A comparative study of the thermal performance of reflective coatings for the urban environment

A. Synnefa, M. Santamouris and I. Livada
National and Kapodistrian University of Athens, Section Applied Physics, Physics Department, Greece

ABSTRACT

This paper presents the results of a comparative study aiming to investigate the effect of reflective coatings on lowering surface temperatures of buildings and other surfaces of the urban environment, and thus test their suitability to lower ambient temperatures and fight the heat island effect. In total, 14 types of reflective coatings on surfaces of the urban environment were studied, from August to October 2004. In order to measure the thermal performance of the reflective coatings, surface temperature sensors and a data logging system as well as infrared thermography procedures were used. The collected data have been extensively analysed. It was demonstrated that the use of reflective coatings can significantly reduce surface temperatures.

1. INTRODUCTION

The phenomenon of the heat island is becoming increasingly more intense in urban areas, changing their microclimate. Heat islands are an energy efficiency concern because increased air temperatures raise air-conditioning loads in buildings, in turn raising energy consumption, peak energy demand and energy prices (Akbari et al., 1992; Santamouris et al., 2001). Furthermore, heat islands increase smog production (Taha et al., 1994). 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 colored 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).

Therefore the use of high albedo urban surfaces is a passive and inexpensive measure that can reduce summertime temperatures (Akbari et al., 1992, 1997; Bretz et al., 1997).

One way to increase the reflectance of surfaces is by using "cool" coatings that are characterized by a high solar reflectance and high infrared emittance values. Architects traditionally have recognized that reflective building colors can reduce building thermal loads. Several studies have been carried out regarding the cooling potential of the application of reflective coatings on buildings. Givoni and Hoffman, (1968) reported that unventilated small buildings in Israel that had white colored walls were approximately 3°C cooler in summer than when the same buildings were painted grey. (Taha et al., 1992) measured the albedo and surface temperatures of various materials used in urban surfaces and found that white elastomeric coatings that have an albedo of over 0.72, were 45°C cooler than black coatings with an albedo of 0.08. (Akbari et al., 1998) reported that increasing the roof reflectance of commercial buildings in California from about 20% to 60% dropped the roof temperature on hot summer afternoon by 45F. Akridge, (1998) showed that the installation of a thermal control coating on a single storey building with identified high roof temperatures, reduced the peak roof temperature by 33°C.

The scope of this study is to report the measured data of the surface temperatures of 14 types of reflective coatings that are used in buildings and some of them are used or could be used in the future in other surfaces of the urban environment (sidewalks, parking lots, etc.). All the coatings were applied on concrete tiles and their ability to reduce surface temperatures was evaluated. Their thermal performance was monitored on 24h basis from August to October 2004. The temperature rise of the surfaces under sunlight as well as their cooling potential during the night was measured and compared to that of an uncoated surface as well as to other "cold" materials. The effect of weathering is also being discussed.

2. EXPERIMENTAL MEASUREMENTS

2.1 Description of the selected coatings

For this study 14 types of reflective coatings were selected from the international market. These coatings are commonly used or can be used in the urban environment's external surfaces (building walls and roofs, sidewalks, pavements, parking lots etc.). Additionally to the 14 reflective coatings a black coating, an uncoated concrete tile, a white marble tile and a white mosaic tile were also studied, to be used for comparison.

All the coatings were applied on white concrete pavement tiles. The tiles had a size of 40cm x 40cm. The selected samples and their possible applications are described in Table 1.

2.2 Instrumentation and description of the experimental site

In order to study the thermal performance of the coatings the surface temperature of the samples was measured on a 24h basis. The basic experimental equipment consists of surface temperature sensors connected to a data logging system. The sensors used were thermocouples (type K), and Analog to Digital (ADAM4018) thermocouple input modules were used for data collection and conversion. The temperature sensors were placed on the center of the surface of each tile. An infrared camera (AGEMA Thermovision 570, 7.5-13μm wavelength) was also used in order to observe the temperature distribution on the surface of the samples as well as to depict the temperature differences between the samples.

Measurements of the ambient meteorological conditions, recorded from a meteorological station near the experimental site, include ambient temperature, relative humidity and wind speed and have been used to characterize the outdoor climatic conditions. During the experimental period, the meteorological conditions were characterized by clear skies, low wind speed (<5m/s), high temperatures and relatively low relative humidity values. The samples were placed on an especially modulated platform covering a surface of $16m^2$. The platform was horizontal 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 months of August, September and mid October of 2004.

