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Hideki Sakai, Hiroyuki Iyota

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Development of Two New Types of Retroreflective Materials as Countermeasures to Urban Heat Islands

Hideki Sakai · **Hiroyuki Iyota**

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Abstract In this study, the side effects of high-reflective and ordinary retroreflective materials, used as countermeasures to urban heat islands, are discussed. In addition, two retroreflective materials are proposed in order to avoid these adverse effects. These materials could be applied to roads and building exteriors to reduce their heat absorption from solar radiation. The first proposed type is the directional retroreflective material, which reflects light only during summer; therefore, it reduces the cooling load in summer, reduces the heating load in winter, and prevents light pollution at night. However, its structure is complicated and fragile; thus it is suited for small areas, such as roofs and walls. The second type is the rough-surface retroreflective material, which shows weak retroreflectivity but can withstand distortion; thus it is suited for roads. These two types require little maintenance, because they have no moving parts. Hence, these materials would not experience any breakdown, which is a great advantage for roads and building materials. Combining high-reflective, ordinary retroreflective, directional retroreflective, and rough-surface retroreflective materials, and assigning each type to the appropriate application would form an advanced mitigation system against urban heat islands.

Keywords Solar radiation · High-reflective materials · Directional retroreflective materials · Rough-surface retroreflective materials · Urban heat island

H. Sakai
Graduate School of Human Life Science, Osaka City University, Sugimoto 3, Sumiyoshi-ku, Osaka, 558-8585, JAPAN
Tel.: +81-6-6605-2826
Fax: +81-6-6605-2826
E-mail: hsakai@life.osaka-cu.ac.jp

H. Iyota
Graduate School of Engineering, Osaka City University, Sugimoto 3, Sumiyoshi-ku, Osaka, 558-8585, JAPAN

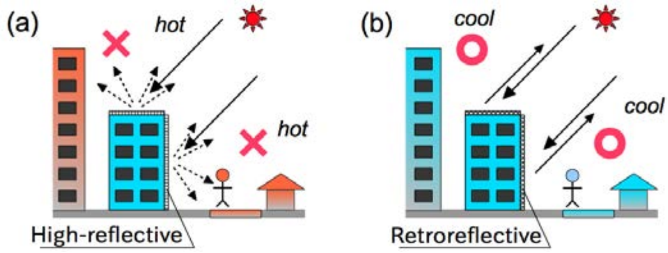

Fig. 1 Comparison between (a) high-reflective and (b) retroreflective materials

1 Introduction

In summer, large cities in the warm regions of the world suffer from extremely hot days and sweltering nights, giving rise to what are known as urban heat islands. This phenomenon occurs partly because the materials used in roads and buildings, such as asphalt and concrete, strongly absorb the solar radiation and their temperatures increase up to 60 or 70 °C in the daytime. Consequently, these hot artificial surfaces increase the temperature of the surrounding air in the urban areas.

To prevent this phenomenon from occurring, high-reflective materials have been employed in the recent past [1]. Transforming the surface of a building or a road into a reflective surface reduces its absorption of solar radiation. Recently, these "cool roofs" and "cool pavements" have been widely used to mitigate the effects of urban heat islands. However, in closely packed building areas, the heat reflected by one surface may be absorbed by another (Fig.1a). Therefore, retroreflective (RR) materials have attracted attention as a substitute that can overcome this problem (Fig.1b) [2], [3], [4].

As illustrated in Fig.1b, RR materials can reflect solar radiation while reducing its glare. In retroreflection, the incident light, e.g., sunlight, is reflected back in the direction of the source, e.g., the sun, with a very small light spread around along this particular direction. Originally, they were developed for road markings and signs to enhance the night-time visibility [5]. Therefore, they would not be efficient, if used in their original form, as solar reflectors.

In this study, methods to control the amount of heat transfer through radiation by adjusting the reflectivity of the absorbing materials are proposed, and it is recommended that the resulting materials should be used as road and building materials, to act as countermeasures to urban heat islands. We explained the background of RR materials in details in Section 2 in this paper. In addition, we introduced two new types of RR materials: the high-spec directional-type in Section 3, and the low-cost, simplified rough-surface-type in Section 4.

