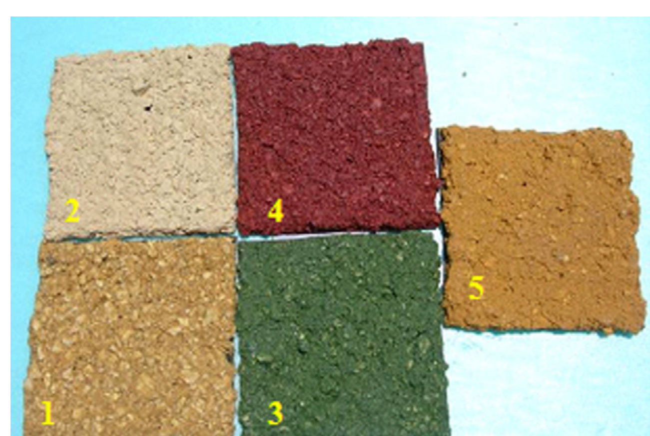

Fig. 1. The five (1. beige, 2. off-white, 3. green, 4. red, 5. yellow) tested color thin layer asphalt samples (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres.
(b) The surface temperature of the samples on a 24 h basis. The basic experimental equipment consists of surface temperature sensors (thermocouples type K) connected to a data logging system. Instantaneous values were measured and saved on a computer hard disc every 15 min. The temperature sensors were placed on the centers of the surfaces of each tile. An infrared camera (AGEMA Thermovision 570, 7.5–13 μm wavelength) was also used to depict the temperature differences between samples.

For the testing of their thermal performance the samples were placed on a specially modulated platform covering a surface of 20 m^2. The platform was horizontal, unshaded during the whole day and insulated from below in order to eliminate the heat transfer effects between the platform and the samples. The experimental procedure took place during the month of July 2008.

Measurements of the ambient climatic conditions, recorded from a meteorological station near the experimental site, include ambient temperature, relative humidity, wind speed, global and direct solar radiation on a horizontal surface and have been used to characterize the outdoor climatic conditions. The experimental period is characterized by typical clear sky conditions. The ambient temperature, the relative humidity, the monthly average daily direct and global solar radiation (W/m^2) on a horizontal surface during the experimental period are described in Table 1.

3. Analysis of the measured spectral optical properties of the tested samples

The results from the spectrophotometric measurements are shown in Fig. 2. Spectral reflectance data were used to calculate the solar reflectance of each sample. The calculation was carried out by weighted-averaging, using a standard solar spectrum as the weighting function. The spectrum employed is that provided by ASTM (see standards ASTM E903-96 and ASTM G159-98). Additionally, the solar reflectance values for the ultra violet (UV, 300–400 nm), visible (VIS, 400–700 nm), and near infrared (NIR, 700–2500 nm) part of the spectrum were calculated. These values for each sample are shown in Table 2.

The reflectance of the color thin layer asphalt samples was found to be higher than the reflectance of the conventional black asphalt in all the cases as it appears in Table 2 and Fig. 3. The solar reflectance of the samples ranges between 27% (red and green samples) and 55% (off-white sample), and the solar reflectance of the conventional black asphalt is 4%. Furthermore, all the samples present quite high absorptance in the UV (300–400 nm), ranging from 90% to 96% (Fig. 2 and Table 2).

In the visible part of the spectrum, the reflectance depends on the specific color. The highest visible reflectance was measured for the off-white colored sample (45%) and the lowest for the black conventional asphalt (3%).

As it is shown in Table 2 and Fig. 2, all the color thin layer asphalt samples demonstrate quite high reflectance values in the near infrared part of the spectrum, ranging from 39% to 56%. For all the samples the NIR solar reflectance is significantly higher compared to the visible reflectance. Even the dark colored samples (low visible reflectance), have high near infrared reflectance. For example, the green thin layer asphalt sample is characterized by a very low visible reflectance (10%), its near infrared reflectance reaches 39%. On the contrary, the conventional black asphalt sample demonstrates very low visible reflectance (3%) and also very low near infrared reflectance equal to 4%.

This high near infrared "invisible" reflectance, explains the fact that the color thin layer asphalt samples are characterized by high solar reflectance values. This is because although sunlight is more intense in the visible range, it also emits a substantial amount of energy in the invisible ultraviolet (UV) and near infrared (NIR). In fact, about half of all solar power arrives as invisible near-infrared radiation.