Table 1: Description of the studied coatings.

Sample	Sample description	Applications	Sample color
S1	Aluminium pigmented acrylic coating	B	Silver gray
S2	Acrylic, ceramic coating	B	White
S3	Acrylic, elastomeric coating.	B	White
S4	Acrylic, elastomeric coating	B	White
S5	Alkyd, chlorine rubber coating	UB, B	White
S6	Aluminum pigmented, alkyd coating	B	Silver gray
S7	Emulsion paint	-	Black
S8	Acryl-polymer emulsion paint	B	White
S9	Acrylic latex	UB, B	White
S10	Aluminum pigmented coating	B	Silver
S11	Acrylic insulating paint	B	White
S12	Aluminum pigmented acrylic coating	B, UB	Silver
S13	Epoxy polyamide coating	UB	White
S14	Acrylic paint	B	White
S15	Uncoated tile (reference)	B, UB	White
S16	Acrylic elastomeric coating	B	White

B: buildings, UB: urban environment

3. ANALYSIS OF THE THERMAL PERFORMANCE OF THE COATINGS

3.1 Experimental results and discussion

Infrared thermography was used to investigate the temperature distribution of the samples and to depict the differences in their thermal performance. It was found that the sample temperatures were quite uniform.

The estimated mean daily (from 08:00 to 19:00) and nocturnal (from 22:00 to 05:00) surface temperatures for each month and for each

