Investigation of the Solar and Thermal Properties of Materials Used in Outdoor Urban Spaces and Buildings

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ABSTRACT

This paper aims to report the solar and thermal data for various common and innovative materials used in outdoor urban applications. The tested materials include various types of coatings, tiles and asphalt pavement. In the framework of this research, the spectral reflectance and the emissivity of the materials were measured using a UV/VIS/NIR spectrophotometer fitted with an integrating sphere and an emissometer. The solar reflectance of the samples was calculated. Furthermore, the influence of the solar reflectance and the infrared emittance on the surface temperature of the materials was analyzed by calculating the surface temperature that each material can reach when exposed to solar radiation. Experimental data on the surface temperature of the tested materials, acquired by using surface temperature sensors and a data logging system, are also reported. Materials with high albedo and emittance, the so-called cool materials, attain lower surface temperatures when exposed to solar radiation, reducing the transference of heat to the environmental air. High surface temperatures increase the demand of energy, they accelerate the formation of harmful smog and cause human thermal discomfort by intensifying the heat island effect in urban areas. The results of this study will assist in a good environmental planning, with the selection of more appropriate materials for buildings and the urban environment, contributing to the mitigation of the heat island effect.

KEYWORDS

Pavement and building materials, passive cooling, solar reflectance, surface temperature, infrared emittance

INTRODUCTION

Urban areas around the world are continuously growing in size and population and open spaces and vegetation are being replaced by building structures. As a result, solar energy is absorbed by concrete and paved surfaces, causing the surface temperature of urban structures to become several degrees higher than ambient air temperatures. As surfaces become warmer, overall ambient temperature increases. This phenomenon, called “urban heat island”, has the effect of increasing the demand of energy, accelerating the formation of harmful smog and causing human thermal discomfort (Oke et al. 1991, Cartalis et al. 2001, Santamouris 2006). Among the factors that contribute to the heat island effect, the thermal properties of the materials used in the urban fabric play a very important role. The presence of dark surfaces, particularly roofs and pavements, absorb solar radiation during daytime and reradiate it as heat during the night and furthermore the replacement of natural soil and vegetation by the materials reduces the potential to decrease ambient temperature through evapotranspiration and shading (Santamouris, 2001; Akbari et al., 1996). The use of cool materials as a heat island mitigation strategy and a cooling energy saving measure has gained a lot of interest during the past few years. Cool materials are characterized by high solar reflectance and infrared emittance

values. These two properties mainly affect the temperature of a surface (Bretz et al. 1997, Akbari et al. 1997, Rosenfeld et al. 1996). Increasing either reflectance and/or emittance lowers a surface' s temperature, which in turn decreases the heat penetrating into the building, if it is a surface of the building envelope, or contributes to decrease the temperature of the ambient air, as heat convection intensity from a cooler surface is lower. In order to make appropriate choices, when selecting materials for buildings or other outdoor urban spaces, it is important to know the optical properties and thermal performance of available materials. Simpson and McPherson (1997) found that white roofs (~albedo 0.75) were up to 20 °C cooler than gray (~0.30 albedo) or silver (~0.50 albedo), and up to 30°C cooler than brown (~0.10 albedo) roofs. Measurements showed that simply increasing the albedo of a building surface may not be effective in reducing its temperature and heat gain if its emissivity is reduced simultaneously. Asaeda et al (1996) found that the surface temperature, heat storage and its subsequent emission to the atmosphere were significantly higher for asphalt than for concrete and bare soil. Santamouris, (2001) reports asphalt temperatures close to 63° C and white pavements close to 45° C. Prado et al. (2004) reports the albedo for various roofing materials and also the temperature that each material can reach when exposed to solar radiation. Doulos et al., (2004) studied the thermal performance of 93 commonly used pavement materials. It was found that tiles made of marble, mosaic and stone were cooler than the tiles made of concrete pavestone and asphalt. Furthermore the light colored tiles with a smooth surface were cooler than the dark colored with rough surfaces. Researchers at LBNL have created a database that reports the solar reflectance, the infrared emittance and the temperature rise of various commonly used roofing materials, aiming to assist with the selection of more appropriate roofing materials.
This study reports the measured solar reflectance and infrared emittance of various common and some innovative materials used on buildings envelopes and other outdoor urban applications. Furthermore, data on the thermal performance of these materials is also given in an effort to characterize them as cool or warm.

