Experimental assessment of the combined effect of retroreflective façades and pavement in urban canyons

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Abstract. Retro-reflective (RR) materials represent an opportunity to reduce UHI phenomenon due to their ability to reflect most of the incident energy towards the same incoming direction. The RR behaviour depends on the angular distribution of the incident energy: for small incident angle the radiation is reflected mainly backward in the incoming direction; for large angles RR materials reflect the radiation symmetrically with respect to the surface normal. To overtake the limit of RR materials of being mainly retroreflective only for small angles of incidence, the investigation is focused on the optic interaction between vertical and horizontal RR surfaces. Therefore, the aim of this paper is to investigate the synergic effect of RR pavements and façades on a physical model in which urban canyon layouts with H/W equal to 1 and 2 are represented. To evaluate the global cooling effect of RR pavements and façades, a new parameter, called equivalent albedo, is introduced and calculated over the canyon’s ceiling. The results show that a canyon with RR vertical surfaces and RR pavement reflects outward more radiation than a canyon with RR vertical surfaces and diffusive pavement due to the interaction of optical properties of the materials.

1. Introduction
Urban heat island (UHI) phenomenon affects most of the major cities in the world [1] with serious effects on environment, health, and social and economic conditions. The morphological, structural and physical characteristics of cities that cause a greater absorption and storage of solar radiation and the increase of anthropogenic heat flux are the main causes of the phenomenon [2]. In order to counterbalance UHI effect several actions have been undertaken. These include studies on building materials, vegetation and urban design. The ability of cool materials as “cool roof” and “cool pavement” to reduce urban temperatures and energy consumption for cooling purposes has been investigated [3-4]. An interesting research line have been developed around retro-reflective (RR) materials and their optic-energy performances [5-8]. The peculiar optic property of these materials consists in their ability to reflect most of the incident energy towards the same incoming direction. In particular, this occurs for small incidence angles with respect to the surface normal. For large angles of incidence, RR materials reflect the radiation mainly symmetrically [9]. The dependence of the RR materials behavior on the angle of incidence induces for a further investigation on the interaction among buildings’ façades and pavements in urban canyon. In effect, this aspect may represent an important chance to reduce the amount of energy that is trapped within the urban canopy, thanks to multiple reflections between RR façades and RR pavements [5].

The present paper aims to investigate the optic interaction between RR façades and RR pavements. To reproduce a real scenario, a scaled physical model of an urban canyon is used for the experimental investigation [9]. Two case studies are investigated and compared. In Case 1, the vertical surfaces are RR and the pavement is diffusive; in Case 2 both the vertical surfaces and the pavement are RR.
The two scenarios are compared to evaluate the cooling potential of RR façades and RR pavement, in terms of the decrease of diffuse reflected energy contributing to the canyon overheating, with respect to the RR façades and diffusive pavement. RR materials could be applied as coatings on urban paving and building envelopes with noticeable benefits in dense urban configurations.

2. Materials and Methods

2.1. Background

Previous studies have already discussed the property of RR materials to reflect backward the incident radiation for small angles and symmetrically for large incidence angles [5, 9]. This peculiar response to the incident radiation can be used to reduce the diffuse reflected energy inside the urban canyon.

Referring to Figure 1, when solar radiation (red arrow) comes from high incidence angles (like in the summer season) and hits RR coating of the walls, this is mainly reflected towards the floor of the canyon (green arrows). The radiation that reaches the floor is reflected in two different ways due to the optical characteristics of the diffusive and RR materials:

- Case a: Diffusive pavement. The radiation hits the floor with a small angle (green arrow). The diffusive pavement diffuses the radiation (yellow arrows). Therefore, a lower percentage of the hitting radiation is reflected back to the wall and consequently a lower percentage of radiation is reflected out of the canyon (blue arrow).

