Evaluation of Outer Structure Solar Reflection Characteristics of Highly Reflective Material in Consideration of Human Thermal Sensation

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Abstract
As a solution to the influence of solar radiation on thermal comfort in urban streets, constructing outer surfaces with highly reflective materials is considered to be controlling the directional reflection of the materials, and to reflect most of the radiation in the retroreflective direction—the same direction as that of the incident radiation. This study experimentally and numerically evaluates the directional solar reflectance of the outer cover material having an uneven surface. There is found to be a strong impact of radiation on human thermal comfort, and reduction of this radiation is the key to improving the thermal environment. Accordingly, the use of highly reflective materials is a good strategy for enabling this improvement, and retro reflection is a promising concept to consider in this regard. The simulation results show that human thermal comfort is determined by retro reflection if solar reflectance is the same.

Keywords: Heat island, Solar radiation, Building outer skin, Retro reflection, Human thermal load

1. Introduction
Recently, the thermal environment in urban areas has worsened with the aggravation of the urban “heat island” phenomenon. As a countermeasure to this problem, it has been suggested that the absorption of solar radiation be restrained by covering the surfaces of buildings and streets with materials exhibiting high solar reflectance. When the solar reflection from the surface is radiated onto the surroundings of the urban space, however, it is a concern that the absorption of solar radiation by other surfaces of structures increases and thermal comfort in urban streets deteriorates. As a solution, it has been suggested that directional reflection of materials be controlled and most of the solar radiation be forced to reflect in the recursion direction, i.e., the same as the direction of insolation, which is called “retro reflection.”

Sakai et al. (date) showed experimentally that retroreflective materials reduce the heat generated by reflected insolation using a miniature model realized in a thermostatic oven, and they evaluated the
solar reflective performance of several retroreflective materials [1, 2]. Iyota et al. (date) proposed a method for measuring retro reflectance using an apparatus containing an emitting–receiving optical fiber and spectrometers for both the visible and the infrared band. The retro reflectance and angular dependency of several sheet-type retroreflective materials were measured using the apparatus [3]. The development of surface materials with a retroreflective function was also promoted, and their performance evaluation was performed by Rossi et al. [4] and Morini et al. [5]. A method for performance testing of retroreflective material was studied by Harima et al. [6]. The same group also developed a film-shaped retroreflective material [7]. The thermal effect when using retroreflective material was investigated by numerical calculation [8, 9].

Human-centered technology has received considerable attention. For the thermal environment, feeling temperature or thermal comfort is an important factor in the study of human-oriented improvement. In general, feeling temperature or thermal comfort is determined by six dominant factors: air temperature, humidity, radiant temperature, wind speed, metabolism, and clothing. However, the present urban thermal environment cannot be improved completely merely by a single idea, and large-scale and complex urban planning projects are required.

In this study, the control of the directional reflection by a sheet material with an unevenly shaped surface was considered, and the characteristics of directional reflection were evaluated with measurement in the laboratory and the field and with numerical computation. The effect of highly reflective materials on human thermal comfort was considered for what?.

2. Measurement on reflection directivity and solar reflectance of a sheet with an uneven surface

Reflection directivity measurements of sheets of polyvinyl chloride resin were made. Two kinds of samples with flat and structurally uneven surfaces were prepared for the measurement. The size of each sample was 150 mm², and the materials were the same kind. Figure 1 shows the surface pattern of the uneven sample. The unit pattern size was 10 mm², and a wider surface element existed in the unit. Figure 2 shows a schematic drawing of the apparatus for measurement of directional reflection strength. A high-intensity discharge lamp was used as a light source. The lamp was fixed above the measuring apparatus, and the light was collimated with a Fresnel lens. The Zenith angle \( \theta \) and azimuth angle \( \phi \) of the incident ray onto the sample surface could be specified by rotating an arm table fixed at the end with a hinge and another table on the arm of the table for fixing the sample. Directional reflection strength was measured with a photodiode module. As shown in Figure 2, reflection from the direction of angle \( \theta \) was measured by changing the angle by moving an arm with a photodiode module installed at the end. The field of view of the photodiode was 8.3°, and the distance between the diode and measuring sample was 250 mm. The observed area of the module was a circle with a diameter of 37 mm and \( \theta = 0° \), and it spread wider in an elliptical shape with an increase of \( \theta \).