EXPERIMENTAL PROCEDURE

In the framework of this study 28 materials were studied. These materials can be devided into 3 categories: a) coatings (white, aluminum and tinted) b) paving materials (asphalt, mosaic, concrete etc.) and c) tiles (Table 1). All the coatings tested are acryl-based coatings that can be used on building envelopes (roofs and walls) and other surfaces in the urban environment.
In order to study the optical properties and the thermal performance of the coatings the following parameters were measured:
a) The spectral reflectance of the samples was measured using UV/VIS/NIR spectrophotometer (Varian Carry 5000) fitted with a 150mm 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).
b) The infrared emittance of the samples was also measured with the use of the Devices & Services emissometer model AE. This emittance device determines the total thermal emittance, in comparison with standard high and low emittance materials.

c) The surface temperature of the samples on a 24h 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 10 minutes. The temperature sensors were placed on the center of the surface of each tile.
For the surface temperature measurements, the coatings were applied on white concrete pavement tiles of 40cm x 40cm and all the samples were placed on a specially modulated horizontal platform, insulated from below covering and a surface of $20m^2$.

OPTICAL AND PHYSICAL PROPERTIES

The results of the spectrophotometric measurements were used in order to calculate the solar reflectance of each sample. The calculation was done by the weighted averaging method, using a standard solar spectrum as the weighting function. The spectrum employed is that suggested by ASTM (ASTME903-96, ASTMG159-91). The values of solar reflectance for each sample are shown in Table 1. The solar reflectance varies according to the color and the construction material. As expected, white and light colored materials have higher values of solar reflectance. For different materials of the same color, the white marble tile for example has a higher solar reflectance than a white concrete tile.
The values for the infrared emittance are also included in Table 1. For the majority of the tested materials the infrared emittance is quite high (about 0.9) with the exception of the two aluminum pigmented coatings. This is because they contain aluminum flakes that have a very low emissivity. High infrared emittance values reveal the ability of a warm or hot material to reradiate some of its heat in the form of infrared radiation and therefore contribute to keeping a surface cooler.
Regarding the coatings, the ones named “cool” were developed at the University of Athens using specialized, inorganic color pigments that are dark in color but have the ability to reflect strongly the near infrared (NIR) (Synnefa et al.2006). Coatings colored with conventional pigments tend to absorb near-infrared radiation. The replacement of these NIR absorbing pigments by cool pigments that have the ability to reflect more near-infrared radiation can lead to the development of coatings that have similar colors and yet higher solar reflectance (Table 1). This is very important because in many cases the aesthetics of darker colors is preferred. The use of cool colored coatings is not limited to their direct application on building envelopes and other surfaces of the urban environment; they can also be used to manufacture other cool colored building materials. Figure 1 depicts the spectral reflectance of cool and conventional black coatings as well as the spectral reflectance of the dark gray concrete tile. As it can be seen, the concrete tile and the conventional black coating show strong absorption over the entire solar spectrum. Cool black however is spectrally selective having NIR reflectance that is significantly higher compared to those of the other two materials. This means that if a cool coating was used for the manufacturing of the dark gray pavement it could have a much higher solar reflectance. Several engineering methods have already been developed to apply cool coatings to roofing materials (clay tiles, concrete tiles, metal roofs and shingles). In general, the solar reflectance of commercially available roofing products has increased from 0.05 to 0.25 to 0.30-0.45 for all materials. (Akbari et al. 2005).

TABLE 1
Solar reflectance, infrared emittance, calculated maximum surface temperature (Tsc) and measured mean maximum surface temperature (Tsm) of tested materials (*the surface of these materials is rough, with a pattern, NA: not available)

Material	Solar reflectance	Infrared emittance	Tsc (°C)	Tsm (°C)
Paving materials				
Black mosaic	0.22	0.9	74	63
Red concrete pavement*	0.38	0.9	66	53
Yellow concrete pavement*	0.56	0.9	57	48
Grey concrete *	0.20	0.9	75	NA
Aged Asphalt	0.15	0.9	78	53
New Asphalt	0.06	0.9	82	62
Dark Grey concrete*	0.13	0.9	79	NA
White Mosaic	0.65	0.9	52	47
White concrete pavement tile	0.55	0.9	58	46
Coatings				
White crylic, ceramic coating	0.83	0.92	43	41
White acrylic, elastomeric coating	0.79	0.93	45	43
White acrylic latex	0.85	0.89	42	41
White alkyd, chlorine rubber coating	0.82	0.91	44	41
White acryl-polymer emulsion paint	0.83	0.91	43	41
Aluminum pigmented coating 1	0.75	0.49	51	55
Aluminum pigmented coating 2	0.65	0.35	59	51
Brown coating	0.09	0.88	80	65
Cool brown coating	0.27	0.88	72	59
Green coating	0.20	0.88	76	61
Cool green coating	0.27	0.88	72	61
Blue coating	0.18	0.88	77	62
Cool blue coating	0.33	0.88	69	56
Black coating	0.05	0.88	82	66
Cool black coating	0.27	0.88	72	60
Tiles				
Red clay tile	0.44	0.9	63	NA
Beige Ceramic tile	0.56	0.9	57	55
Brown ceramic tile	0.38	0.9	66	61
White marble	0.73	0.9	49	45

ANALYSIS OF THE THERMAL PERFORMANCE OF THE MATERIALS

In order to evaluate the thermal performance of the materials surface temperature measurements were taken during one month under warm summer conditions. The average maximum temperature was estimated (Table 1). Additionally, the surface temperature that each material can reach when exposed to solar radiation was calculated using the equation describing the thermal balance of a surface under the sun that is insulated underneath (eqn 1) (Bretz, S. et al. 1997), as is the case for the samples of this experiment.