- Case b: RR pavement. As in Case a, the radiation hits the pavement with a small angle (green arrow). The RR reflects the radiation mainly backward to the incoming direction, and thus towards the vertical walls (yellow arrows). The incidence angle is now large. Therefore the incoming radiation is mainly reflected symmetrically, that is beyond the canyon (blue arrow).

This induces to quantify the global cooling effect generated by the interaction of RR pavement and RR façades. To this purpose, the concept of equivalent albedo have been introduced with Equation 1:

\[
A_{eq} = \frac{\int_{A_{lid}} W_r dA}{\int_{A_{lid}} W_i dA}
\]

The equivalent albedo is defined as the ratio between the reflected radiation \( W_r \) and the incident radiation \( W_i \) over the canyon’s ceiling. This parameter, calculated from the punctual values distributed in the considered domain, is discussed in this paper and results are presented.

2.2. Equipment

The experimental facility consists of a small-scale urban canyon exposed to outdoor radiation and an ad-hoc pyranometer (AHP). The urban canyon is reproduced with two metal frames (H = 0.6 m and L = 4.2 m) supporting insulating panels (t = 0.2 m). The frames’ distance represents the canyon width (W) can be changed to reproduce several canyon ratios (H/W). In the presented configuration, W was set to 0.3 m and 0.6 m. The investigated value of the H/W ratio is 2 and 1 respectively. The vertical panels were covered with a RR coating for their whole length (Figure 2). The horizontal surface, which represents the pavement of the canyon, was covered with two coatings characterized by different directional optical properties: a diffusive film (Scotchcal 50 -10) and a RR film (3M Sheeting Series 3930). The diffusive material is a self-adhesive, stabilized, polymeric, calendered, vinyl sheet with a thickness of 200 µm. The RR material is a white high-intensity microprismatic reflective...
sheeting with a thickness of 200 µm. Three measurement points were selected over the ceiling of the canyon, at the middle length of the canyon in order to neglect any boundary effect (Figure 3). The selected points represent the punctual distribution of the equivalent albedo. At each point, the incident radiation and the reflected radiation were measured, with two photodiodes. Technical characteristics and pictures of the used photodiodes are in [9], as well as the quantification of measurement uncertainty. The pyranometer provides an outlet signal in mV proportional to the radiation, collected by an analogue input acquisition device, supplied by National Instruments (NI 9219, NI cDAQ-9172).

Figure 2. Experimental facility on the left: urban canyon case H/W ratio = 1 (H = 0.6 m, L = 4.2 m, and W = 0.6 m). Investigated materials on the right: a) retro-reflective (RR) and b) diffusive.

Figure 3. Measurement points. Canyon a) H/W = 2, distance 0.05 m from the internal edges of the canyon. Canyon b) H/W = 1, distance 0.1 m from the internal edges of the canyon.

2.3. Methodology

In the present paper, samples of the used materials were characterized in terms of both spectrophotometric and directional properties. The global hemispherical solar reflectance even in terms of spectral distribution of the samples is measured by Shimatzu SolidSpec 3700 spectrophotometer equipped with 60 mm integrating sphere. The range of measurements is 280–2500 nm, which includes the 99 % of the solar energy. The solar reflectance of the samples was then calculated using the appropriate standards (ASTM Standard G 173 [11-12]). The angular reflectance of the used materials (RR and diffusive) was evaluated by an ad-hoc experimental facility introduced in a previous article [9]. For measurements of albedo, two canyon scenarios were considered: each canyon wall had a RR surface, and the canyon floor had either a RR surface or a diffusive surface. The ad-hoc pyranometer (AHP) was used to sample the downflux and upflux at 3 points, that represent the punctual values distributed in the considered domain over the canyon ceiling: West Row and East Row (side rows) and Central Row (in accordance with the measurement grid in Figure 3). For each one of the two materials tested as paving in the canyon physical model, the following experimental procedure was followed. The AHP was positioned on the selected points of the measurement rows.
Then, positioning the AHP in each measurement point, the voltage signals from the two photodiodes are acquired ten times, every 5 seconds, and then averaged, obtaining $V_{d1}$ (downward signal from photodiode 1) and $V_{u2}$ (upward signal from photodiode 2). The same procedure was repeated after flipping the photodiodes, obtaining other two values: $V_{d2}$ (downward signal from photodiode 2) and $V_{u1}$ (upward signal from photodiode 1). The values were measured hourly, in order to have values for different sun positions through the day. Canyon equivalent albedo ($A_{eq}$) is evaluated as the ratio of area-integrated upflux to area-integrated downflux.

