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Analysis of retro-reflective surfaces for urban heat island mitigation: A new analytical model

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HIGHLIGHTS

- Retro-reflective (RR) pavements are an effective strategy for mitigating UHI.
- Directivity properties of RR samples are assessed by a new experimental facility.
- An analytical model is proposed to describe the optic-energy profiles of RR films.
- RR materials may be treated as common diffusive surfaces by a correction factor.
- The model may be used to evaluate the mitigation effects in urban canyons.

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ABSTRACT

Solar reflectance of buildings' envelope and urban paving represents an important optic-energetic property for the characterization of building energy performance for cooling and to reduce the urban heat island effect. Together with the emissivity, it represents the main feature contributing to the overheating reduction of a surface exposed to sunlight. Additionally, solar reflectance depends, among other factors, also on the angular distribution of the incident energy Additionally, solar reflectance depends on the angular distribution of the incident energy, which effect is rarely taken into account to estimate its cooling potential. This paper deals with an experimental and analytical study for the assessment of the angular reflectance of retro-reflective films. An ad hoc experimental facility is designed to measure the angular reflectance of retro-reflective samples. Measurement results are used to determine an original analytical model which describes the optic-energy behavior of retro-reflective materials. The experimental campaign and a novel analytical model showed that retro-reflective materials could be effectively applied as coatings on urban paving and building envelope, in order to reflect the solar radiation beyond the urban canyon and the urban canopy in general.

1. Introduction

The continuous growth of the urban area and its density, together with a general lack of a proper energy design has produced a huge impact on urban microclimate [1]. Both building energy efficiency and microclimate are influenced by the morphology and the density of the constructions [1,2]. In particular, the Urban Heat Island (UHI) phenomenon is essentially produced by:

(i) the dense constructions' surfaces which absorb the solar radiation more than natural surfaces [3],
(ii) the growing anthropogenic heat flux, due to energy requested for the space cooling and heating [4–6].

The phenomenon gets even worse because the temperature increase in urban context yields to a further increase of buildings' cooling energy demand and, therefore, of peak electricity demand; it also exacerbates the urban environmental pollution and human discomfort together with a further greenhouse gasses production [7].

Intensive research has been carried out in recent years in order to investigate possible innovative and effective mitigation strategies, such as energy saving solutions and innovative tools to evaluate building energy efficiency [8–10], new renewable energy sources aimed at reducing the use of fossil fuels [11–14], innovative paving [15], land use change [16–18]. For what concerns building energy efficiency, the passive role of materials in buildings' envelope is essential for thermal balance. In fact, surface materials are responsible for the absorption of the solar radiation and for the heat exchange rate with the atmosphere [3]. In this perspective, the research is focused around the so called "cool materials": cool

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Nomenclature

D	width of the urban canyon in Fig. 7 (m)
H	height of the urban canyon in Fig. 7 (m)
K	constant of Eq. (7) (W/m^2·sterad)
n	concentration factor
r	reflectance on solar spectrum
W_i	incident global (hemispherical) energy (W/m^2)
W_r	reflected global (hemispherical) energy (W/m^2)
$W_{r,\alpha}$	reflected energy in the α direction (W/m^2·sterad)
$W_{r,\perp}$	reflected energy in the perpendicular direction (W/m^2·sterad)
W_{r,α_j}^{Meas}	measured value of reflected energy in the α_j direction (W/m^2·sterad)
W_{r,α_j}^{Theor}	value of reflected energy in the α_j direction predicted by the mathematical model (W/m^2·sterad)
α	angle between the perpendicular direction to the surface and the direction of reflection (deg, values between $-90°$ and $90°$)
α_0	angle represented in Fig. 7 (°)
Δ_j	error functions calculated between the measured values and the theoretical values in the α_j direction (W/m^2·sterad)^3
ε	sum of Δ_j functions (W/m^2·sterad)^3
η_0	reduction factor, ratio between reflector and diffusive short wave reflected energies which remains inside the canyon
θ_i	angle between the perpendicular direction to the surface and the direction of an incident beam (°)
Ω	solid angle (sterad)
Ω_0	solid angle referred to α_0 (sterad)

