Evaluation of upward and downward reflectance of different building facade reflectors between urban canyons

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Abstract
Research explores using retro-reflective (RR) materials in building walls to reduce urban heat island (UHI) effect and conserve energy. Indoor/outdoor wall-model experiments measured upward/downward solar reflectance of different reflective wall materials. RR facades increased upward reflectance and reduced negative effects of downward reflectance compared to diffuse highly reflective (DHR) walls with similar solar reflectance. Regardless of wall material, upward reflectance was highest when the incident light source faced the front of the wall-model. Implementing RR materials instead of DHR materials with similar reflectance mitigates UHI effect and conserves energy. Experimental models provide practical data to analyze wall reflectance impact on urban albedo, enhancing reliability and complementing previous numerical simulations.

Highlights

- Research explores using RR materials on building exterior walls to mitigate UHI effect and conserve energy
- Simple wall-model measures upward/downward reflectance of different wall materials using outdoor/indoor experiments
- RR walls increase upward reflectance and reduce negative impact of downward reflectance compared to DHR walls
- Using RR materials instead of DHR materials with similar solar reflectance can potentially mitigate UHI and conserve energy

Introduction
Several recent studies have shown that the UHI phenomenon is becoming more severe and has negative impacts on health (Solecki et al., 2005), energy consumption (Manoli et al., 2019), and outdoor comfort (Livada et al., 2002). The UHI effect is of global concern, with studies in China, Japan, the United States, and the European Union indicating its intensity and asymmetric nature. In China (Liao et al., 2018), Eastern regions experience greater UHI intensity during humid climates, and a simulation study in Japan (Kato and Yamaguchi, 2005) showed a 100 W/m² increase in sensible heat flux during summer. Urban areas in the United States are much warmer than suburban areas, with an average UHI amplitude of 4.3°C during summer (Imhof et al., 2010). In the European Union (Zhou et al., 2013), UHI intensity varies with seasons, with maximal saturation during summer at approximately 3.0°C.

Strategies to combat UHI phenomenon include highly reflective (HR) building coating materials (Cozza et al., 2015; Yuan et al., 2012). These have been developed and applied to building walls, roofs, and pavements for UHI mitigation and outdoor thermal comfort improvement. However, most HR materials are diffused HR (DHR) materials, which means incident solar radiation remains within the urban canyon. To better mitigate UHI phenomenon, RR materials have been developed and studied for their ability to reflect incident solar radiation to the sky without it being absorbed by nearby buildings or road pavements (Castellani et al., 2019).

RR materials have been widely researched for UHI mitigation and outdoor thermal comfort improvement. A numerical simulation found that glass beads with a refractive index of 1.9 were most effective for retro-reflecting incident light (Yuan et al., 2015). RR film used for building windows was found to increase upward reflection ratio, mitigating the UHI effect (Ichinose et al., 2017). RR building facades were found to be more effective for decreasing mean radiation temperature and reducing outdoor radiation-environment indicators compared with DHR building facades in both computational fluid dynamics analysis and outdoor actual-facade-model experiment studies (Yuan et al., 2022b).

This paper aims to provide realistic and accurate experimental data on the upward and downward reflection of different exterior walls of reflective materials, which is lacking in actual measurements for urban buildings. To achieve this, simple wall-models were used to predict the upward and downward reflectance of building walls under different coating conditions (DHR and RR) by using indoor artificial light and real outdoor solar conditions, improving upon the prediction of numerical models.

Methods
This paper uses simple wall-models (H=150 mm; D=150 mm; W=100 mm) to predict the upward and downward
reflectance of walls under DHR and RR materials through indoor artificial lighting and real outdoor experiments.

**Indoor artificial lighting experiment**

The materials used for the experiment are shown in Figure 1. As an experimental material, we used prism-shaped RR material and ivory-colored DHR material that assumes actual wall surfaces. Furthermore, the black ground sheet was used to suppress reflection from the ground. The solar reflectance of prismatic RR material, ivory DHR material, and black ground sheet, through optical measurements with wavelength range of 300–2500 nm, was 72%, 80%, and 5%, respectively.

