Study on the characteristics of solar radiation in the geometrically complex urban spaces by using a spectroradiometer

Yasunobu ASHIE , NILIM*
Tsukuba, Japan
Daisuke Itoh, BRI
Tsukuba, Japan
**Corresponding author email: ashie-y92ta@nilim.go.jp*

ABSTRACT

In recent years, high-albedo materials and products have been utilized for urban building roofs and roads to lower their surface temperatures. These high-albedo materials and products include those with spectral selectivity. Accordingly, a scale model experiment and a numerical simulation were conducted to investigate the spectral dependency and characteristics of the urban albedo. The experimental results suggest that the spectral albedo is high in the near-infrared region especially in hours with low solar elevations.

Introduction

The surface albedo is considered an essential factor for investigating the urban heat budget. Increased albedo of the urban surface curtails the heat storage of buildings and roads, and reduces sensible heat transfer from the urban surface to the urban atmosphere. A number of case studies on urban albedo have been reported in the literature. In some studies, the characteristics of the urban albedo were investigated using urban scale models. Aida (1982) experimentally demonstrated a reduction of the albedo of urban surfaces with respect to a flat surface, and attributed the cause to the enhanced absorption of solar radiation due to multiple reflections within the urban geometry (solar radiation trapping effect, hereafter). Katsuyama et al. (2002) conducted scale model experiments with various building-to-land ratios and suggested the building-to-land ratio that minimizes the albedo.

In recent years, various products have been developed to enhance solar reflectance so that heat island effects are mitigated and air-conditioning cooling loads are reduced. Such products include high reflectance paints (Fujimoto et al. 2006), high-performance glass (Ichinose et al. 2004), and window films (Ashie et al. 2008). Use of high reflectance paint on roof surfaces has been found effective to improve the indoor thermal environment in summertime (Kondo et al. 2008). Similarly, use of high reflectance paint has been shown effective to reduce the temperature increase of road pavement (Nishioka et al. 2006).

The above-mentioned products include those which possess distinctive spectral selectivity such as those which enhance the reflectance sharply in the near-infrared region. However, limited research has been conducted on the behavior of radiation reflected by high-reflectance materials with a spectral selectivity in the urban environment. Therefore, it is necessary to take into consideration the spectroscopic characteristics of the urban albedo in order to improve understanding of the thermal influence of the albedo. Given this background, the present study investigates the spectral albedo with the use of scale model experiments and numerical computations.

Measurements of the Urban Spectral Albedo

The following are known methods for measuring the solar reflectance of a material: 1) spectral reflectance is measured with a spectral photometer. With the measured spectral reflectance, the weighting coefficients in a solar spectral model are determined (Sakai et al. 2007); 2) the surface temperature and other properties of various materials are measured outdoors. The solar reflectance of each material is evaluated from the heat budget equation (Fujimoto et al. 2006); 3) the solar reflectance is measured directly with an albedometer (Aida 1982; Katsuyama et al. 2002; Murata et al. 2008). Applicability of these techniques for evaluations of the urban spectral albedo is summarized below:

Method 1 is not well-suited for measurements of a large scale model. This method is only applied indoors, thus there is a limitation on the size of the testing body, i.e., the scale model. The spectroscopic measurements in this method have been standardized by Japan Industrial Standards (JIS) (JIS R3106 1998; JIS K5759 2008; JIS K5602 2008). Method 2 is inapplicable for scale models with non-flat surfaces for theoretical reasons. The spectroscopic measurement in this method is also not well-suited for scale models. Method 3 allows a relatively easy assessment of the spectral albedo with the measurements of upward and downward radiation made by an appropriate spectral measuring instrument (Aoki et al. 1998). The present method has been applied for albedo measurements in urban scale models (Aida 1982; Katsuyama et al. 2002; Murata et al. 2008).

Accordingly, the present study will use and expand Method 3 to evaluate the spectral albedo by using an all-sky spectroradiometer.

The Urban Scale Model Experiment

Location, Time, and Date of the Experiment

The experiment was conducted on the roof of the Building Research Institute, Tsukuba, Japan between 6:00 and 18:00 on July 12, 2008.