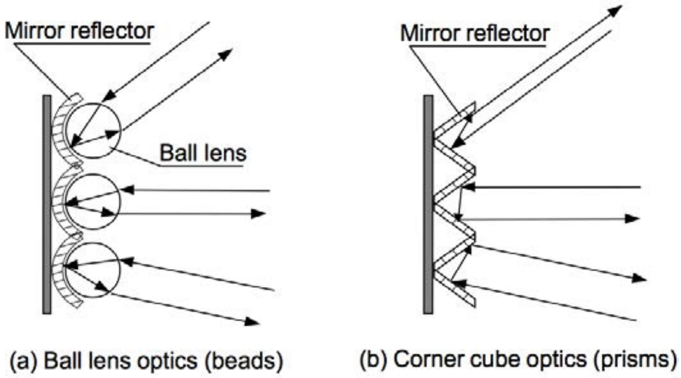

Fig. 2 Cross-sections of the structures of ordinary retroreflective (RR) materials

2 Background

Retroreflection is a unique optical property in which the incident light returns back in the direction of its source. Two main optic structures are used to achieve this property: ball lens optics constructed using glass beads, and corner cube optics constructed using prisms. As shown in Fig.2a, the incident light is focused by a ball lens onto a mirror reflector, and then it is reflected back to its source. Similarly, a corner cube reflector can return an incident light to its source by reflecting the light several times, as shown in Fig.2b [5].

Because RR materials have no moving parts, they do not experience any breakdown, and they require little maintenance, which is a great advantage for road and building materials. Technically, computer-controlled mirrors can also reflect sunlight upward and prevent the side effects in a similar way as RR materials. However, their mechanical moving parts are complicated and need constant maintenance. Thus, covering wide areas of road surfaces and building exteriors with movable mirrors is impractical.

Nevertheless, there is still room for improvement as far as the present forms of RR materials are concerned. For example, the current RR materials reflect winter sunlight as well as summer sunlight, which causes an increase in the heating load in winter. In addition, they reflect street lights and headlights, which causes light pollution at night. Therefore, a directional-type RR that reflects only summer sunlight is ideal. In this study, we have introduced this type of RR and discussed it in Section 3. Moreover, RR materials should have a precise structure, where beads have an exact spherical shape and the corners of the cubes have an exact 90° angle (Fig.2), which makes them fragile and not suited for road materials as they are subjected to repeated rubbing and pressure. Therefore, we proposed a new RR structure that can withstand such conditions; thus, it would be suited for road applications as discussed in Section 4.

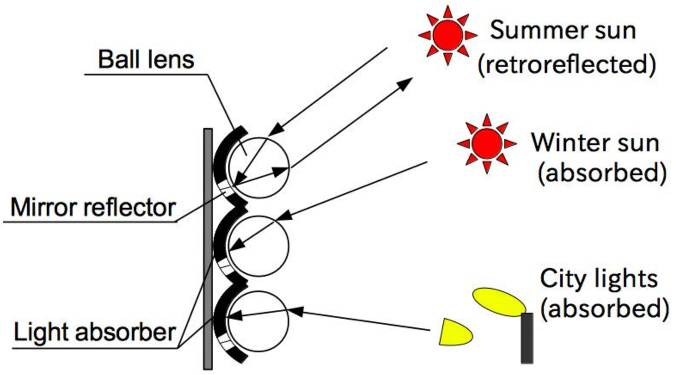

Fig. 3 Cross-section of the structure of directional-type RR for a south-facing wall

3 Proposal 1: Directional-type RR

3.1 Basic concept

A directional-type RR was developed based on the ordinary ball-lens RR [6], where we used the relationship between the angle of the incident light and its focal position on the mirror reflector after passing through the ball lens (Fig.2a), i.e., the incoming light at a certain angle of incidence would be focused on a particular position of the reflector relative to each ball lens. Therefore, if the mirror reflectors that represent the focus regions of winter sunlight and city lights were replaced with light absorbers as shown in Fig.3, RR materials that retroreflect only summer sunlight would be achieved. These light absorbers (illustrated with black parts in Fig.3) prevent the incoming winter sunlight, streetlights, and headlights from being reflected. Thus, the directional-type RR does not increase the heating load in winter or causes light pollution at night.

The path of the sun has an annual cycle, and the direction of the sunlight depends on the location on the Earth. The patterns of the absorbers should be designed according to location (based on latitude/longitude data) and wall orientation in order to achieve the desired directional reflectance. In Fig.3, the pattern of absorbers was designed for a south or north- facing exterior wall in the Northern or Southern hemisphere, respectively.