Figures 3 and 4 show directional reflection strength profiles concerning reflection angle \( \theta \) and azimuth angle \( \phi \) for the samples in the cases wherein the incident angle \( \theta \) changed with the 0° or 30°. The ordinate in each figure shows the value of the photodiode module output divided by \( \cos \theta \) to eliminate the influence of the increase of the observed surface by \( \theta \), and the value is defined as the directional reflection strength. As shown in Figure 3, the directional reflection strength profile in the azimuth direction was almost uniform in the case of \( \theta = 0° \). However, that of \( \theta = 30° \) changed with the azimuth angle. In Fig. 4, the left side of the figure corresponds to the result of the flat-surface sample, and the right side to that of the uneven-surface sample. It was found that the reflection directivity in reflection zenith angle \( \theta \) existed for both incident angle conditions. As shown in the left side of the figure, maximal directional reflection strength is observed near the specular reflection angle for each incident angle \( \theta \). However, at the right side of the figure, maximal strength is observed in the direction of the specular reflection angle. The directional reflection strength of the uneven surface was smaller than that of the flat surface.

Field measurement of the solar reflectance of two kinds of sheet sample with flat and uneven
The surface pattern of uneven sample

Figure 1. The surface pattern of uneven sample

Figure 2. Schematic of the apparatus for measurement of directional reflection strength

Figure 3. Directional reflection strength profile in azimuth angle

Figure 4. Directional reflection strength profile in reflection angle (left: flat surface, right: uneven surface)
3. Numerical analysis for reflection directivity of uneven surface

Numerical analysis based on a ray-tracing method was performed for evaluation of reflection directivity on the sample with an uneven surface. The conditions of solar radiation, incident angle, total radiation, and spectrum were specified, and the conditions of the sample surface, spectral absorptance, and the ratio of specular and diffuse reflection to the total reflection were specified. In the analysis, multireflection between the surface elements constructing the uneven surface was also considered. The incident position and wavelength of the beam element, reflection/absorption on the surface element, and direction of reflection in the case of diffused reflection were decided according to the Monte Carlo method.

Numerical analysis was performed while assuming the solar radiation at Osaka on August 1. The solar altitude and azimuth and the spectrum of direct solar radiation were calculated every 1 h employing the Bird model [10]. The shape of the sheet surface was assumed to be the same as that of Fig. 1 used in the measurement. The analysis was performed for the conditions of 0- and 2-mm height. The condition of 0-mm height corresponded to that of the flat surface. In the analysis, the sample was located such that the widest surface element faced south. The spectral absorptance was assumed to be gray, and the value was considered to be 0.7 uniformly in wavelength. The results were evaluated for hemispherical reflectance and the ratio of specular reflection or retroreflection to solar reflection every 1 hour. Each ratio was defined as the total energy of the reflected beam within the cone whose axis represented the exact direction of reflection based on the horizontal surface, and the opening angle of 60° was divided by the total energy reflected in the hemispherical direction. In the overlapping area between two cones, the beam reflected into half the area of the incidence side was counted as retro reflection and the rest as specular reflection. Figure 5 shows the results at the condition wherein all surface elements were perfectly diffuse reflective surfaces. This figure shows the effect of the unevenness of the surfaces on the hemispherical reflectance and reflection directivity. In the figure, the left ordinate corresponds to hemispherical reflectance and the right ordinate to the ratio of specular reflection or retroreflection. As shown in the figure, hemispherical reflectance tended to be smaller as the unevenness increased, which is similar to the experimental result in Figure 4. Almost no difference between the ratios of specular and retroreflection on a flat surface existed. A slight difference on an uneven surface existed between the morning and evening. Figure 6 shows the results of changing the ratio of specular reflection to total reflection for each surface element of an uneven surface, which was set to be 0, 5, 20, and 50%.

![Figure 5](image)  
**Figure 5.** Effect of unevenness on hemispherical reflectance and reflection directivity (left: flat surface, right: uneven surface): all surface elements are a perfectly-diffused reflection
Figure 6. Effect of specular reflection of an uneven surface on reflection directivity

The effect of the ratio of specular reflection on hemispherical reflection was not observed. At noon, when the incident direction almost agreed with the normal direction of the widest surface element facing south, the ratio of retroreflection became larger with the increase of specular reflection of the surface element. These results indicate that it may be possible to control the reflection directivity by changing the unevenness of the sheet surface and specular reflection of the surface elements constructing the uneven surface.