Scale Model

A diagram of the scale model is shown in Figure 1. The scale model consists of blocks and a plate that are made of typical pavement concrete. The blocks and plate represent urban buildings and streets. A block size of 150 mm x 150 mm x 150 mm was selected to facilitate comparison of the results from the present study to those from previous studies. The building–to-land ratio of the model is 25%. Figure 2 shows a photo of the scale model. To avoid the influence of a parapet, the model was deployed on a 650-mm high platform. The sky view factor from the concrete plate is 0.97; thus, in terms of diffuse radiation, the influence of the surrounding environment on the model is considered nearly negligible.

[1] The industrial standards JISR3106 (1998), JISA5759 (2008) and JISK5602 (2008) are intended for direct solar radiation reaching the Earth's surface and/or global solar radiation with wavelengths of 300 ~ 2500 nm. The wavelength range of most pyranometers compliant with ISO and WMO standards is 305 ~ 2800 nm. In the present study, radiation in the range of 350 ~ 2200 nm is referred to as the amount of solar radiation due to the specification and accuracy of the spectroradiometer.

Figure 1. Scale model of urban geometry. Units of all dimensions are mm

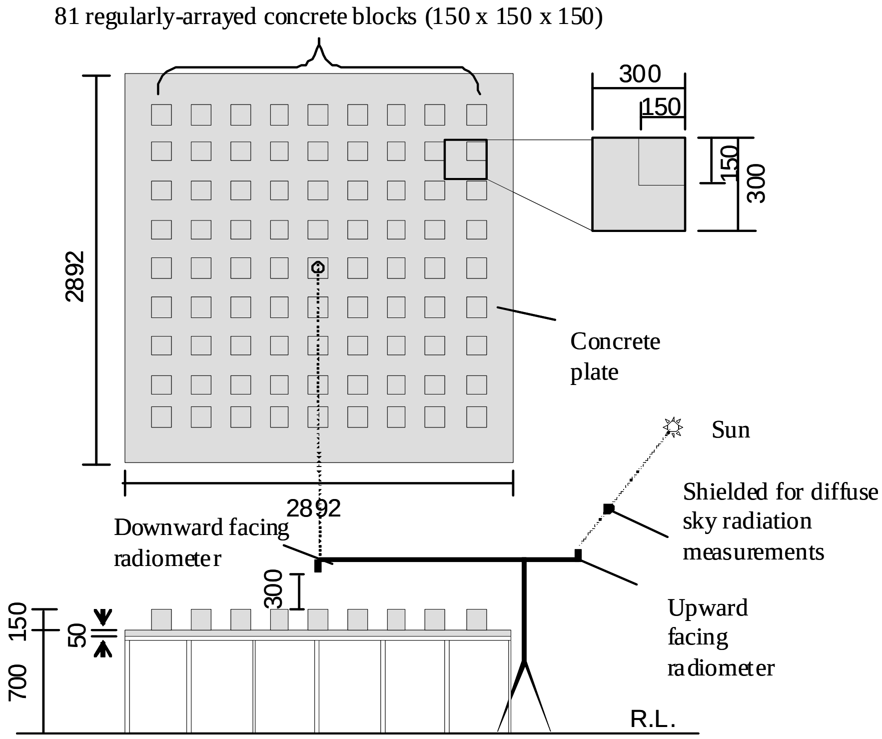


Figure 2. View of scale model experiment and measurements

Measurement Method

Spectrally-resolved reflected light from the ground and buildings, spectrally-resolved global solar irradiance and spectrally-resolved diffuse sky irradiance were measured by a FieldSpec 3FR spectroradiometer (Analytical Spectral Devices, Inc) (Figure 3 and Table 1). Three measurements were made once an hour. The collected data that were obviously contaminated by cloudiness were removed, and the three measurements were averaged at each wavelength.

The spectral reflection from the urban scale model surface was measured at the center of the model (Figure 1, downward facing measurement). The sensor was deployed at a height of 300 mm above the roofs of the model buildings. At the location of the sensor, the view factor of the scale model was 0.96. The measurements of global solar and diffuse sky irradiances were made near the scale model (Figure 1, upward facing measurement). To measure the diffuse sky irradiance, the sensor of the spectroradiometer (ϕ15mm) was shielded from direct solar radiation simply by a black sphere (ϕ40mm) installed 300 mm from the sensor.