3.2 Experiment

In this study, we designed two prototypes for RRs with light absorbers (i.e. directional-type RRs) and evaluated their reflective properties by an outdoor exposure test.

As shown in Fig.4, we prepared two 100 x 100 mm mirror stainless steel plates with different light absorber patterns and placed 42 clear ball lenses (soda-lime glass, 12.5 mm in diameter, refractive index n = 1.5) on each plate.

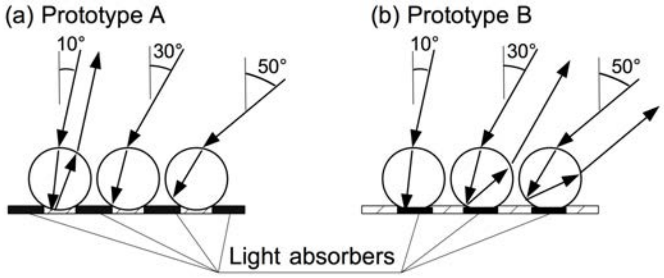

Fig. 4 Two prototypes of directional-type RRs: (a) Prototype A with light absorbers for incoming light with an angle of incidence of more than 30° (b) Prototype B with light absorbers for incoming light with an angle of incidence of less than 30°

In prototype A, the plate was painted black at the focus regions, where the incident angle of the light is more than 30°, to allow it to only retroreflect the incoming light with an incident angle below or equal to 30° (Fig.4a). On the other hand, the plate in prototype B was partly painted black on the focus regions where the incident angle of the light is less than 30° to allow it to only retroreflect the incoming light with an incident angle higher than 30° (Fig.4b).

We performed an outdoor exposure test to evaluate the dependence of the reflectance of both prototypes on the incident angle, as shown in Fig.5. We placed two prototype plates tilted at a 22° angle towards the south on the rooftop of the university building (at latitude: 34.5° N and longitude: 135.5° E) on a summer day (Aug. 18, 2010). During the light exposure, we measured the direct and sky solar radiations on the 22° tilted plane and the temperature of the backside of the plates every 10 s with Type T (copper-constantan) thermocouples. In addition, we placed white, gray, and black plates in the same fashion (Fig.5), where their solar reflectances were measured by UV-VIS-NIR spectrophotometer (Shimadzu Inc. UV-3600), and they were found to be as follows: white = 70.9 %, gray = 23.7 %, and black = 3.5 %. Then they were used as references to estimate the solar reflectances of the prototypes that were calculated according to the measured plate temperatures.

The results of the test are shown in Fig.6. The values of the incident angles of the direct solar radiation on the plates, which vary according to the time of day, are indicated by two oblique lines in Fig.6c.

As shown in Fig.6b, the temperatures measured for prototype A were high close to the black sample at 7:00 to 10:00, medium between the black and white samples at 11:00 to 13:00, and again high close to the black sample after 14:00. On the other hand, the temperatures measured for prototype B were low close to the white sample at 7:00 to 10:00, medium between the black and white samples at 11:00 to 13:00, and again low close to the white sample after 14:00. As shown in Fig.6c, the reflectance of prototype A changed from about 15 % to about 35 % at large and low incident angles, respectively, while prototype B changed its reflectance from about 60 % to about 35 % at large and low incident angles, respectively.

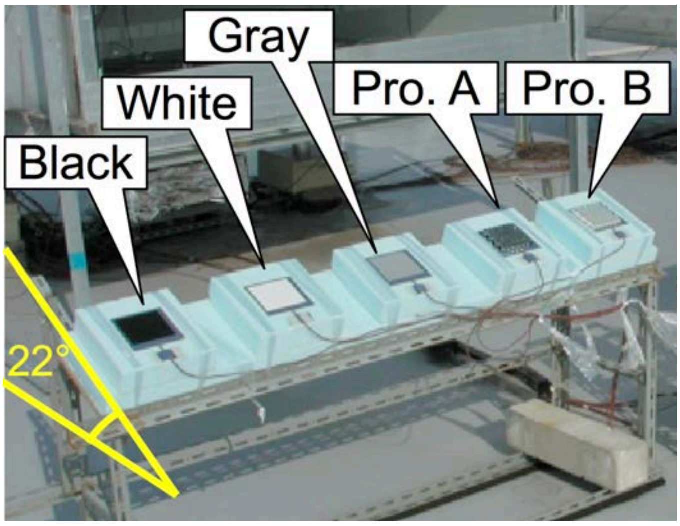

Fig. 5 Photo of the outdoor exposure test conducted to evaluate the dependence of the prototypes' reflectance on the incident angle. All samples were tilted at a 22° angle towards the south, so that the incident angle of the sunlight was 0° (i.e., normal to the surface) at culmination altitude

In summary, we can confirm that RR materials with light absorbers exhibit directional properties of reflectance, which can be controlled by the patterns of the light absorbers.