![Image 1](image1.png)

(a) RR material  (b) DHR material  (c) Black sheet

**Figure 1: Experimental materials.**

The artificial solar lighting which simulates actual solar radiation, was used in pitch-black indoor environments. As shown in Figure 2, in order to verify the uniformity of the irradiation distribution, the artificial solar lighting was installed 500 mm from the wall, and the incident angles were 0, 10, 20, and 30 degrees, and measurements were taken with a pyranometer at 15 points.

![Image 2](image2.png)

**Figure 2: Installation of artificial solar lighting.**

As shown in Figure 3, the incident conditions for the artificial solar lighting experiment were three conditions: 0 degrees (parallel incidence to the wall surface), 45 degrees, and 90 degrees (normal incidence to the wall surface).

![Image 3](image3.png)

**Figure 3: Incident conditions for the artificial solar lighting experiment.**

The reflected solar radiation from the upward-facing wall and the downward-facing incident solar radiation at every 25 points (see Figure 3) in the boundary layer of the urban building consisting of two walls were measured with a pyranometer (wavelength range of 300–2000 nm) to determine the upward reflectance using Equation 1.

\[
\rho_{up} = \frac{I_{up}}{I_{down}} \times 100 \quad (1)
\]

where \(\rho_{up}\) is the upward reflectance [%], \(I_{down}\) and \(I_{up}\) are the downward incident and upward reflected solar radiation for each of the 25 points, respectively.

**Outdoor simple wall-model experiment**

Figure 4 depicts the outdoor simple wall-models, the same as the wall-models used in indoor artificial solar lighting experiment used to determine the upward and downward reflectance of different reflective walls (DHR and RR) in the actual solar radiation environment. The outdoor experiment took place in Toyohashi City, Japan on a sunny day on 24 September from JST 10:00 to 16:00, with an urban aspect ratio (H/D) of 1.0 for the wall-model experiment.

![Image 4](image4.png)

**Figure 4: Detail of outdoor wall-models experiment.**

A completely black wall-model was created to modify the upward and downward reflection of the two DHR and RR building walls. Additionally, all wall-models were placed on a deep black sheet plate with low solar reflectance of about 0.05 for the exposure experiment. The upward and downward reflectance of the DHR and RR walls were determined using Equation (2)–(5), as referenced in Yuan et al. (2022a),

\[
E_{wall} = E_{model} (Wall) - E_{model} (Black Wall) \quad (2)
\]

\[
E_{wall} = E_{model} (Wall) - E_{model} (Black Wall) \quad (3)
\]

\[
\rho_{wall} = 100 \times \frac{E_{wall}}{E_{h}} \quad (4)
\]

\[
\rho_{wall} = 100 \times \frac{E_{wall}}{E_{h}} \quad (5)
\]

where \(E_{wall}\) is the modified downward reflection of the DHR and RR walls [W/m²], \(E_{wall}\) is the modified upward reflection of the DHR and RR walls [W/m²], \(E_{h}\) is the measured horizontal solar radiation [W/m²], \(E_{model} (Wall)\) is the downward reflection of the DHR and RR wall-models [W/m²], \(E_{model} (Black Wall)\) is the downward reflection of the black wall-model [W/m²], \(E_{model} (Wall)\) is the upward reflection of the DHR and RR wall-models [W/m²], \(E_{model} (Black Wall)\) is the upward reflection of the black wall-model [W/m²], \(\rho_{wall}\) is the downward
reflectance of the DHR and RR walls [%], and $\rho_{wall}^{up}$ is the upward reflectance of the DHR and RR walls [%].

**Results**

Figure 5 shows the measured solar radiation distribution (15 points) of the artificial solar lighting for each incident angle (0, 10, 20, 30 degrees) (see Figure 2).