roofs [19,20], cool pavements [21] and other innovative solutions such as phase change materials and thermochromic coatings. [1]. In particular, “cool roofs” produce an acknowledged impact on local peak ambient temperature [22,23]; their impact in terms of urban climate mitigation potential has been studied in important contributions. Savio et al. [24] evaluated the daily average temperature decrease at 2 m height above ground in New York City through the Pennsylvania State University/National Center for Atmospheric Research numerical model, known as MM5 regional climate model simulation. Synnefa et al. [25] evaluated their effect in the reduction of the UHI in Athens by the MM5 climate model by comparing two modified albedo scenarios; they found out a maximum effect in terms of temperature decrease up to 2.2 K. Rosenfeld et al. [26] estimated the cooling potential of the albedo increase in 1250 km^2 of pavements in Los Angeles by 0.25. The results show a temperature reduction of 1.5 K and the consequent reduction of energy requirement for cooling and environmental pollution. Coherent results have been also found out by several studied by utilizing the MM5 mesoscale climate model [27–29]. Additionally, important results have been found by the analysis of the urban albedo change through cool roof applications in terms of global climate mitigation potential. An increase of roof and pavement by 0.25 is estimated to decrease the radiative forcing by 0.15 W/m^2, with a corresponding 44 Gt of emitted CO_2 offset [30,31].

Many other studies have also documented the role of “cool materials” in terms of building energy efficiency [32–34]. They represent a relatively simple and cost-effective technique aimed at improving the urban microclimate and reducing building energy demand for cooling [35]. “Cool materials” are typically characterized by:

(i) high solar reflectance (capability to reflect the solar spectrum radiation),
(ii) high infrared emittance (ability of a surface to emit energy by radiation when its temperature is higher than 0 K).

Façades, roofs and pavements, no matter the material they are composed by, generally behave as diffusive materials for their reflectance and emission is mainly ruled by the Lambert law [8]. In this paper, a specific experimental and analytical assessment is carried out on materials with peculiar optical performances: retro-reflective (RR) materials. They are studied through traditional methodologies and through an ad hoc experimental setup aimed at defining their angular reflectance distribution and their surplus potential to mitigate the UHI phenomenon. An original analytical model is finally determined by the measurement results, which allows to describe the optic-energy behavior of RR materials.

2. Motivation

Given the contribution of “cool materials” to mitigate the UHI phenomenon and to improve building energy efficiency, this paper deals with the experimental analysis and the mathematical modelization of RR materials. In this way, a comparison between RR and traditional cool materials may be carried out in terms of UHI mitigation.

In terms of the characterization of cool materials, the common procedures to estimate the reflectance capability concern several technologies, which allow to calculate the hemispherical reflectance of each surface through both in lab and in situ analysis, such as:

1. a spectrophotometer equipped with integrating sphere, which allows to measure the hemispherical radiation reflected by the tested surface, because the integrating sphere appraises both the specular and the diffuse radiation reflected by a flat, uniform, 0.1 cm^2 sample [1,36,37],
2. a portable solar reflectometer [38],
3. the pyranometer for in situ measurements [39],

For what concerns the emissivity, this property is usually measured by a portable emissometer which is able to give back an integrated value, following the guidelines reported in ASTM C1371-04 and ASTM E408 [40,41].

RR materials mostly reflect the incident radiation in the same direction of the incoming radiation (i.e. the reflected beam has the same direction of the incident beam, Fig. 1). Their reflectivity should be characterized through specific technologies and procedures which are able to capture their singular behavior over the hemisphere, in different directions. In fact, the profile of their reflectance capability does not describe hemispherical shape, as assumed by the Lambert law. Therefore, the most common testing procedures, such as the in-lab spectrophotometer measurements with integrating sphere [8] and the in situ pyranometer applications [42–44], could not be used to investigate their optical characteristics over different directions. Additionally, previous analysis of RR materials only concerns the calculation