4. Effect of surface treatment on human thermal comfort

An attempt was made to describe the thermal environment in human living spaces by combining the characteristics of highly reflective materials with a human thermal-comfort index. Any heat gain or loss from a thermally neutral state was considered to be a hot or cold sensation of discomfort. The human thermal load $Q$ was calculated from Equation (2) as the remaining amount of each energy balance item [11, 12]. It is objective and is the basis of the energy balance formula for the human body incorporating the amount of physiology.

$$Q = M - W + R_{\text{net}} - E - C,$$

where $M$ is metabolism [W/m²], $W$ is workload [W/m²], $R_{\text{net}}$ is net radiation [W/m²], $E$ is latent heat loss [W/m²], and $C$ is sensible heat loss [W/m²]. The relationship between human thermal load and thermal sensation based on the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) standard was expressed using the least mean square approximation for the numerical analysis as:

$$\text{(Thermal sensation)} = 0.0146 \times \text{(Human thermal load)} - 0.748$$

For the human model, the 65MN model [13] was modified for outdoor use [11]. The 65MN model is a thermoregulation model and was used for estimating skin temperatures. This is because the human thermal load was calculated from skin temperatures, clothing insulation, and environmental conditions.
It was assumed that various materials of interest were placed horizontally on the ground surface in a wide and open space. A human was assumed to be standing in the south. One-dimensional heat transport was used for thermal environmental analysis [14]. The earth’s surface heat was focused on, and surface temperature, air temperature, and humidity were calculated. The wind speed was constant at 0.5 m/s. For the urban space, typical surface treatments, such as water-retentive material and asphalt concrete, were also considered. The details of each case are shown in Table 1. The results of time average values of air temperature, human perception based on human thermal load, thermal sensation, sensible heat flux, and latent heat at 12:00-2:00 p.m. JST at Osaka on August 1 are shown in Table 2. The average values of thermal sensation shown were obtained using Equation (3). The human considered was 1.72 m in height and 56 kg in weight. The human was standing (M = 80 W/m²) with 0.68 clo of clothing insulation, and he did not perform external work.

Because water-retentive material holds water and this water vaporizes slowly, the temperature of the material remained relatively low for a long time. The degree of heat storage decreased, and this material contributed to thermal environment improvement. In fact, the surface and air temperatures were lower than that of asphalt concrete, which had the same reflectance because of the latent heat component. Because the material exhibited relatively high reflectance, the amount of heat in terms of radiation that was absorbed on the earth’s surface was small, and this material could reduce the environmental thermal load. The primary cause of human thermal load can be seen in direct and reflected solar radiation represented in Figure 7. As the reflectance became higher, the amount of reflected solar radiation became larger, and the human was subjected to more heat. This is why the human felt hot, even when the temperature levels around him were lower. Because the highly reflective material’s effect of reducing environmental thermal load was known, the best way to achieve a human- and the eco-friendly surface was to cut the solar radiation reflected into the human. Cases 3–7 represent the investigation based on this idea. When the material had the same reflectance, human thermal comfort was determined by retroreflection (Cases 3–5).

Table 1. Properties of material

| Case | Material       | Evaporation ratio | Solar reflectance | Retro reflectance |
|------|----------------|-------------------|-------------------|-------------------|
| 1    | Asphalt        | 0                 | 0.10              | 0                 |
| 2    | Water retentive| 0.15              | 0.10              | 0                 |
| 3    | Highly reflective| 0               | 0.30              | 0                 |
| 4    | Highly reflective| 0                | 0.30              | 0.2               |
| 5    | Highly reflective| 0               | 0.30              | 0.5               |
| 6    | Highly reflective| 0                | 0.25              | 0                 |
| 7    | Highly reflective| 0               | 0.20              | 0                 |

Table 2. Results of each case (*thermal sensation is normally expressed from -3 to 3)

| Case | Air Temperature (°C) | Surface Temperature (°C) | Thermal Sensation N.D. | Sensible heat W/m² | Latent heat W/m² |
|------|-----------------------|--------------------------|------------------------|--------------------|------------------|
| 1    | 31.6                  | 45.9                     | 2.7                    | 146                | 0                |
| 2    | 30.9                  | 44.4                     | 2.6                    | 135                | 53               |
| 3    | 30.6                  | 41.8                     | <<3 (3.4)*             | 114                | 0                |
| 4    | 30.6                  | 41.8                     | <<3 (3.2)*             | 114                | 0                |
| 5    | 30.6                  | 41.8                     | 2.7                    | 114                | 0                |
| 6    | 30.8                  | 42.8                     | <<3 (3.2)*             | 122                | 0                |
| 7    | 31.1                  | 43.8                     | ≈3 (3.0)*              | 130                | 0                |
The improvement effect in the case of 50\% retro reflection (30\% reflectance, case 5) was larger than that in the case of 20\% reflectance (case 7) based on human thermal sensation.

5. Conclusions
Measurements and numerical analysis for sheet materials having uneven surfaces were performed to evaluate reflection directivity. As a result, it was possible to measure the reflection directivity given to the sheet material surface by constructing an uneven surface and changing the reflection directivity of each surface element.

The effect of surface treatment was considered based on human thermal comfort, and the following results were obtained. (1) Radiation has a strong impact on human thermal comfort, and reduction of radiation is a method to establish a better thermal environment. (2) The use of highly reflective materials can enable improvement, and retroreflection is an important concept to be considered.

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