3.3 Proposal

We propose using directional RR materials as building exteriors that reflect only summer sunlight. Further, light absorber patterns were designed for a cubic-shaped building with east, south, and west-facing walls to demonstrate the feasibility of these materials. First, we set the location at latitude: 34.5° N and longitude: 135.5° E (Osaka, Japan). Then, we estimated the different positions of focal points of the sunlight passing through the glass ball lenses (their refractive index n = 1.5) during one day in summer, spring/autumn, and winter for all the exterior walls of the test building. Fig.7 shows the calculated results of the positions of focal points and the corresponding absorbing regions for the west-facing wall as an example, which revealed that positions of focal points vary according to the season. Therefore, as depicted in the right-hand side of Fig.7, which shows the absorber patterns for 37 ball lenses arranged in a hexagonal shape, if the focus regions of winter sunlight are painted black, the retroreflectivity of the materials for winter sunlight would be eliminated.

A miniature model of cube-shaped building was built, where we have painted the absorbing areas according to the calculated results for the east, south, and west-facing walls as well as the horizontal roof; then, ball lenses (soda-lime glass, 12.5 mm in diameter) were fixed on their places on top of

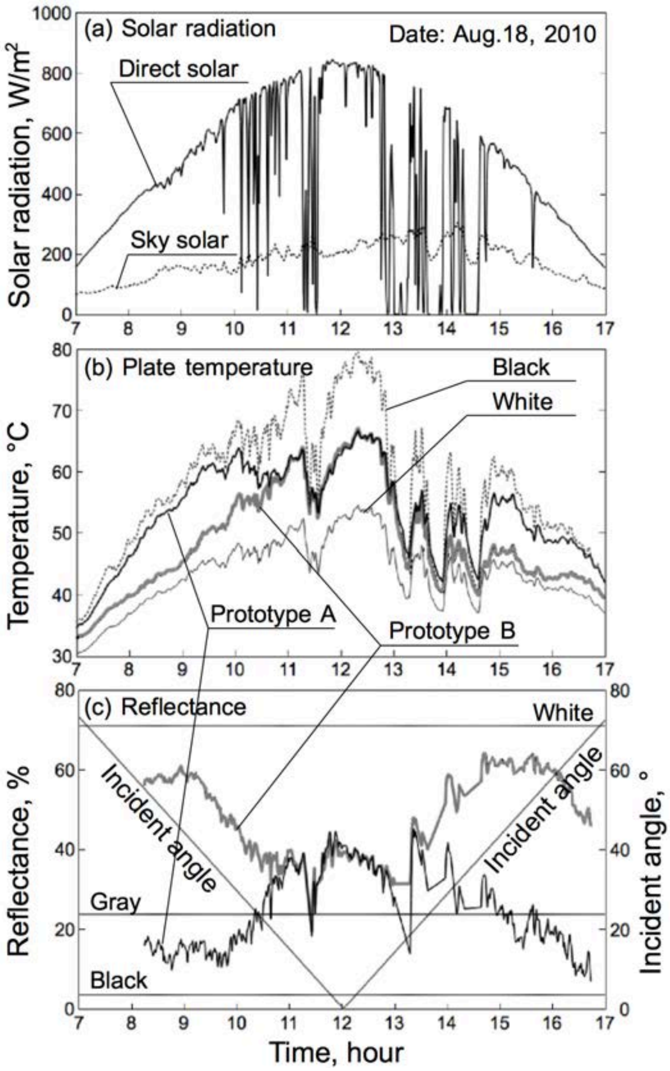

Fig. 6 The results of the exposure test: (a) The amount of direct and sky solar radiations measured by a pyranometer tilted at 22° towards the south (b) Measured plate temperatures (c) The solar reflectances of the prototypes calculated using the solar reflectance of white, gray, and black plates as references

them. Moreover, the flash of a camera was used to simulate sunlight in order to check the directional retroreflectivity of each wall. Fig.8 shows photos of the miniature building taken using the flash, for different positions of the sun, at 8:00 (from east at low altitude), at 12:00 (from south at high altitude), and at 16:00 (from west at low altitude), in winter, spring, and summer. The white regions in these photos represent blown-out highlights, i.e., high-reflective and retroreflective areas.