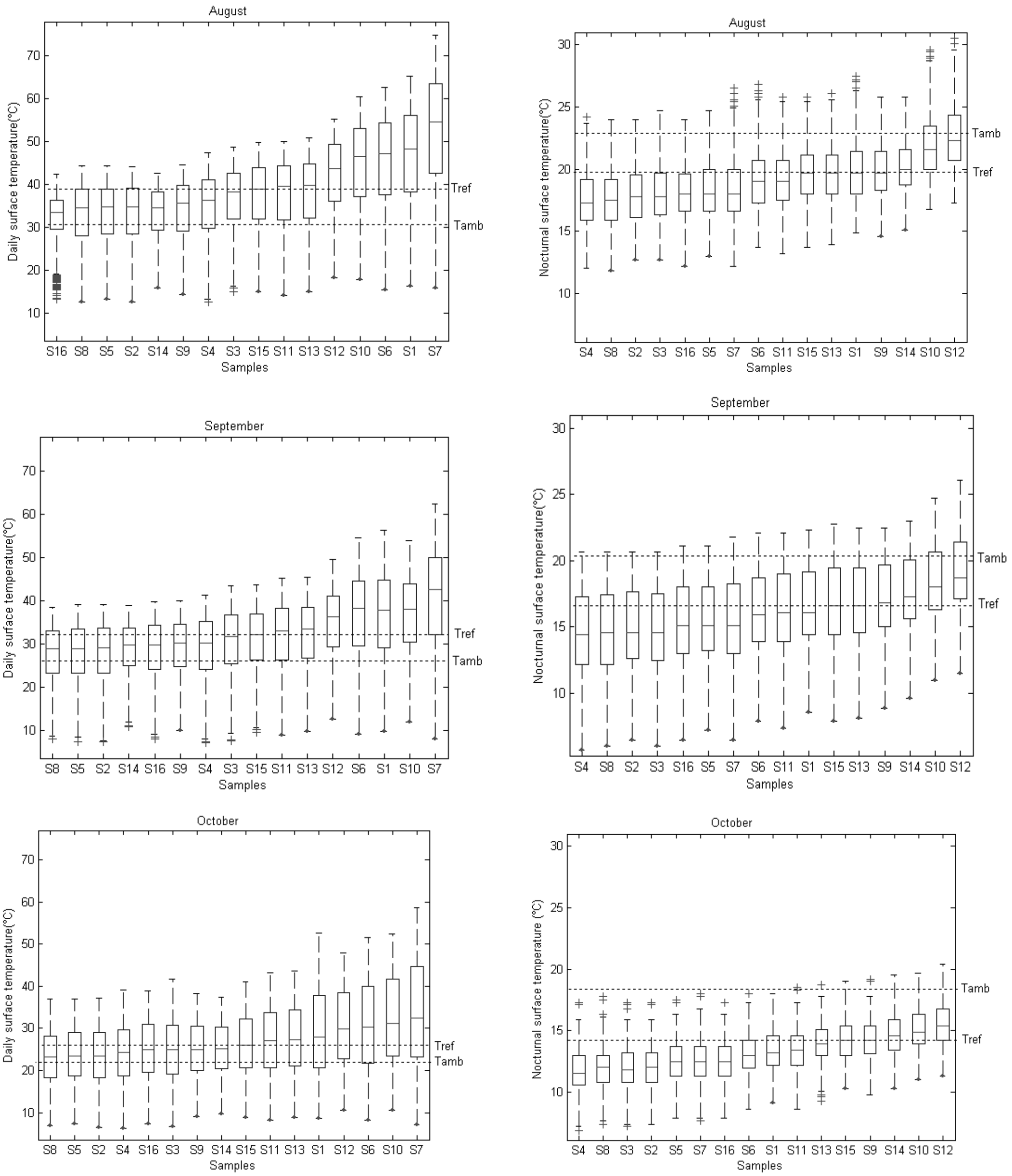

Figure 1: Boxplots of the daily (08:00-19:00) and nocturnal (22:00-05:00) surface temperatures during the experimental period.

coating sample are given in statistical boxplots (Fig. 1). The boxplots represent a statistical distribution of the measured surface temperatures of each one of the coating samples. In these figures the median, lower and upper quartile values are represented as well as the extent of the rest of the data. Outliers are data with values beyond the ends of the tails. The coatings with the smallest average surface temperature are presented at the left part of each graph, while the warmest coatings are presented at the right part. Additionally, on the boxplot figures the mean surface temperature of the reference uncoated tile (Tref) as well as the mean ambient temperature (Tamb) are indicated by dotted lines.

The minimum values of the mean and absolute maximum daily surface temperatures were observed for the white coatings. On the contrary the maximum corresponding values were noticed for the silver colored coatings. For the first month of the experimental period, mean daily surface temperatures ranged between 32.1°C (for S16) and 46.2°C(for S1), for the second month, between 27.7°C (for S5) and 36.8°C(for S10), and for the third month between 23°C (for S2) and 32.1°C(for S10). The absolute maximum daily surface temperatures, for the total experimental period, varied from 42.3° C (for S2) to 65.1°C (for S1).

During the night period, the mean surface temperature ranged between 17.5°C, 14.4°C, and 11.6°C (for S4) and 22.6°C, 18.8°C and 15.5°C (for S12), for each month of the experimental period respectively. The absolute maximum nocturnal surface temperature, for the total experimental period, varied from 24°C (for S2 and S8) to 30.5°C (for S12).

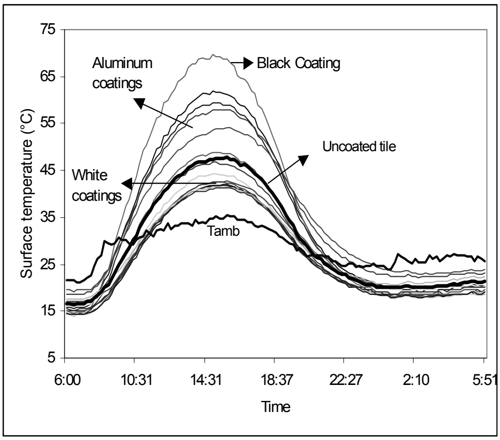

Figure 2: Typical 24h distribution of surface temperatures.

Figure 2 shows typical thermal behaviour prevailing throughout a 24h period.

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. Emissivity 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. The convection coefficient can be assumed equal for all the tiles, since all the samples are exposed to the same wind conditions, they are placed on the same height and their surfaces roughness are similar. At some point during the night the term $T_s – T_a$, becomes negative, which means that heat is transferred from the ambient air to the samples by convection, because the samples have lower temperatures than the ambient air.

This explains why the white coatings stay cooler during the day compared to the aluminum-pigmented coatings. Although all the studied types of coatings are characterized by a quite high solar reflectance, aluminum coatings stay warmer during the night due to their lower infrared emittance, because they reradiate as heat smaller parts of the solar energy they had absorbed during the day. On the contrary, a white coating radiates more of its stored heat back to the sky. For this reason, aluminum does not perform as well as a white coating with similar solar reflectance.