4. Study and analysis of the thermal performance of the samples

Based on the surface temperature measurements, the mean diurnal surface temperature (07:00–19:00 LST) and the mean nocturnal surface temperature (00:00–07:00 and 19:00–00:00) were calculated for each sample. The results of the calculations are shown in Table 3. The differences of the mean and the mean maximum surface temperature between the conventional black asphalt and the five color thin layer asphalt samples are also shown in Table 3.

Fig. 4 shows the 24 h distribution of the mean hourly surface temperatures of the tested samples during the experimental period. Mean hourly values of the ambient air temperature are also depicted.

During the day all the samples demonstrate surface temperatures that were higher than the ambient air temperature. During the night the air temperature is always higher than the surface temperature of the tested samples. This is because all the samples are characterized by high values of emissivity and thus have the ability to release faster the heat they have absorbed due to night sky radiative cooling.

As it is shown in Table 3 and Fig. 4, all the 5 colored thin layer asphalt samples demonstrate lower surface temperatures compared to the black conventional asphalt. The mean diurnal temperature of the color thin layer samples ranges from 39 °C for the off-white asphalt sample to 43.6 °C for the red sample. The corresponding temperature for the black conventional asphalt sample is 46.7 °C. The mean maximum diurnal surface temperature of the colored thin layer samples ranges from 48 °C for the off-white asphalt sample to 55.8 °C for the red sample. The corresponding temperature for the black conventional asphalt sample is 60 C, which means 12 ° higher than the off-white sample. It can be concluded that the red sample has a maximum surface temperature that is by 7% lower compared to the surface temperature of the black conventional asphalt, the green sample by 8%, the beige and yellow by 13% and 15% respectively, and the greatest difference was recorded for the off-white sample that equals 20%. Given the fact that all the samples are characterized by similar (about 0.9) values of thermal emittance then these temperature differences between the samples can be explained if we take into account the solar reflectance values of the samples. More specifically, the higher the solar reflectance, the lower the surface temperature, as less solar radiation is absorbed by the sample.

Table 1
Ambient climatic conditions during the experimental period (Source: National Observatory of Athens).

Time	Air temperature (°C)			Relative humidity (%)	Wind speed (m/sec)	Monthly average daily direct solar radiationα (W/m^2)	Monthly average daily global solar Radiation (W/m^2)
	Mean	Max	Min				
1st – 31st July 2008	28.7	39.3	20.5	44	3.7	6536	8004