3. Results and discussion

3.1. Characterization of RR materials

The spectral reflectance measurements show that the reflectance of the two samples is comparable. The diffusive sample reflectance is equal to 69.6 % while the RR sample reflectance is equal to 62.4 %. The angular distribution of reflected light is represented using polar coordinates in Figure 4, for the following angles of incidence: 10°, 30°, 50° and 70°. The incident solar radiation strikes the samples with positive angles of incidence. Since retro-reflected radiation has the same direction of the incident radiation, it has always positive angles of reflection, from 0° to 90°. On the other hand, the amount of radiation symmetrically reflected has always negative angles, from 0° to -90°. RR sample shows the preponderance of retro-reflected radiation for 10° and 30°. At 60° retro-reflection property is maintained, although symmetrically-reflected radiation percentage is higher than the retro-reflected one. At 70°, retro-reflection is completely lost and there is only specular reflection. The diffusive sample does not have a preferential retro-reflecting direction.

3.2. Canyon equivalent albedo results

Two campaigns were carried out to investigate the interaction between canyon’s façades and pavement. On the vertical surfaces, the RR material was used, while the floor was covered with two different materials, diffusive and RR. The evaluation is a comparison between two materials that show the same global reflectance but different directional properties.

In Figure 5, the equivalent albedo distribution in the measurement points through the day for the analysed configurations and the average values are shown. The ratio between reflected and incident energy increases over the canyon’s ceiling in case of RR pavement, reaching values of about 95% in proximity of the façades. Table 1 shows the average daily value of albedo for each row and the equivalent albedo, defined as the ratio between the reflected radiation $W_r$ and the incident radiation $W_i$ over the entire canyon’s ceiling, was calculated for both the cases discussed in this paper. The value of the ratio of reflected and incident radiation calculated in the central row is much higher (about 5%) in the RR pavement setup than in the diffusive pavement one. In fact, although the two materials have comparable global reflectance, RR material shows a much higher reflectance (about 26%) in the perpendicular direction in comparison with the diffusive one (about 13 %). The orthogonal
radiation on the floor is in fact mainly diffused by the diffusive coating, while it is mainly reflected backward by RR coatings.

![Graphs showing equivalent albedo variation during the day for investigated configurations.](image)

**Figure 5.** Equivalent albedo variation during the day for the investigated configurations.

| Case                      | Central Row | RR | West Row | East Row | Equivalent albedo (%) |
|---------------------------|-------------|----|----------|----------|-----------------------|
| Diffusive pavement H/W = 1| 87%         | 91%| 91%      | 94%      |                       |
| RR pavement H/W = 1       | 93%         |    | 95%      | 95%      | 93%                   |
| Diffusive pavement H/W = 2| 87%         | 91%| 91%      |          | 89%                   |
| RR pavement H/W = 2       | 92%         | 94%| 94%      |          | 89%                   |

Some considerations are then dedicated to the values recorded on the lateral rows: there is an increase of the energy sent beyond the canyon with respect to the central row in both the scenarios. Nevertheless, in case of diffusive pavement the difference between side rows and central row is equal to about 2 %, while with the RR pavement, the difference is equal to about 4 %. Comparing the effect of the pavement on the albedo in the side rows, the values pass from about 91 % with the diffusive one to 95 % with the RR one.