![Fig. 5](https://example.com/fig5.png)

Figure 5: Measured solar radiation distribution (15 points) of the artificial solar lighting for each incident angle of (a) 0 degrees, (b) 10 degrees, (c) 20 degrees and (d) 30 degrees.

It was found that the amount of incident solar radiation decreased when the neck angle of the artificial solar lighting was changed from 0 degrees to 30 degrees. However, it was confirmed that the distribution of solar radiation at 15 points did not vary greatly under the condition of each angle. Thus, it is possible to be used for the indoor artificial solar experiments (neck angle is 30 degrees).

Figures 6 - 8 show contour plots of upward reflectance obtained from artificial solar lighting experiments at DHR and RR wall-models under the conditions of three incidence (0-deg, 45-deg, 90-deg), respectively.

![Fig. 6](https://example.com/fig6.png)

Figure 6: Contour plots of upward reflectance under the condition of incidence of 0 degrees; left is for DHR wall and right is for RR wall.

![Fig. 7](https://example.com/fig7.png)

Figure 7: Contour plots of upward reflectance under the condition of incidence of 45 degrees; left is for DHR wall and right is for RR wall.

![Fig. 8](https://example.com/fig8.png)

Figure 8: Contour plots of upward reflectance under the condition of incidence of 90 degrees; left is for DHR wall and right is for RR wall.

To compare the upward reflectance of two different reflective walls (DHR and RR), the above boundary layer contours are averaged and shown in Figure 9.

![Fig. 9](https://example.com/fig9.png)

Figure 9: Average upward reflectance under three conditions of incidence of 0, 45 and 90 degrees.

The study compared three incident conditions on the vertical model-wall of artificial solar lighting. The results revealed that the upward reflectance ($\rho_{up}$) is highest at a 90-degree incident angle (normal incidence), regardless of DHR and RR wall surfaces. The second highest reflectance was observed at a 45-degree incident angle, while the smallest reflectance occurred at a 0-degree incident angle (parallel incidence).

Furthermore, the study found that the average upward reflectance ($\rho_{up}$) of the RR wall is approximately 1.4% greater than that of the DHR wall at a 90-degree incident angle. At a 45-degree incident angle, the RR wall had an approximately 2.4% higher reflectance compared to the DHR wall. However, at a 0-degree incident angle, the upward reflectance difference between the DHR and RR walls was very small, only approximately 0.25%.

Figure 10 illustrates the atmospheric conditions of an outdoor simple wall-model experiment. It includes 1-hour averaged solar radiation and 1-hour averaged temperature data from JST 10:00 to 16:00 on 24 September.
Figures 11 - 12 show 1-hour averaged upward and downward reflectance obtained from outdoor wall-models experiments on 24 September from JST 10:00 to 16:00, with an urban aspect ratio (H/D) of 1.0, respectively.

The outdoor wall-models experiment results (Figures 11-12) indicate that the upward reflectance ($\rho_{\text{wall}}^\uparrow$) of the RR wall-model is approximately 1.0% higher than that of the DHR wall-model. Conversely, when comparing the downward reflectance ($\rho_{\text{wall}}^\downarrow$) of the two wall-models, the $\rho_{\text{wall}}^\downarrow$ of the DHR wall-model is approximately 2.4% higher than that of the RR wall-model.

**Discussion**

From the experiment of artificial solar lighting, we can obtain that when the incident direction of solar radiation changes from parallel to the wall (0 degrees) to vertical to the wall (90 degrees), no matter what kind of reflective wall material, the upward reflectance of DHR and RR walls increases by about 7.1% and about 9.0% respectively accordingly. Therefore, we believe that in the design of the wall orientation of urban buildings, the north-south orientation will make better use of the reflection of the exterior wall to increase the upward reflectance, thereby reducing the surface temperature of the exterior wall.