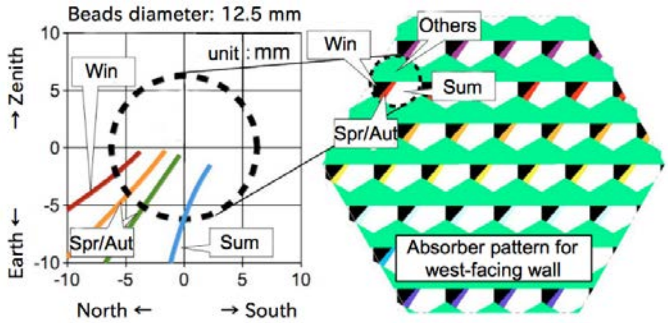

Fig. 7 Left: positions of focal points of the sunlight during one day in winter (Jan), spring/autumn (Mar. and Apr. / Oct. and Nov.), and summer (Aug.) for the west-facing wall Right: the absorber pattern for 37 glass ball lenses arranged in a hexagonal shape

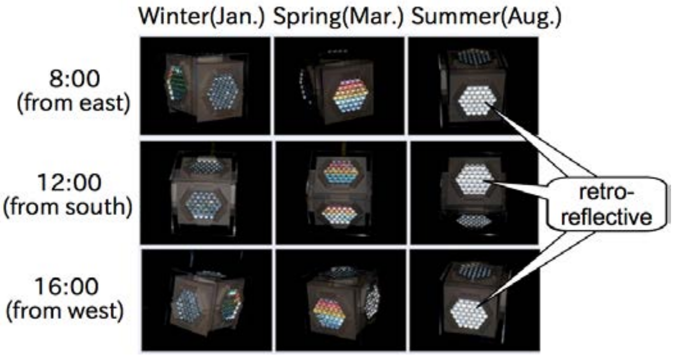

Fig. 8 Photos of a miniature building taken using a flash from directions of the sun position at specific times

The ball lenses on the wall appear completely white in the summer photos shown on the right-hand column of Fig.8. They exhibited high-reflectivity (retroreflectivity) regardless of the time. On the other hand, they appeared slightly darker in the spring photos, which means they have medium reflectivity. Further, they appeared black in the winter photos, which implies they have low reflectivity. This demonstrates the exclusive high-reflectivity of the manufactured directional RR exteriors for summer sunlight.

Therefore, the directional-type RR materials can achieve high energy-saving properties for all seasons without any moving parts. However, their structures are slightly more complicated than the ordinary type because of the absorber patterns. Moreover, they are fragile and are not suited to be applied on roads. Therefore, we suggest using them for roofs and walls.

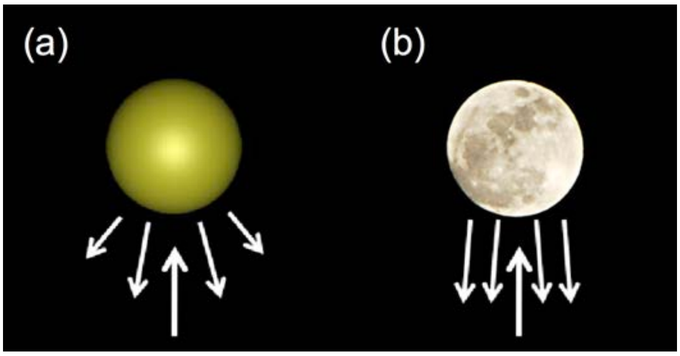

Fig. 9 (a) A ball with diffuse reflection (computer graphics), (b) The full moon with retroreflection (photograph)

4 Proposal 2: Rough-surface-type RR

4.1 Basic concept

As mentioned in Section 2, there are two main RR structures: the ball lens optics constructed using glass beads, and the corner cube optics constructed using prisms. The directional-type RR introduced in Section 3 is a version derived from the ball lens optics type. However, we proposed another completely different RR structure called the rough-surface-type. This structure was originally found on the lunar surface and was actively studied during the Apollo missions [7,8]. The lunar surface is retroreflective and this is why a full moon looks like a disk not a ball. A ball, with diffuse reflection, becomes darker toward the edges when lighted from the front; thus, its spherical shape can be recognized as illustrated in Fig.9a. However, when the sunlight hits the lunar surface from the front (full moon), its entire surface has the same brightness, because it is retroreflective property as shown in Fig.9b.