Furthermore, it is interesting to notice the daily trend of reflected/incident energy in canyons with H/W equal to 2, that is the narrower setup. The daily trend shows two different behaviours in the RR and in the Diffusive pavement cases. In the Diffusive one, the reflected/incident value is maximum in the middle hour and decreases when the solar direction diverges from zenith or the perpendicular to the pavement. In the RR pavement case, the daily trend of reflected/incident energy is almost constant: the amount of the energy that strikes the vertical surface before and after the central hours of the day
that is reflected towards the pavement, kicking of the interaction that was foreseen in the theory section. Such results demonstrate experimentally that a synergic interaction between RR façades and RR pavements occurs.

The interaction between RR vertical and horizontal surfaces brings an overall increase of the equivalent albedo on the canyon of about 5 %, from 89.0 % to 94.0 %, with a consequent reduction of the thermal energy trapped inside the canyon.

4. Conclusions
This paper investigates the cooling potential of RR materials in urban canyons to reduce UHI effect. Since in this study only radiative properties are taken into account, data obtained in the physical model are valid also for a full-scale case.

Results show that the optic synergy between façade and pavement is strongly influent if the RR materials are applied on both the surfaces. In this case, in fact, the albedo on the canyon’s ceiling is increased up to 95%.

A new parameter, called equivalent albedo, is introduced and defined as the ratio between the reflected radiation and the incident radiation which passes through the entire area of the canyon’s ceiling. Results show that the equivalent albedo on the canyon increases from 89.0 % to 94.0 % employing RR materials on both vertical and horizontal surfaces, with a consequent reduction of the thermal energy trapped inside the canyon.

References
[1] Santamouris, M. (2007) Heat island research in Europe—the state of the art, *Adv. Build. Energy Res.*, 1, 123–150.
[2] Santamouris, M. (2015) Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions. *Science of The Total Environment*, 512, 582–598.
[3] Morini, E., Touchaci, A.G., Castellani, B., Rossi, F., Cotana, F. 2016. The impact of albedo increase to mitigate the urban heat island in Terni (Italy) using the WRF model, *Sustainability*, 8(10), 999; doi:10.3390/su8100999.
[4] Morini, E., Castellani, B., Presciutti, A., Anderini, E., Filipponi, M., Nicolini, A., Rossi, F. Experimental analysis of the effect of geometry and façade materials on urban district's equivalent albedo (2017) *Sustainability* (Switzerland), 9 (7), art. no. 245.
[5] Rossi, F., Castellani, B., Presciutti, A., Morini, E., Filipponi, M., Nicolini, A., Santamouris, M. 2015. Retroreflective façades for urban heat island mitigation: Experimental investigation and energy evaluations, *Applied Energy*, 145, 8-20.
[6] Morini, E., Castellani, B., Presciutti, A., Filipponi, M., Nicolini, A., Rossi, F. 2017. Optic-energy performance improvement of exterior paints for buildings, *Energy and Buildings*, 139, 690-701.
[7] Rossi, F., Morini, E., Castellani, B., Nicolini, A., Bonamente, E., Anderini, E., Cotana F. 2015. Beneficial effects of retroreflective materials in urban canyons: results from seasonal monitoring campaign. *Journal of Physics: Conference Series*, 655, 012012.
[8] Castellani, B., Morini, E., Anderini, E., Filipponi, M., Rossi, F. Development and characterization of retro-reflective colored tiles for advanced building skins (2017) Energy and Buildings, 154, pp. 513-522.
[9] Rossi, F., Castellani, B., Presciutti A., Morini, M., Anderini, E., Filipponi M., Nicolini, A. 2016. Experimental evaluation of urban heat island mitigation potential of retro-reflective pavement in urban canyons. Energy and Buildings, 126, 340–352.
[10] IEC 60904-9:2007. Photovoltaic devices - Part 9: Solar simulator performance requirements.
[11] ASTM E903-12. Standard test method for solar absorptance, reflectance, and transmittance of materials using integrating spheres.
[12] ASTM G 173-03. Standard tables for reference solar spectral irradiances: direct normal and hemispherical on 37° tilted surface; 2012.