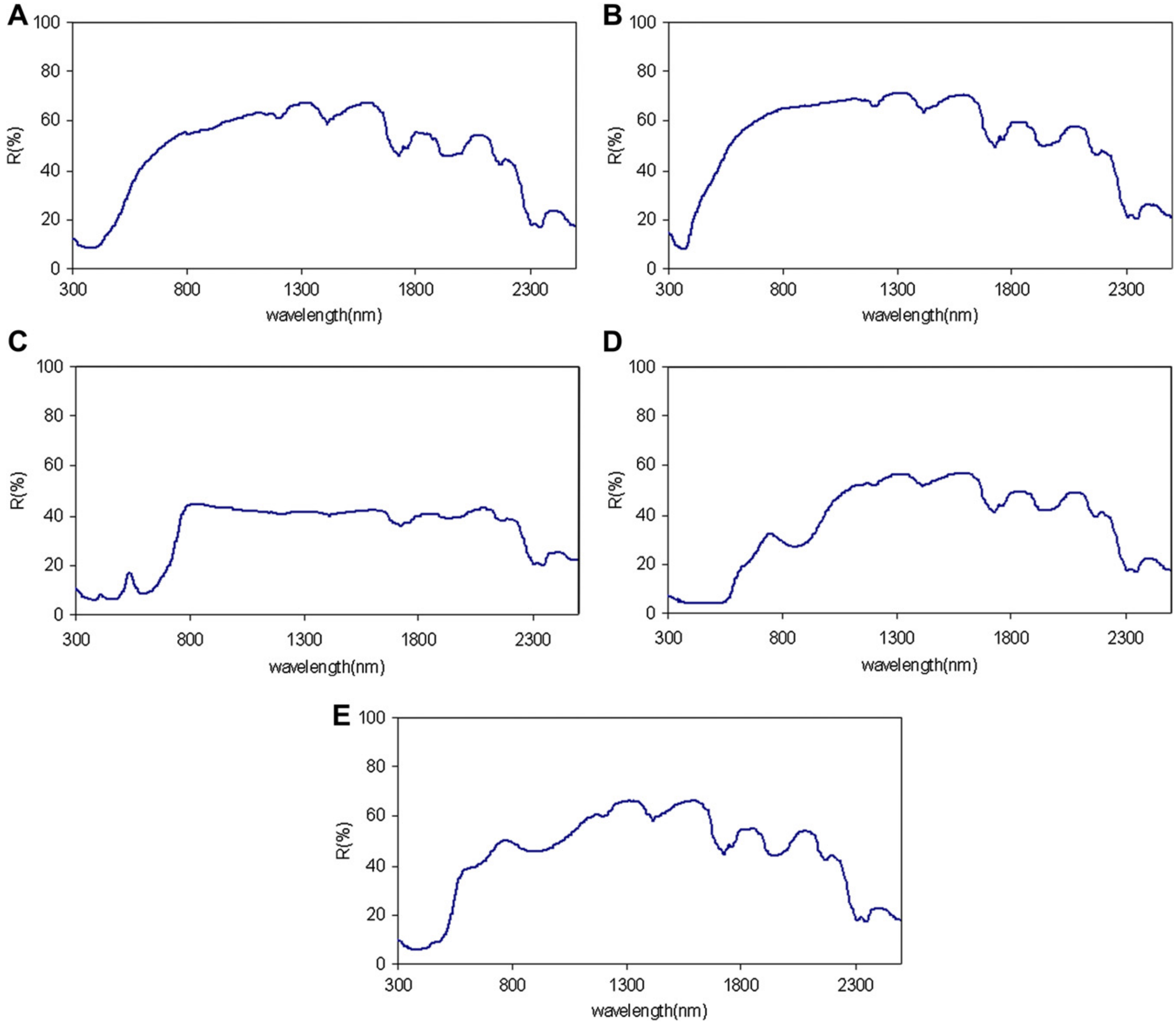

Fig. 2. The five (A. beige, B. off-white, C. green, D. red, E. yellow) tested color thin layer asphalt samples and the conventional black asphalt (F) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Infrared thermography was used to investigate the temperature distribution of the samples and to depict the differences in their thermal performance. Fig. 5 represents a visible and an infrared image of the six tested coatings. It was found that the sample temperatures were quite uniform. The visible and IR photos were taken during peak surface temperature time and for a hot summer day. As expected the black conventional asphalt sample that presents the lowest solar reflectance (0.04), appears as the hottest,

Table 2
Solar reflectance values (SR, 300–2500 nm) and solar reflectance values in the UV (300–400 nm), VIS (400–700 nm) and NIR (700–2500 nm) part of the spectrum of the five tested samples and the sample of conventional black asphalt.

Sample	SR (%)	SR_{UV} (%)	SR_{VIS} (%)	SR_{NIR} (%)
Beige thin layer asphalt	45	10	31	56
Off-white thin layer asphalt	55	10	45	63
Green thin layer asphalt	27	8	10	39
Red thin layer asphalt	27	6	11	40
Yellow thin layer asphalt	440	8	26	51
Conventional black asphalt	4	4	3	4

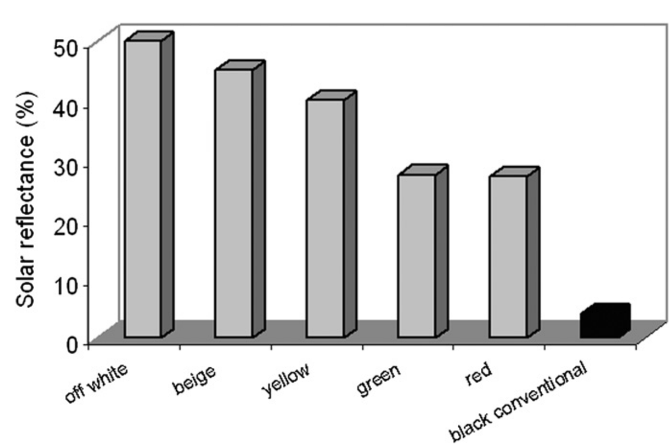

Fig. 3. The solar reflectance of the five tested color thin layer asphalt samples and the conventional black asphalt.

