Journal of Heat Island Institute International Vol.7-2 (2012)

Reduction of Reflected Heat of the Sun by Retroreflective Materials

Hideki Sakai*[1], Kazuo Emura, Norio Igawa and Hiroyuki Iyota

*[1]Osaka City University,Osaka, Japan

Corresponding author email: hsakai@life.osaka-cu.ac.jp

ABSTRACT

It is demonstrated that walls made of retroreflective materials can reduce the reflected heat of the sun in the directions of neighboring roads and buildings. To mitigate the urban heat island (UHI) effect, the applicable area of retroreflective materials is larger than that of high-reflective paint because retroreflective materials can be used not only as "cool roofs," but also as "cool walls." The solar retroreflectance of several retroreflective materials, which cannot be measured directly by a spectrophotometer, were measured for the first time. The procedures were as follows. First, the reflectance without retroreflection was measured by using a spectrophotometer with the integrating sphere. Then, the total reflectance was deduced from the amount of temperature rise by solar irradiation. Finally, the retroreflective component was calculated by subtracting the former from the latter. The measured retroreflectances were 20% to 30% for the prism-array type, about 20% for the capsule-lens type, and about 10% for the bead-embedded type.

Introduction

Making a building reflective reduces the amount of solar heat it absorbs. In closely packed building areas, however, heat reflected by one building can be absorbed by another (Figure 1a). To prevent this opposite effect by high-reflective materials, we propose to use retroreflective materials to reduce the reflected heat (Figure1b). In retroreflection, the incident light is returned in the direction of the source (i.e., the sun), with a very small spread in the light around this particular direction (CIE 2007).

In principle, computer-controlled mirrors also can reflect sunlight upward and prevent the opposite effect in much the same way as retroreflective materials. However, mechanical moving parts are complicated and expensive, and need constant maintenance. Thus, covering wide areas of a building's exterior with these movable mirrors is impractical. In contrast, retroreflective materials have no moving parts, and thus cannot break down; they require little maintenance. This is a great advantage for building materials.

Retroreflective materials are now widely used as road markings and signs to enhance night-time visibility (CIE 2007). Thus, they have already been carefully evaluated with respect to visibility. From the viewpoint of heat transfer, however, their characteristics are unknown.

In this study, first we showed experimentally that retroreflective materials reduce the heat generated by reflected sunlight. Then we evaluated the solar reflective performance of several retroreflective materials for the first time.

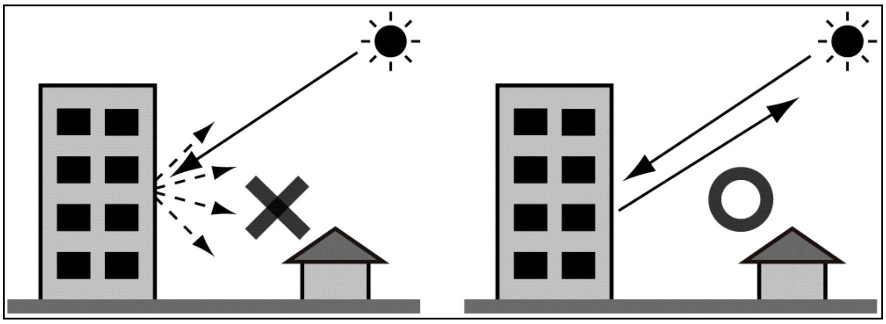

Figure 1. (a) High reflective materials and (b) retroreflective materials

Materials and Method

The experimental setup used is shown in Figure 2. It is a miniature model of an urban canopy, consisting of an exterior wall of a building, a road, and the opposite building wall.

For the wall samples, three kinds of retroreflective sheets (i.e., two bead-embedded ones and a capsule-lens one), which were commercially available and designed for traffic signs, were used. For comparison, four kinds of paints (i.e., high-reflective white, high-reflective gray, high-reflective black, and ordinary black) were used and two kinds of metallic surfaces (i.e., Galvalume and glossy aluminum). All of the samples were 75 mm by 70 mm in size and were heat insulated by attaching the polystyrene foam with a thickness of 60 mm on their back side.

As shown in Figure 2, each wall sample was placed vertically in an incubator maintained at temperature Tsurrounding = 25° C and was irradiated from above with a 60-watt infrared heat lamp (artificial sunlight E) at the incident angle of 45°.

During irradiation, the sample surface temperature (T_1), the opposite wall temperature (T_2), and the road temperature (T_3) were monitored with type T thermocouples. The lamp continued to irradiate until these temperatures were stabilized, which took about 40 minutes.