Figure 3. Spectral radiometer used for measurements

Spectral solar irradiance

The spectral solar irradiance data are analyzed to provide statistics of the cumulative solar radiation (Table 2). The ratio of the cumulative radiation was approximately 2:59:39 for the ultraviolet region (350nm - 380 nm), the visible region (380 nm - 780 nm) and the near-infrared region (780 nm - 2200 nm), respectively. Igawa et al. (2004) proposed the sky index, Si, to express the sky condition. The average sky index, Si, on the day of the experiment was 1.58 (standard deviation: 0.24), indicating a generally sunny day.

To examine the change of the spectral solar irradiance with the time of the day, the ratio of the spectral global irradiance from 13:00, 15:00 and 17:00 to that from noon was computed (Figure 4). The spectral distribution from 13:00 closely agrees with that from noon. As the solar elevation decreases, the value of the ratio generally decreases over the entire spectral range, particularly at short wavelengths; and the ratio increases with increasing wavelength. This result is attributable to Rayleigh scattering, that is, the peak of the spectral global solar irradiance is shifted to longer wavelengths with a decreasing solar elevation. As for the water vapor absorption band, the attenuation of solar irradiance in the band becomes larger later in the day because the path length in the atmosphere becomes longer at low solar elevations.

Table 1. Specifications of the spectroradiometer used in the present study (provided by the manufacturer)

Items	Specifications
Spectral range	350-2500nm
Angle of measurement	180° ※1
Spectral accuracy	±1nm
Detector and spectral resolution*2	350-1000nm：512 element Si photodiode array(3nm) 1000-1800nm：TE cool, graded index InGaAs(10nm) 1800-2500nm：photodiodes(10nm)

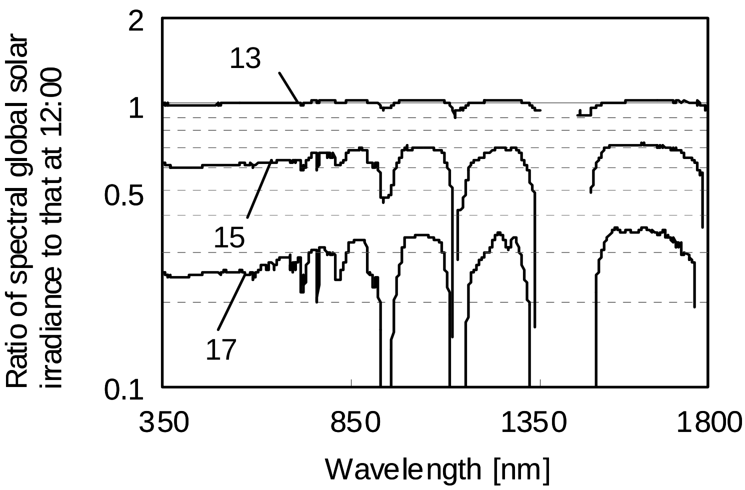
※1 When the all sky adaptor is attached.
※2 Numerical values in parentheses indicate spectral resolutions.

Table 2. Cumulative solar radiation on the day of the experiment (July 12, 2008)

Wavelength regions [nm]	Horizontal direct insolation [MJ/m^2]	Diffuse solar irradiance [MJ/m^2]	Global solar irradiance [MJ/m^2]
Ultraviolet region 350～380	0.186 (0.7)	0.431 (1.6)	0.616 (2.2)
Visible region 380～780	8.21 (29.6)	8.18 (29.5)	16.4 (59.0)
Near-infrared region 780～2200	7.85 (28.3)	2.90 (10.4)	10.8 (38.7)
All wavelengths 350～2200	16.3 (58.5)	11.5 (41.5)	27.8 (100)

Values in parentheses indicate the ratio relative to the global solar radiation from all wavelengths [%]