Table 3
Mean and mean maximum diurnal and nocturnal surface temperature of the tested samples during the experimental period.

Sample	Surface temperature (°C)				
	Diurnal				Nocturnal
	Mean	ΔT_{mean}	Mean max	ΔT_{max}	Mean
Black conventional	46.7	–	59.9	–	21.6
Off-white	39	7.7	48	11.9	21.1
Yellow	40	6.7	50.7	9.2	19.4
Beige	40.5	6.2	52	7.9	19.1
Red	43.6	3.1	55.8	4.1	20.7
Green	43.5	3.2	55.1	4.8	19.7

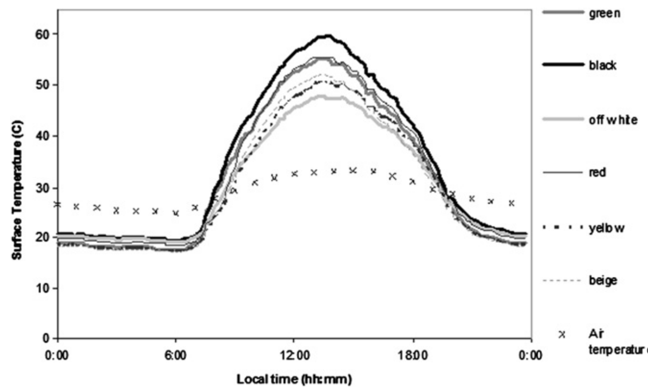

Fig. 4. 24h distribution of the mean hourly surface temperatures of the tested samples and air temperature during the experimental period (July 2008).

having surface temperature above 70 °C, followed by the red (SR = 0.27), the green (SR = 0.27) which present temperatures around 70 °C, while the yellow (SR = 0.40) and the beige (SR = 0.45) are about 8° cooler, as shown at the temperature scale of Fig. 5. The off-white thin layer asphalt sample with the highest solar reflectance (0.55) appears to have the lowest temperature, around 55 °C.

5. Evaluation of the impact of applying the samples in outdoor spaces

Decrease of the outdoor ambient air temperature has a very important impact on the cooling load of buildings. To evaluate the possible drop of the ambient temperature, computational fluid dynamics (CFD) techniques have been used. The exact impact of cool asphalt on air temperatures at local scale between a base case where conventional asphalt was used and another case using the off-white (SR = 0.55) sample has been investigated. The evaluation of the current as well as the proposed situation after the application of the examined cool material for microclimatic modification was achieved with the use of PHOENICS CFD (http://www.cham.co.uk/) model.

The PHOENICS CFD package has been configured to solve the Navier Stokes equations and it is a useful and efficient tool in the simulation of fluid flow. To represent the effects of turbulence the standard k-ϵ model was applied. The boundary conditions convey the necessary information about the temperature and wind field of the fluid on entry. The values of the surface temperatures were introduced as a boundary to PHOENICS and simulations of the ambient temperature and wind speed distributions have been performed. At the inflow boundaries, the wind field is specified.

Simulations were performed for the summer period for a leading north wind of 2 m/s at 10 m height (representative summer conditions) and the measured surface temperatures and solar reflectance of the samples reported in Sections 3 and 4 have been taken into account in the model. For the ambient temperature the mean daily maximum value for the summer period has been used in order to investigate the maximum impact of the materials. The examined area is a main, commercial road (Ag. Ioannou st. Agia Paraskevi) situated in the suburbs of Athens (Fig. 6A), surrounded mainly by a residential area and where cool asphalt materials were decided to be applied. The specific location has been chosen because a lot of field data were available from an experimental campaign carried out in the area in the framework of a project. The solution domain is illustrated in Fig. 6.

There are 4–5 story buildings adjacent to the road. The grid of the calculation domain has dimensions of 1380(x) × 1704(y) × 150 (z) m and consists of 80 × 140 × 50 cells at each axis respectively. Concerning the interference coming from boundaries to the flow and the necessary flow to develop, the distance between the object and the domain boundaries was arranged 6 times of the characteristic length for the position of the inlet (6H), 8 times for the position of outlet (8H) and 5 times for the lateral boundaries (5H). The top and side boundaries were treated as the symmetry conditions. For the ambient climatic conditions data from the National Observatory of Athens have been used.