The comparison of the thermal performance of the coated concrete tiles with the uncoated reference tile demonstrated that the use of an appropriate coating can significantly reduce the surface temperature of the tile. More specifically:

During the daytime period, the white colored coatings, except from S11 and S13, had the ability to reduce the surface temperature of the concrete tile on which they were applied. The maximum temperature decrease was observed for the coatings S8, S5 and S2 that reduced the concrete tile's surface temperature by 4.3°C, 4°C and 4°C, respectively during the first month of the experiment. On the contrary, the silver colored coatings were found to increase the concrete tile's surface temperature. The maximum temperature increase was observed for the coating S10 whose mean surface temperature was averagely 6.3 higher than the uncoated tile's surface temperature.

The cooling potential of the coatings is even greater regarding the peak surface temperature. The maximum surface temperature of a tile coated with S14 (white acrylic paint) was by 7.5°C cooler than the uncoated tile.

During the night period, ten coatings demonstrated surface temperatures that were lower than the surface temperature of the uncoated concrete tile. The coolest coatings were S2, S3, S4 and S8 that managed to reduce the surface temperatures by averagely 2°C.

3.2 The effect of weathering

A very important factor regarding the thermal performance of coatings is weathering and "dirt pick-up" resistance. Weathering is caused by surface contamination (atmospheric pollution, biological growth) and/or other alterations like UV radiation, sudden temperature swings, moisture penetration etc. As it is shown in Figure 1, there is degradation in the thermal performance of several coatings, mainly S16, S14 and S9. The most important change in the thermal behavior was observed for the coating S16: acrylic elastomeric coating, that was the coolest coating during the daytime period the first month of the experiment, but became a lot warmer during the second and third month of the experimental period (Fig. 1). A graph (Fig. 3) was created depicting this degradation in the thermal performance of the coating S16. On the vertical axis appears the temperature difference between the

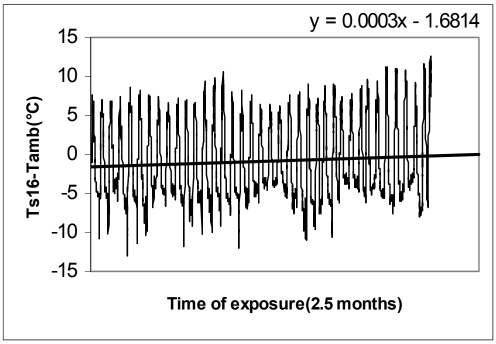

Figure 3: The effect of weathering for the sample S16.

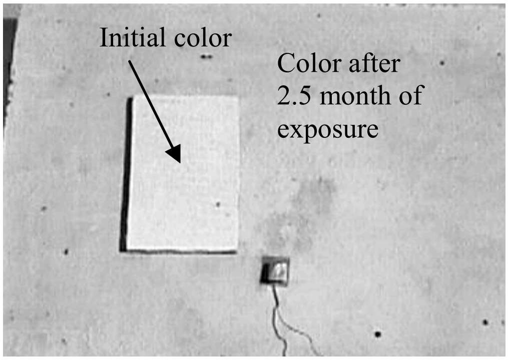

Figure 4: S16's surface colour after 2.5 months of exposure to outdoor conditions in comparison with its initial colour.

surface of S16 and the ambient air (in order to exclude the influence of weather conditions) and on the horizontal axis is the time of exposure (2.5 months). Although the time of exposure is short, the surface temperature of the coating S16 clearly shows an increasing trend. Figure 4, depicts S16 and S5 coatings' surface color after 2.5 months of exposure to outdoor conditions in comparison with their initial color. There is clearly a change in the surface color of S16 that is due to weathering and its low "dirt pick-up" resistance.

3.3 A comparative analysis between the surface coatings temperatures and the ambient temperature.

Comparing the coatings sample's mean surface temperature with the mean ambient air temperature during the experimental period, the following can be concluded:

A) All the studied coatings were characterized by greater average surface temperatures than the average air temperature, during the daytime period. The coolest coatings were the white colored ones. Among the white colored coatings, S2, S5 and S8 were warmer than the ambient air by only 2°C, while S11 and S13 were averagely by 6°C warmer than the ambient air. Among the silver coloured materials the minimum temperature difference was observed for S12 and was estimated at 9.6°C and maximum temperature difference was observed for S10 and was estimated at 11.7°C.

B) During nighttime, all the samples were characterized by lower mean surface temperatures than the ambient air. The maximum temperature difference was observed for the coatings S4, S8, S3 and S2 that were cooler than the ambient air by 6°C, 5.9°C, 5.7°C and 5.7°C respectively.