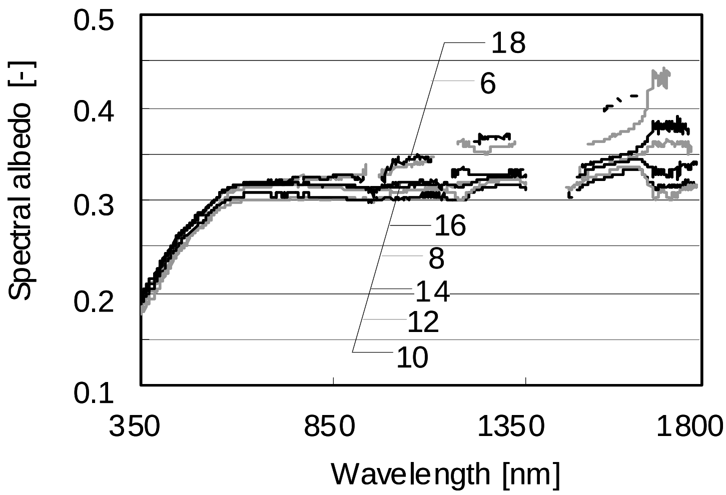
Figure 4. Ratio of spectral global solar irradiance at 13:00, 15:00 and 17:00 to that at 12:00 on July 12, 2008 (numerical labels on the figure indicate time). Discontinuities in the data are due to solar absorption by molecules such as water vapor



Urban spectral albedo

Subsequently, the urban spectral albedo was examined for each hour of the day (Figure 5). In computing the urban spectral albedos, data with spectral global irradiances of less than 0.01 $W/m^2/nm$ were excluded. For all hours, the urban spectral albedo generally increases with increasing wavelength. This trend is most obvious in hours of low solar elevations.

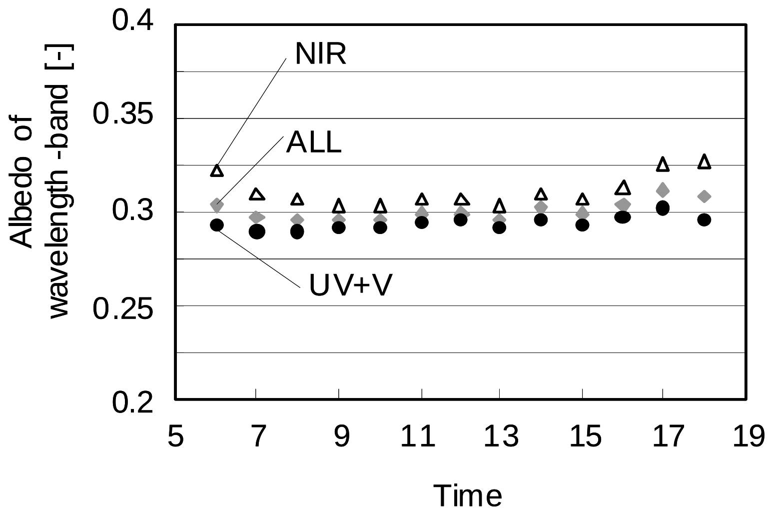
Figure 5. Spectral albedo of urban surface (July 12, 2008; numerical values on the figure indicate the time of day)



Temporal change of urban wavelength-band dependent albedos

When spectrally selective materials are applied to the urban environment, their reflective performance in the near-infrared region is of particular interest. Accordingly, albedos were computed for the near-infrared (NIR), ultraviolet-visible (UV + V) and all wavelength (ALL) bands. In this paper, albedos computed for a band of wavelengths are defined as averages of the albedos at the relevant individual wavelength weighted by the incoming global solar radiation at those wavelengths. The temporal changes of the wavelength-band dependent albedos are shown in Figure 6. The albedo over the entire spectrum (ALL) remained approximately constant during the middle part of the day. In the morning and evening, the values of the corresponding albedo became slightly larger than those from the middle of the day. The present trend is consistent with the result of Katsuyama et al. (2002). The albedo of the ultraviolet-visible (UV + V) region remained almost constant throughout the day. In contrast, the albedo of the near-infrared (NIR) region changed significantly accordingly to the solar elevation.

Figure 6. Temporal change of the wavelength-band dependent albedos for the urban geometry (July 12, 2008)



Incident-angle Related Characteristics of the Spectral Albedo

In this section, albedos of a plate and an urban geometry are compared to examine the incident-angle related characteristics of the urban albedo.