According to the results of the simulations for the case where the conventional black asphalt (SR = 0.04 and maximum surface temperature 60 °C) is applied on the road, the air temperature at 1.5 m height, ranged between 37 °C and 47 °C (average 42 °C). For the second case, where the off-white thin layer asphalt (SR = 0.55 and maximum surface temperature 45 °C) was applied on the road, the air temperature at 1.5 m height, ranged between 36 °C and 41 °C (average 37 °C).

Fig. 7, describes the air temperature field at 1.5 m height for the simulated area for the case of the black asphalt (A) and for the case of the off-white thin layer asphalt (B).

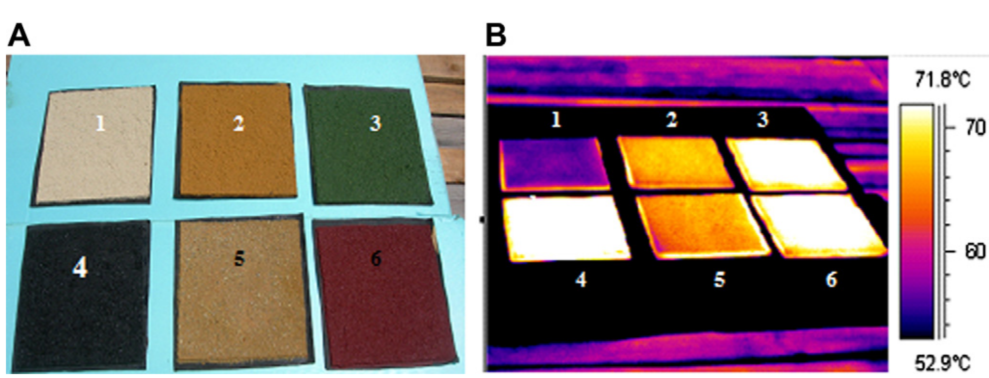

Fig. 5. Visible (A) and infrared (B) images of the five color thin layer asphalt samples and black conventional asphalt sample: 1. off-white, 2. yellow, 3. green, 4. black (conventional) 5.beige, 6. red (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

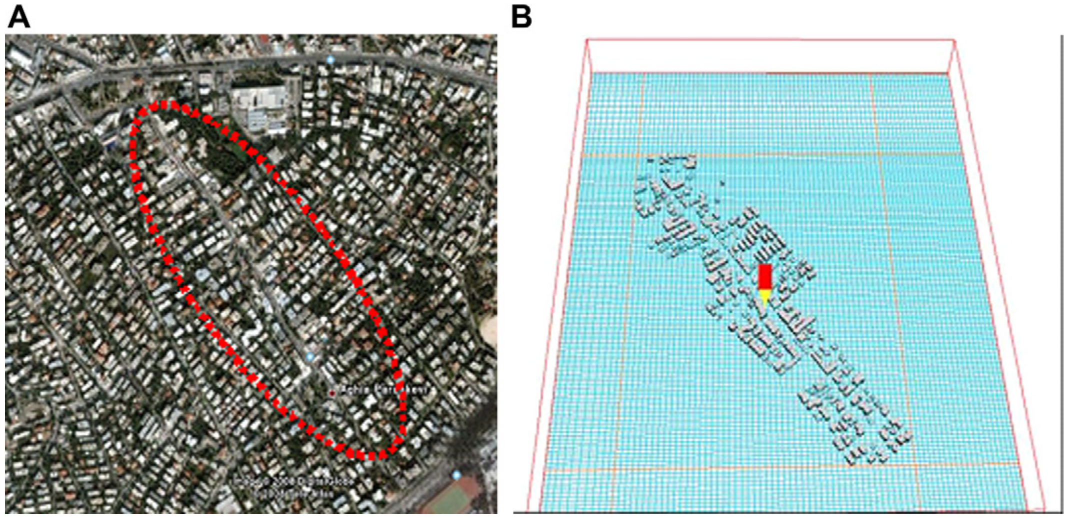

Fig. 6. Satellite image (A), geometry and calculation domain (B) of the simulated area.