Additionally, from the measurement results of Figure 9, we can conclude that although the solar reflectance (72%) of RR materials is about 8% lower than that of DHR materials (80%), when applied to dense building walls in cities, the upward reflectance of the city composed of RR material walls is still about 2% higher than that of cities composed of DHR material walls, except for the case where the incident solar radiation is parallel to the building walls, the two reflection cases (DHR and RR walls) are about the same.

From the outdoor simple wall-model experiments, we can see that the upward reflectance of the RR wall is higher than that of the DHR wall at different times of the day. Specifically, at JST 10:00, the RR wall has a upward reflectance of 10.27%, which is about 1% higher than the DHR wall's upward reflectance of 9.12%. At JST 12:00, the RR wall has a upward reflectance of 8.7%, which is higher than the DHR wall's upward reflectance of 6.9%.

At JST 14:00, the wall has a upward reflectance of 2.31%, which is about 1% higher than the DHR wall's upward reflectance of 1.44%, and at JST 16:00, the RR wall has a upward reflectance of 8.16%, which is higher than the DHR wall's upward reflectance of 7.13%. Consequently, there is a difference in upward reflectance between the RR and DHR walls of about 1% to 3%, and it is considered that the RR material, with a lower solar reflectance, has a higher upward reflection of urban buildings while compared to that of the urban buildings composed of DHR walls.

For the downward reflectance of the DHR and RR walls derived in the outdoor simple wall-model experiments, it is shown that the downward reflectance of the RR wall is lower than that of the DHR wall at different times of the day. Specifically, at JST 10:00, the RR material has a downward reflectance of 9.1%, which is about 0.4% lower than the DHR wall's downward reflectance of 9.5%.

At JST 12:00, the RR wall has a downward reflectance of 16%, which is about 9% largely lower than the DHR wall's downward reflectance of 25%. At JST 14:00, the RR wall has a downward reflectance of 4.8%, which is about 2% lower than the DHR wall's downward reflectance of 6.7%, and at JST 16:00, the RR wall has a downward reflectance of 12%, which is about 0.6% lower.
than the DHR wall's downward reflectance of 12.6%. Consequently, there is a difference in downward reflectance between the RR and DHR materials of about 0.4% to 9%, and the RR material, with a lower solar reflectance, has a lower downward reflectance of urban buildings while compared to that of the urban buildings composed of DHR walls. These trends have been confirmed in the outdoor simple wall-model experiments. The reason for the observed trends in upward and downward reflectance at different times of the day is likely due to the reflection characteristics of the RR material. Specifically, the specular downward reflection component of the RR material increases with higher incident angles (Yuan et al., 2018; Rossi et al., 2014). It is worth noting that the DHR material exhibited similar reflection tendencies, suggesting that it may have similar specular reflection performance as the RR material.

Conclusion

This study examined the upward and downward reflectance characteristics of two wall materials, DHR and RR, using both indoor artificial solar lighting experiments and outdoor simple wall-model experiments. The indoor experiments revealed that the upward reflectance of both DHR and RR walls increased as the incident angle of solar radiation changed from parallel to the wall (0 degrees) to vertical to the wall (90 degrees). The outdoor experiments demonstrated that despite having a lower solar reflectance, the RR material exhibited higher upward reflectance compared to the DHR material at different times of the day. Conversely, the RR material had lower downward reflectance than the DHR material during the same time periods. These observations can be attributed to the reflection characteristics of the RR material. Based on these findings, it is recommended that urban buildings be oriented in a north-south direction to maximize the reflection of exterior walls, thereby increasing the upward reflectance and reducing the surface temperature of the walls. Furthermore, the similar reflection tendencies observed in the DHR material suggest that it may also possess similar specular downward reflection performance as the RR material. Overall, this study provides valuable insights into the reflectance characteristics of wall materials and their potential impact on urban environments.

Acknowledgement

The authors are sincerely grateful to the “The Naito Research Grant” (representative: Dr. Jihui Yuan) for their support.

References


Yuan, J., Masuko, S., Shimazaki, Y., Chai, J. (2022a) Researching the design of a glass-bead retro-reflective material to reduce downward reflection for urban heat