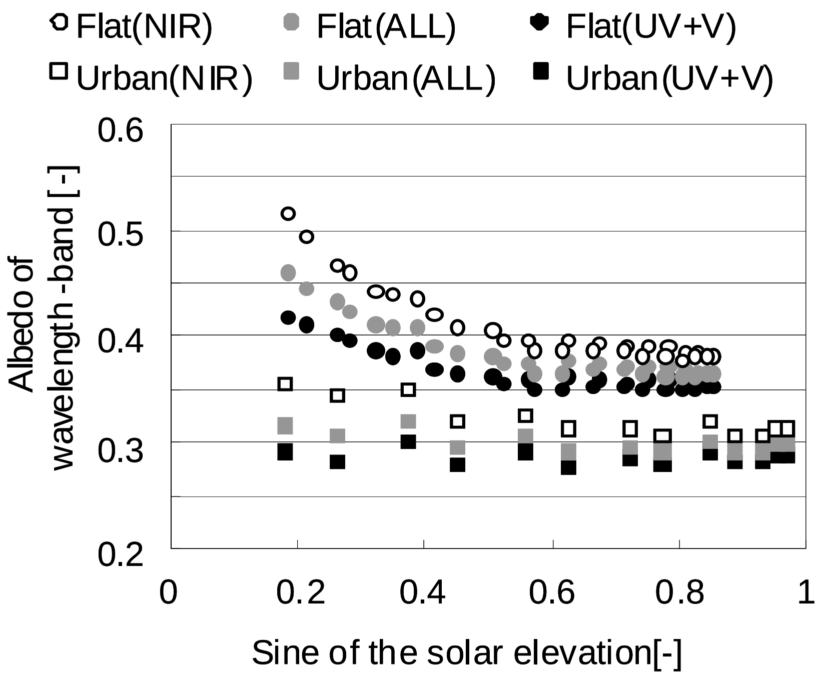
Measurement of Plane Spectral Albedo

The plane spectral albedo of a concrete plate was measured in sunny hours in early and mid-September of 2008. The sky index, Si, during the measurement hours was 1.55 on average (standard deviation: 0.08). For this experiment, the concrete plate introduced after was used. The same variables and methods as those from Section 3 were measured and adopted.

Comparison of Plane and Urban Albedos

The relationship between the solar elevation and the wavelength-band dependent albedos of the plate and the urban geometry is summarized in Figure 7. The urban albedo is smaller than the plane albedo in all the wavelength ranges probably due to the solar radiation trapping effect. Furthermore, Figure 7 suggests that the urban albedo is less sensitive to the solar elevation than the plane albedo. The different behaviors of the plane and urban surfaces with respect to the solar elevation may be explained by the following two reasons. First, in the urban geometry, the fraction of the incident solar radiation on the walls increases with decreasing solar elevation. As a result, the contribution of the walls to the reflection is expected to be enhanced relative to that of the ground surface. Second, multiple reflections were present in the urban geometry unlike on the plane surface. The combined effect of the multiple reflections with the incident-angle-related characteristics of the materials likely contributed to the different behaviors of the plane and urban surfaces in terms of the solar-elevation dependent reflection of sunlight.

Figure 7. Comparison of wavelength-band dependent albedo between flat and urban surfaces

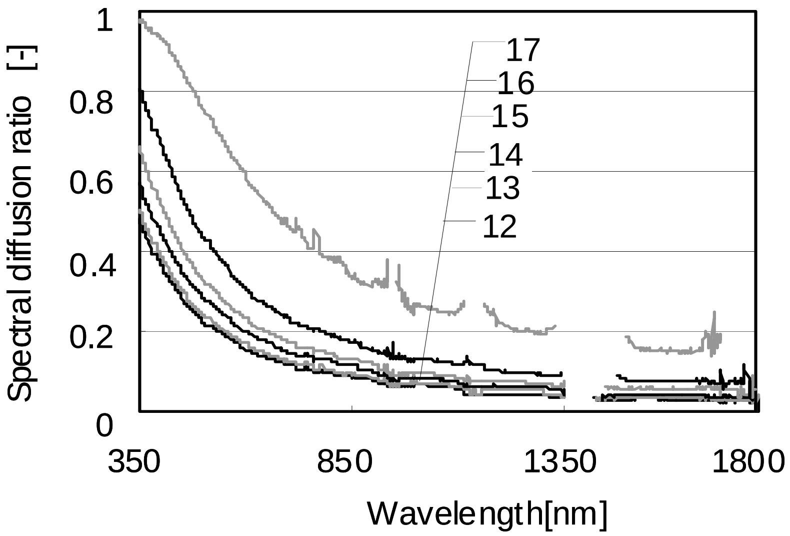


Influence of the Diffuse Spectral Ratio on Reflectance

The diffuse spectral ratio was computed for each hour with the observational data (Figure 8). The diffuse spectral ratio is defined as the ratio of the diffuse solar radiation to the global solar radiation. Figure 8 confirms that generally, the diffuse spectral ratio increases with decreasing solar elevation. In addition, the ratio tends to increase for radiation of shorter wavelengths.