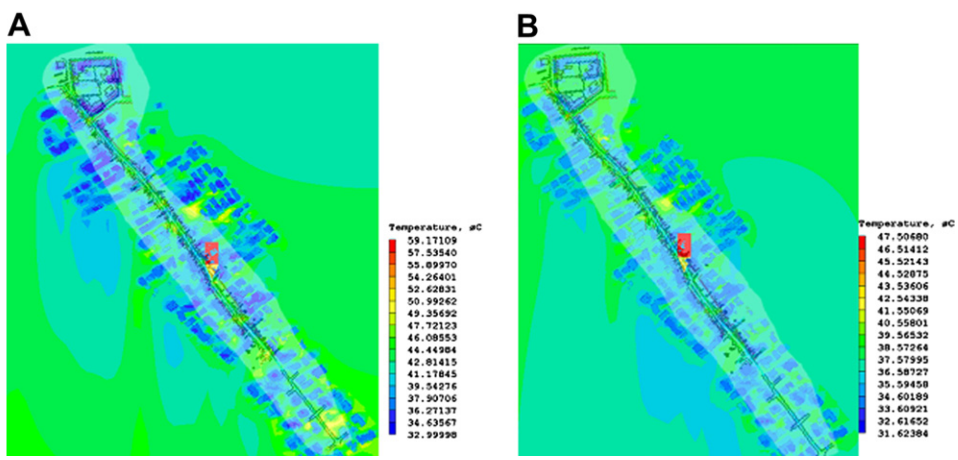

Fig. 7. The air temperature field at 1.5m height for the simulated area for the case of the black asphalt (SR = 0.04)(A) and for the off-white thin layer asphalt (SR = 0.55)(B).

Comparing the results of the first and second case it can be concluded that the application of the off-white thin layer asphalt on the road, resulted in a significant air temperature reduction in the simulated area equal to 5 °C on average under low wind speed conditions. Higher wind speeds may decrease the thermal contribution of cool asphalt as warm air will be transferred to the area by advection processes. This is explained by the fact that a surface with higher solar reflectance (e.g. off-white thin layer asphalt) will remain cooler under the sun compared to the surface covered with conventional absorbing dark asphalt, as it was verified experimentally. Consequently, from a cooler surface less heat will be transferred to the surrounding ambient air through convection and radiation.

Considering the fact that in most urban areas pavements cover a large percentage of the surface, a large scale application of this cool thin layer asphalt could have a significant impact in lowering surface and air temperatures, contributing to the mitigation of the heat island effect and its consequences.

6. Conclusions

Five colored thin layer asphalt samples that can be applied on existing and new asphalt pavements have been developed and tested in order to evaluate their optical and thermal performance. It was found that all the samples demonstrated higher solar reflectance values and lower surface temperatures compared to conventional black asphalt. CFD simulations showed that replacing conventional asphalt in a road could lead to an average air temperature decrease of 5 °C under low wind speed conditions. The results of this study indicate that the use of color thin layer asphalt in roads and pavements can have significant impact in lowering surface and air temperatures, mitigating thus the heat island effect and its consequences. It should be pointed out that although cool pavement technologies like the one investigated in this paper are already available, local governmental agencies lack the information and incentives to apply these in a coordinated and consistent way throughout city areas. It is important to create a strategic plan to promote cool pavements including measurement standards, defined rating and evaluation procedures as well as and financial incentives and policies for their application.

References

[1] Oke TR, Johnson DG, Steyn DG, Watson ID. Simulation of surface urban heat islands under 'ideal' conditions at night – part 2: diagnosis of causation. Bound-Layer Meteorology 1991;56(4):339–58. doi:10.1007/BF00119211.
[2] Santamouris M, editor. Energy and climate in the urban built environment. London: James and James Science Publishers; 2001.
[3] LBNL. Heat island group, http://heatisland.lbl.gov/.
[4] Santamouris M. Heat island research in Europe – state of the art. Advances Building Energy Research 2007;1:123–50.

[5] Kataoka K, Matsumoto F, Ichinose T, Taniguchi M. Urban warming trends in several large Asian cities over the last 100 years. Science of the Total Environment 2009;407(9):3112–9. doi:10.1016/j.scitotenv.2008.09.015.