3.4 A comparative analysis between the surface coatings temperatures and two other cool materials

A white marble tile and a white mosaic tile, that have been characterized as “cold” materials (L. Doulos et al., 2004), were also studied. The concluding remarks, comparing the coatings’ and the two materials’ surface temperatures during the experimental period are the following:

A) During daytime, seven coatings samples (S2, S4, S5, S8, S9, S14 and S16) had lower mean surface temperatures than both the marble’s and the mosaic’s mean surface temperature. The maximum difference in mean surface temperature was found to be between S2 and the marble tile (3.8°C) and between S2 and S8 and the mosaic tile (4.1 °C).
B) Regarding the daily absolute maximum temperatures, the differences were even greater. The absolute maximum surface temperature of the coating S14 was found to be lower by 4.7°C and 6.3°C than the maximum surface temperatures the marble tile and the mosaic tile, respectively.
C) During the night period, the majority of the coating samples demonstrated mean surface temperatures that were similar or a little higher than the surface temperatures of the white marble and white mosaic tile, except from coating samples S4, S2 and S8 that had lower mean surface temperatures by 0.4°C, averagely.

These measurements demonstrate that the thermal performance of a concrete tile on which a reflective coating has been applied is superior to the performance of a white marble and mosaic tile.

4. CONCLUSIONS

Fourteen types of reflective coatings were studied and it was found that the use of an appropriate reflective coating can significantly reduce surface temperatures. As it was expected 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. A “cool” coating can reduce a white concrete tile’s surface temperature under hot summer conditions by 4 °C and during the night by 2°C. It can be warmer, than the ambient air by only 2°C during the day and cooler than the ambient air by 6°C. However, the effect of weathering can cause degradation in the thermal performance of a coating, therefore coatings with good weathering and “dirt pick-up” resistance should be chosen.

This study arises from the need to put forward passive solutions, which can mitigate the negative effects of the heat island phenomenon. At building scale, the use of reflective coatings could improve building comfort and reduce cooling energy use, and at city scale it could contribute to the reduction of the air temperature due to heat transfer phenomena and therefore improve outdoor thermal comfort and reduce the heat island effect.

REFERENCES

Akbari, H., S. Davis, S. Dorsano, J. Huang and S. Winert, 1992. Cooling our Communities –A Guidebook on Tree Planting and White Colored Surfacing, US Environmental Protection Agency, Office of Policy Analysis, Climate Change Division.

Akbari, H., M. Pomerantz, H. Taha, A. Rosenfeld and J. Romm, 1996. Policies to reduce heat islands: magnitudes of benefits and incentives to achieve them. Proceedings ACEEE Summer study on energy efficiency in buildings Vol.9: pp.177.

Akbari, H., S. Bretz, D.M. Kurn and J. Hanford, 1997. Peak power and cooling energy savings of high-albedo roofs. Energy and Buildings:Vol. 25:pp. 117-126.

Akbari, H., L.M. Gartland and S.J. Konopacki, 1998. Measured energy savings of light coloured roofs: Results for three California demonstration sites. ACEEE 1998 Summer study on energy efficiency in buildings: Efficiency and sustainability Vol.3:pp.3.1-3.12.

Akridge, J.M., 1998. High-albedo roof coating-Impact on energy consumption. ASHRAE Transactions Vol. 104, Pt.1b: pp. 957-962

Bretz, S., H. Akbari and A. Rosenfeld, 1997. Practical issues for using solar-reflective materials to mitigate urban heat islands. Atmospheric Environment Vol.32: pp. 95-101.

Doulos, L., M. Santamouris and I. Livada, 2004. Passive cooling of outdoor urban spaces. The role of materials. Solar Energy Vol.77: pp.231-249.

Givoni, B. and M.E. Hoffman, 1968.Effect of Building Materials on Internal Temperatures. Research Report, Building Research Station, Technion Haifa.

Santamouris, M. (Ed.), 2001. Energy and climate in the urban built environment. James and James Science Publishers, London.

Taha, H., D. Sailor and H. Akbari, 1992. High albedo materials for reducing Cooloing energy use. Lawrence Berkley Laboratory Report 31721, UC-350, Berkley CA.

Taha, H., 1994. Meteorological and photochemical simulations of the south coast air basin, in Taha (ed), Analysis of Energy Efficiency of Air Quality in the South Coast Air Basin - Phase II, Rep. No LBL-35728, Lawrence Berkeley Laboratory, Berkeley CA, Ch. 6, p.p. 161-218.