Accordingly, with a low solar elevation, the fraction of direct solar radiation becomes small, and the incident angle characteristics of both the plane and urban albedos become less apparent. This trend is evident particularly for the ultraviolet-visible band in Figures 6 and 7.

Figure 8. Hourly values of the diffuse spectral ratio (September 9, 2009). The numbers in the figure indicate the time of observation



Summary

A scale model experiment was conducted to investigate the urban spectral albedo. The findings from the present study are summarized below:

1) According to the scale model experiment, the value of the urban spectral albedo was large in the near-infrared region. The value became particularly large in hours with low solar elevation.

2) Compared to the albedo of a flat surface, the values of the urban spectral albedo were small both in the ultraviolet-visual and the near-infrared regions. This result confirms the effect of solar trapping due to multiple reflections, which was identified in previous studies, even for the albedo averaged over wavelength bands smaller than the entire spectrum.

3) The experimental data showed that daytime variation of the urban spectral albedo in the ultraviolet-visual region was small. The diffuse spectral ratio was suggested as one reason to explain this observation.

The present study suggests the importance of investigations on the spectral characteristics of the high-albedo products on the market and on the application conditions of spectrally selective building materials in the future. With the results of such investigations, simulations of the spectral albedo in conditions similar to the actual environment are necessary.

References

Aida, M.. 1982. *Urban albedo as a function of the urban structure - A model experiment (Part1)*. Boundary Layer Meteorology, 23, pp.405-413

Aoki, Te., Aoki, Ta., Fukabori, M., Tachibana, Y., Zaizen, Y., Nishio, F. and Oishi.. 1998. *Spectral albedo observation on the snow field at barrow*. Boundary Layer Meteorology, Alaska, Polar Meteorol. Glaciol., 12, pp.1-9

Ashie, Y., Itoh, D., Fujimoto, T.. 2008. *Investigation on spectral characteristics of adhesive films for glazings*. AIJ journal of technology and design, 28, pp.487-490 (in Japanese)

Fujimoto, T., Okada, T., Kondo, Y.. 2006. *Reduction of solar heat gain by using reflective paints for building envelops*. AIJ Journal of environmental engineering, 601, pp.35-41 (in Japanese)

Ichinose, M., Ishino, H., Nagata, A.. 2004. *A study on spectral sensitivity of splar transmission and reflection performance of architectural materials*. AIJ Journal of environmental engineering, 583, pp.15-21 (in Japanese)

Igawa, N., Koga, Y., Matsuzawa, T. and Nakamura, H.. 2004. *Model of sky radiance distribution and sky luminance distribution*. Solar Energy, 77-2, pp.137-157

Katsuyama, J., Kanda, M., Kawai, T. and Nakagawa, K.. 2002. *Experiment using 3D small-scale model in urban canopy*. JSCE Journal of hydraulic engineering, 46, pp.85-90 (in Japanese)

Kondo, Y., Ogasawara, T., Ohki, T., Udoh, K.. 2008. *Production of sensible heat emission by increasing roof solar reflectance as a countermeasure of heat island phenomena*. AIJ Journal of environmental engineering, 629, pp.923-929 (in Japanese)

Nishioka, M., Nabeshima, M., Wakama, S., Ueda, J.. 2006. *Effects of surface-temperature reduction and thermal environment on high albedo coating asphalt pavement*. Journal of Heat Island Institute International, 1, pp.46-52(in Japanese)

Murata, Y., Sakai, K., Kanamori, H., Takebayashi, H., Matsuo, Y. Moriyama, M., Yoshida, A., Nishioka, M., Yano, N., Shimizu, R., Miki, K., Murase, T., Akbari, H.. 2008. *A study on insolation reflectivity measurement of the cool painting surface : a proposal of measuring method by the 2 point correction and accuracy testing on the horizontal surface*. AIJ Journal of environmental engineering, 632, pp.1209-1215 (in Japanese)

Sakai, H., Emura, K., Igawa, N.. 2007. *Mehod for measureing the solar reflectance of building materials by using a spectrophotometer*. AIJ Journal of environmental engineering, 616, pp.31-36 (in Japanese)