[6] Livada I, Santamouris M, Niachou K, Papanikolaou N, Mihalakakou G. Determination of places in the great Athens area where the heat island effect is observed. Theoretical and Applied Climatology 2002;71:219–30.

[7] Mihalakakkou P, Santamouris M, Papanikolaou N, Cartalis C, Tsangrassoulis A. Simulation of the urban heat island phenomenon in mediterranean climates. Journal of Pure and Applied Geophysics 2004;161:429–51.

[8] Mihalakakou P, Santamouris M, Asimakopoulos D. Modeling ambient air temperature time series using neural networks. Journal of Geophysical Research 1998;103(D16):19509–17.

[9] Mihalakakou G, Flocas HA, Santamouris M, Helmis CG. Application of neural networks to the simulation of the heat Island over Athens, Greece, using synoptic types as a predictor. Journal of Applied Meteorology 2002;41:5519–27.

[10] Kolokotroni M, Giannitsaris I, Watkins R. The effect of the London urban heat island on building summer cooling demand and night ventilation strategies. Solar Energy 2006;80(4):383–92.

[11] Kolokotroni M, Zhang Y, Watkins R. The London heat island and building cooling design. Solar Energy 2007;81(1):102–10.

[12] Santamouris M, Paraponiaris K, Mihalakakou G. Estimating the ecological footprint of the heat Island effect over Athens, Greece. Climate Change 2007;80:265–76.

[13] Akbari H, Davis S, Dorsano S, Huang J, Winert S. Cooling our communities—A guidebook on tree planting and white coloured surfacing. US Environmental Protection Agency, Office of Policy Analysis, Climate Change Division; 1992.

[14] Hassid S, Santamouris M, Papanikolaou N, Linardi A, Klitsikas N, Georgakis C, et al. The effect of the Athens heat island on air conditioning load. Energy and Buildings 2000;32:131–41.

[15] Cartalis C, Synodinou A, Proedrou M, Tsangrasoulis A, Santamouris M. Modifications in energy demand in urban areas as a result of climate changes: an assessment for the southeast mediterranean region. Energy Conversion and Management 2001;42(14):1647–56.

[16] Santamouris M, Papanikolaou N, Livada I, Koronakis I, Georgakis C, Argiriou A, et al. On the impact of urban climate to the energy consumption of buildings. Solar Energy 2001;70(3):201–16.

[17] Tselepidaki I, Santamouris M, Asimakopoulos DN, Kontoyiannidis S. On the variability of cooling degree days in an urban environment: application to Athens, Greece. Journal Energy and Buildings 1994;21:93–9.

[18] Santamouris M, Mihalakakou G, Papanikolaou N, Assimakopoulos DN. A neural network approach for modelling the heat island phenomenon in urban areas during the summer period. Geophysical Research Letters 1999;26(3):337–40.

[19] Voogt JA, Oke TR. Thermal remote sensing of urban climates. Remote Sensing of Environment 2003;86(37):370–84.

[20] M Pomerantz, B Pon, H Akbari, SC Chang. The Effect of Pavements' Temperatures On Air Temperatures in Large Cities. LBNL Report-43442 2000.

[21] EPA. Reducing urban heat Islands: compendium of strategies cool pavements, http://www.epa.gov/hiri/resources/compendium.htm; 2009. Available on line at:.

[22] Santamouris M, Pavlou K, Synnefa A, Niachou K, Kolokotsa D. Recent progress on passive cooling techniques. Advanced technological developments to improve survivability levels in low – income households. Energy and Buildings 2007;39:859–66.

[23] Asaeda T, Ca VT, Wake A. Heat storage of pavement and its effect on the lower atmosphere. Atmospheric Environment 1996;30(3):413–27.

[24] Stathopoulou M, Synnefa A, Cartalis C, Santamouris M, Karlessi T, Akbari H. A surface heat island study of Athens using high-resolution satellite imagery and measurements of the optical and thermal properties of commonly used building and paving materials. International Journal of Sustainable Energy 2009;28(1):59–76.

[25] Synnefa A, Dandou A, Santamouris M, Tombrou M, Soulakellis N. Large scale albedo changes using cool materials to mitigate heat island in Athens. Journal of Applied Meteorology and Climatology 2008;47(11):2846–56.