Historically, the disk-like appearance of the full moon was the clear evidence of the retroreflection of its surface. However, the cause of retroreflection was unknown, because it was unlikely that there could be lots of prisms or ball lenses with mirror reflectors on the lunar surface. Eventually, it was confirmed by inspecting the soil Apollo astronauts obtained from the moon that the cause for retroreflectivity is a combination of surface roughness and its diffuse reflection [8].

Figure 10a illustrates how retroreflectivity is realized on a rough surface with diffuse reflection. Microscopically, an incoming light is reflected diffusely in all directions, but the rough surface consists of tilted small surfaces (convex or peak-shaped parts) that cover the entire macroscopic surface (dashed line in Fig.10) and block the reflected lights. Therefore, the intensity of the reflected light is being reduced in the directions distant from the incident light. The rough surface structure contains no prism or beads, but achieves an overall retroreflective property by this blocking effect (Fig.10a). However, this

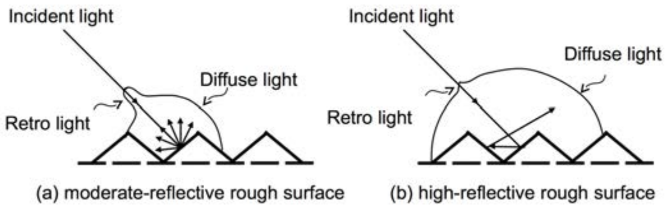

Fig. 10 Cross-sections of the rough-surface-type RR structures

blocking effect occurs only when the microscopic diffuse reflectance is not very high, while when it is too high, the blocked lights would be reflected several times between the tilted small surfaces, and the final effect would be reflecting the incident light in every direction as illustrated in Fig.10b. Therefore, the intensity of the retroreflectivity of the rough-surface-type RR is limited.

4.2 Proposal

To the best of our knowledge, the rough-surface RR discovered in the 1960s during a lunar study has not been intensively investigated, because there was no specific application for it. Therefore, the precise conditions that should be applied to obtain retroreflectivity on rough surfaces are unknown. However, these materials can likely withstand distortion without losing their retroreflectivity, because they are made of diffuse reflective materials, which is insensitive to the incident angle; thus, a slight distortion of the structure would have a little influence on its reflective properties. Therefore, we recommend using the rough-surface-type RR as road materials, because they would withstand the repeated rubbing and pressure.

The other advantage for using them as road materials is that the additional cost for making the road surfaces retroreflective would likely be minimal. This was assumed because the lunar rocks and soil are literally unweathered and not rounded because of the absence of atmospheric air and water on the moon. Further, the surfaces of the asphalt pavement are similarly very rough in nature; therefore, they are suitable to be transformed into retroreflective materials with minimal expenses. Currently, we are investigating the necessary conditions to achieve retroreflectivity and are studying the optimum shape for road materials [9].

5 Conclusions

The following points were discussed in this paper:

1) The side effects of using high-reflective and ordinary RR materials as countermeasures to urban heat islands were pointed out.

2) Two types of RR materials, high-spec directional-type and low-cost rough-surface-type, were proposed to overcome these side effects.

3) The directional-type RR materials reflect only summer light, which can reduce the cooling load in summer, reduce the heating load in winter, and prevent light pollution at night. The structures of these materials are complicated and fragile; thus, they are suited for small areas, such as roofs and walls.

4) The rough-surface-type RR materials have a completely different structure from the ordinary RR materials, and their retroreflectivity is caused by a combination of surface roughness and its diffuse reflection. Therefore, they can withstand distortion and are suited for road surfaces.

We have introduced two novel materials to mitigate the effects of urban heat islands. Therefore, countermeasures against urban heat islands can be enhanced by selecting the appropriate material for each application from these new materials and the traditional ones, such as high-reflective and ordinary RR materials.

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