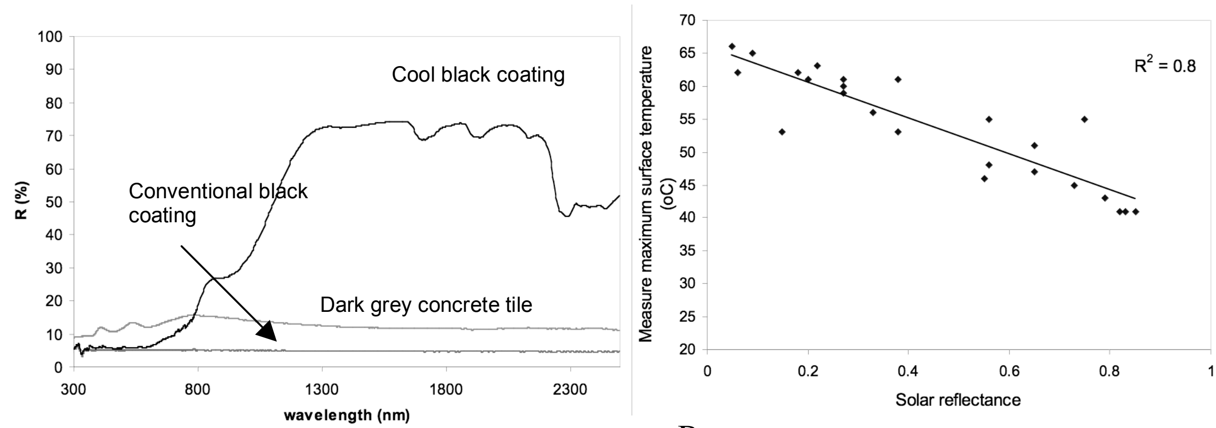
$$(1-a)I = \varepsilon\sigma(T_s^4 - T_{sky}^4) + h_c(T_s - T_a) \qquad (1)$$

where:

a solar reflectance or albedo of the surface

I	total solar radiation incident on the surface (I= 1000 *W/m*^{2}*)*
ε	emissivity of the surface
σ	Stefan-Boltzmann constant, 5.6685 × 10^{-8} $Wm^{-2}K^{-4}$
T_s	equilibrium surface temperature, K
T_{sky}	the effective radiant sky temperature (T_{sky} =300K)
h_c	convection coefficient, (h_c =12 $Wm^{-2}K^{-1}$)
T_a	air temperature, (T_a =310 K).

The calculations were performed according to the ASTM standard E1980-01. During the day the thermal performance of the samples is mainly affected by their surface solar reflectance because it represents the part of the incident total solar radiation that is reflected. Figure 1B shows that there is a strong correlation (R^2 = 0.8) between the maximum surface temperature measurements and the solar reflectance of the samples. The differences that are observed between the calculated and the measured values of surface temperature could be due to several reasons like the surface roughness that could have introduced errors to the calculation of solar reflectance and infrared emittance, or the fact that the convection coefficient was assumed equal for all the tiles, etc. The coolest materials were the white coatings and the white marble with maximum surface temperatures around 40°C. The warmest materials were found to be the dark colored ones like the new asphalt, the conventional black coating that reached temperatures higher than 60°C . White colored coatings performed better than aluminum-pigmented coatings. Although all the coatings are characterized by a high solar reflectance, aluminum pigmented coatings are less desirable because they tend to remain hotter due to their low infrared emittance.missivity has a lower impact compared to reflectance. During the night, when there is no solar radiation, emissivity becomes the predominant factor affecting the thermal performance of the tiles.



A B

Figure 1:A) The spectral reflectance of dark gray concrete tile and of the cool and conventional black coatings. B) The correlation between the measured maximum surface temperatres and the solar reflectance of the samples.

CONCLUSIONS

In the framework of this study the solar reslectnce, infrared emittance and surface temperature of various building and paving materials were measured and reported. Materials with higher solar reflectance and infrared emittance like white marble, white coatings and in general light colored materials reach lower surface temperature staying cooler under the sun compared to dark colored materials. It was also demonstrated that there is the possibility for further improvement of the solar reflectance of dark colored building and paving materials by using cool coatings/ pigments instead of conventional ones in the process of their manufacturing. The results of this study can contribute to the selection of more appropriate materials for buildings and other outdoor urban applications, contributing to the mitigation of the heat island effect.

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