The amount of increase in temperature depended on the reflectance characteristics of the sample. That is, the higher the total reflectance (R_{Tot}) of the sample, the lower the sample surface temperature (T_1). The higher the diffuse reflectance (R_{Dif}) of the sample, the higher the opposite wall temperature (T_2). The higher the specular reflectance (R_{Spe}) of the sample, the higher the road temperature (T_3). That is to say, the amount of reflected heat in each direction can be estimated by monitoring these temperatures.

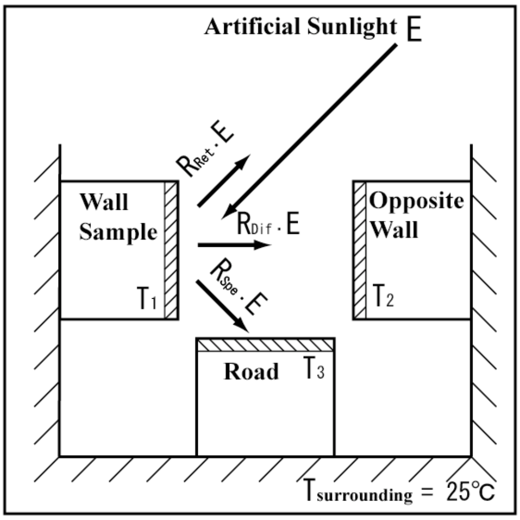

Figure 2. Experimental setup (miniature model of urban canopy)
E: irradiation energy of lamp, RSpe: specular reflectance,
RDif: diffuse reflectance, RRet: retroreflectance

Results and Discussion

The amounts of increase in temperature from a 40-minute irradiation are shown in Table 1. The values of reflectance RSpe and RDif of the samples are shown in the fifth column of Table 1; these values were obtained by using a spectrophotometer with the integrating sphere (RTC-060-SF, Labsphere, Inc.) at an incident angle of 45° (Storm 1998).

For four paint samples, as expected, the temperature of the wall sample (ΔT1) increased with decreasing sample reflectance. The value of ΔT1 for the high-reflective white paint, which had the highest reflectance, was smallest (ΔT1 = 3.5 K), and that of the ordinary black paint, which had the lowest reflectance, was highest (ΔT1 = 8.0 K). This demonstrates that making a building reflective reduces the amount of solar heat it absorbs. In contrast, the temperature of the opposite wall (ΔT2) and that of road (ΔT3) decreased with decreasing sample reflectance. The values of ΔT2 and ΔT3 of the ordinary black paint were smaller than those of the high-reflective paint. This shows the opposite effect of high-reflective paints; that is, heat reflected by one building is absorbed by the other.

For the two metallic samples, the values of ΔT1 were similar or smaller than those for the high-reflective paint samples, as was expected from their high reflectance. However, the value of ΔT3 for the metallic samples was larger than those for the paint samples. These were caused by the intense specular reflection of the metallic surfaces. Thus, a metallic surface is good for keeping itself cool under the burning sun, like a high-reflective paint. However, its reflected heat is focused in one place (i.e., specular reflection geometry).

Table 1 Experimental result: Amount of temperature increase for a 40-minute irradiation

Samples	Sample ΔT_1 [K]	Opposite ΔT_2 [K]	Road ΔT_3 [K]	Reflectance $R_{Spe}+R_{Dif}$ [%]
1: high-reflective white paint	3.5	2.7	2.6	79.5
2: high-reflective gray paint	3.7	2.7	2.6	71.1
3: high-reflective black paint	4.4	2.5	2.4	61.9
4: ordinary black paint	8.0	1.9	1.9	9.3
5: Galvalume sheet	3.6	2.6	3.3	72.6
6: Aluminum sheet (glossy)	2.3	2.5	5.4	84.0
7: retroreflective 1 (bead-embedded)	3.2	2.3	2.1	66.8
8: retroreflective 2 (bead-embedded)	3.4	2.4	2.5	69.0
9: retroreflective 3 (capsule-lens)	3.6	2.2	2.6	53.3

For the three retroreflective samples, the temperature increase (ΔT1) was a bit smaller than expected from their reflectances (R). For example, the value of reflectance for retroreflective sheet 1 (No.7; R = 66.8%) was lower than that for the high-reflective gray paint (No. 2; R = 71.1%). However, the value of ΔT1 = 3.2 K was smaller than that of No. 2, ΔT1 = 3.7 K. This may seem strange at first glance, but there is no inconsistency. The point is that retroreflectance cannot be measured by an integrating sphere measurement because the retroreflected light escapes through the hole for the incident light (Figure 3). The actual (i.e., total) reflectance of the three retroreflective samples should be higher than the measured reflectances shown in Table 1 by the amount of retroreflectance. In fact, when the retroreflective materials were used as samples, not only its surface temperature (ΔT1), but also the opposite wall (ΔT2) and road (ΔT3) temperatures were kept low, compared with the temperatures of the other high-reflective samples. The reflected heats "disappeared." (Actually, they returned in the direction of the light source, as depicted in Figure 1b.)