[26] Doulos L, Santamouris M, Livada I. Passive cooling of outdoor urban spaces. The role of materials. Solar Energy 2001;77:231–49.

[27] Karlessi T, Santamouris M, Apostolakis K, Synnefa A, Livada I. Development and testing of thermochromic coatings for buildings and urban structures. Solar Energy 2009;83(4):538–51.

[28] Santamouris M, Synnefa A, Kolokotsa D, Dimitriou V, Apostolakis K. Passive cooling of the built environment – use of innovative reflective materials to fight heat island and decrease cooling needs. International Journal Low Carbon Technologies 2008;3(2):71–82.

[29] Bretz S, Akbari H. Long-term performance of high albedo roof coatings. Energy and Buildings 1997;25:159–67.

[30] EPA. Reducing urban heat islands: compendium of strategies cool roofs, http://www.epa.gov/hiri/resources/compendium.htm; 2009. Available on line at:.

[31] Synnefa A, Santamouris M, Livada I. A study of the thermal performance and of reflective coatings for the urban environment. Solar Energy 2006;80:968–81.

[32] Levinson R, Akbari H, Reilly JC. Cooler tile-roofed buildings with near-infrared-reflective non-white coatings. Building and Environment 2007;42(7):2591–605.

[33] Levinson R, Berdahl P, Akbari H, Miller W, Joedicke I, Reilly J, et al. Methods of creating solar-reflective nonwhite surfaces and their application to residential roofing materials. Solar Energy Materials and Solar Cells 2007;91(4):304–14.

[34] Synnefa A, Santamouris M, Apostolakis K. On the development, optical properties and thermal performance of cool colored coatings for the urban environment. Solar Energy 2007;81:488–97.

[35] Energy star roof products, http://www.energystar.gov/index.cfm?c=roof_prods.pr_roof_products.

[36] Cool roof rating council, http://www.coolroofs.org/.

[37] Epa: US environmental protection agency, http://www.epa.gov/hiri/mitigation/index.htm.

[38] EU cool roofs project web site, http://www.coolroofs-eu.eu/.

[39] Cambridge Systematics, Inc.. Cool pavements draft report, http://www.epa.gov/hiri/resources/pdf/CoolPavementReport_Former%20Guide_complete.pdf; 2005. Available on line at.

[40] Akbari H, Pomerantz M, Taha H. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy 2001;70(3):295–310.

[41] Rosenfeld AH, Akbari H, Romm JJ, Pomerantz M. Cool communities: strategies for heat island mitigation and smog reduction. Energy Build 1998;28 1:51–62.

[42] Taha H. Modeling the impacts of large-scale albedo changes on ozone air quality in the south coast air basin. Atmospheric Environment 1997;31(11):1667–76.

[43] Taha H. Meteorological and Air Quality Impacts of Increased Urban Surface Albedo and Vegetative Cover in the Greater Toronto Area, Canada, Lawrence Berkeley National Laboratory Report No. LBNL-49210, Berkeley, CA; 2002.

[44] Taha H. Potential Impacts of Climate Change on Tropospheric Ozone in California: A Preliminary Episodic Modeling Assessment of the Los Angeles Basin and the Sacramento Valley, Lawrence Berkeley National Laboratory Report No. LBNL-46695, Berkeley, CA; 2001.

[45] Taha H, Chang S-C, Akbari H. Meteorological and Air Quality Impacts of Heat Island Mitigation Measures in Three U.S. Cities, Lawrence Berkeley National Laboratory Report No. LBL-44222, Berkeley, CA; 2000.

[46] Akbari H, Menon S, Rosenfeld A. Global cooling: increasing world-wide urban albedos to offset CO2. Climatic Change 2009;94:275–86. doi:10.1007/s10584-008-9515-9.

[47] Pomerantz M, Akbari H, Harvey JT. The benefits of cooler pavements on durability and visibility, Lawrence Berkeley National Laboratory Report No. LBNL-43443, Berkeley, CA; 2000.

[48] Kinouchi T, Yoshinaka T, Fukae N, Kanda M. Development of cool pavement with dark colored high albedo coating, Fifth Conference for the Urban Environment, Vancouver, Canada; 2004.