To mitigate the UHI effects, high-reflective paints are usually used for cool roof materials. They are not used for exterior walls because the reflected heat from them is absorbed by the surroundings. However, retroreflective materials can be used not only as cool roofs but also as cool walls. Therefore, the applicable area of retroreflective materials is larger than that of high-reflective paint.

Figure 3. Geometry of integrating sphere measurement

Results and Discussion

Finally, we examined how to measure the retroreflectane of the samples. As pointed out above, retroreflectance cannot be measured using a spectrophotometer with an integrating sphere because the retroreflected light escapes through the hole for the incident light (Figure 3).

Therefore, we propose the following procedure. First, the reflectance without retroreflection, RSpe and RDif, is measured through integrating sphere measurement (CIE 2004). Next, the total reflectance, RTot, is deduced from the amount of temperature increase from irradiation. Here, the total reflectance of sample RTot is:

$$RTot = RSpe + RDif + RRet \quad (1)$$

Following the above procedure, we evaluated the solar retroreflectance of the five kinds of retroreflective materials listed in Table 2. The reflectances (RSpe + RDif) in the second column of Table 2 were measured by a spectrophotometer with an integrating sphere (UV-3600, Shimadzu Scientific Instruments) at the incident angle of 7°. From the third to the sixth columns, the total reflectance (RTot) is shown; these values were derived from the amount of temperature increase from an outdoor exposure with a 7° incident angle of direct sunlight. The experiment was repeated four times on different days, and the averaged values of RTot were used to calculate the retroreflectance, RRet, as shown in the eighth column of Table 2. The calculated retroreflectances are 29.5% and 23.5% for the prism-array retroreflective sheets, 17.8% for the capsule-lens retroreflective sheet, and 12.9% and 4.9% for the bead-embedded retroreflective sheets. Therefore, it seems that retroreflectance depends on structural type.

for non-transmissive materials. Then, the retroreflective component, RRet, can be deduced by subtracting RSpe + RDif from RTot.

Table 2. Reflectance by integrating sphere measurement (RSpe+RDif), total reflectance deduced from the amount of temperature increase (RTot), and the estimated retroreflectance (RRet) of the retroreflective samples

Retroreflective Samples	Reflectance by integrating sphere $R_{Spe}+R_{Dif}$	Total reflectance deduced from temperature rise R_{Tot} day 1	day 2	day 3	day 4	Average	Retroreflecntance $R_{Ret} = R_{Tot} - R_{Spe} - R_{Dif}$
1: Prism-array sheet 1	48.2	77.5	78.0	78.0	77.5	77.8	29.5
2: Prism-array sheet 2	47.5	70.8	71.1	70.9	71.4	71.0	23.5
3: Capsule-lens sheet	42.1	60.8	59.5	59.9	59.7	60.0	17.8
4: Bead-embedded sheet 1	55.6	68.1	68.7	68.8	68.3	68.5	12.9
5: Bead-embedded sheet 2	62.2	66.7	67.1	67.9	66.7	67.1	4.9

[%]

Conclusions

The following results were obtained from the present study.

1. By using a miniature model of an urban street, it was demonstrated that retroreflective materials can reduce the reflected heat of the sun in the direction of neighboring roads and buildings. They have a "cool wall" effect and can be used as building materials to reduce the UHI effect. Therefore, the applicable area of retroreflective materials is larger than that of high-reflective paint.

2. A method is proposed for measuring solar retroreflectance, which cannot be measured directly by a spectrophotometer.

3. The solar retroreflectance of several retroreflective sheets was measured. Their reflectance generally depends on structural type. The reflectance was 20% to 30% for the prism-array type, about 20% for the capsule-lens type, and about 10% for the bead-embedded type.

Acknowledgment

This work was supported by Grant-in-Aid for Scientific Research 19560578 from the Japan Society for the Promotion of Science and by a research grant for urban problems from Osaka City University.

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(Received Feb 9, 2012, Accepted Oct 10, 2012)