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Highly Reflective Roofing Sheets Installed on a School Building to Mitigate the Urban Heat Island Effect in Osaka

Jihui Yuan *, Kazuo Emura and Craig Farnham

Department of Housing and Environmental Design, Graduate School of Human Life Science, Osaka City University, 558-8585 Osaka, Japan; emura@life.osaka-cu.ac.jp (K.E.); farnham@life.osaka-cu.ac.jp (C.F.)

* Correspondence: yuanjihui@hotmail.co.jp; Tel.: +81-6-6605-2820

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Abstract: Currently, strategies to mitigate urban heat island (UHI) effects and reduce building energy consumption are implemented worldwide. In Japan, as an effective means of mitigating UHI effects and saving energy of buildings, highly reflective (HR) roofs have increasingly been used. In this study, in order to evaluate the effect of HR roofs on building energy conservation, we investigated the solar reflectivity of a subject school roof in Osaka, Japan, in which HR roofing sheets were installed on the roof from 2010. Additionally, monthly and annual thermal loads, including the cooling load and heating load of the top floor of the school, were calculated using the thermal load calculation software New HASP/ACLD-β. Comparing the calculated thermal loads of the school after HR roofing sheet installation to before, the annual thermal load decreased about 25 MJ/m^2/year, and the cooling load decreased about 112 MJ/m^2/year. However, the heating load increased about 87 MJ/m^2/year in winter. To minimize the annual thermal load, thermal insulation of the roof was also considered to be used together with HR roofing sheets. Thermal load calculations showed that the combination of HR roofing sheets and thermal insulation can be effective in further reducing the annual thermal load.

Keywords: urban heat island; building roofs; highly reflective roofing sheets; thermal insulation; thermal load

1. Introduction

The urban heat island (UHI) effect is a well-documented climatic change phenomenon [1]. UHI intensity in hot climates may raise temperatures by 10 °C [2,3], resulting in increased discomfort and higher pollution levels, while it has a serious impact on the cooling energy consumption of buildings [4,5]. Many UHI mitigation technologies have been implemented by scholars worldwide. Akbari *et al.* [6] summarized the existing UHI mitigation strategies in detail, such as the development of highly reflective (HR) materials, the development of cool and green roof technologies, the development of cool pavement technologies, urban trees, *etc.* It showed that these UHI mitigation strategies can decrease ambient and surface temperatures in cities. Furthermore, the mitigation of UHIs leads to energy and energy expenditure savings, improves urban air quality and ambient conditions, and helps to counter global warming (GW). Santamouris *et al.* [7–9] reviewed many articles aiming to present the actual state of the art on the development and the assessment of cool materials for buildings and structures and showed that the mitigation strategies, such as HR and emissive light colored materials, cool colored materials, phase change materials (PCMs), and dynamic cool materials, used for building roofs or facades, increasing urban albedo, green roofs, *etc.* can significantly contribute to UHI mitigation and the improvement of urban environmental quality.

Among the strategies of UHI mitigation and building energy conservation, HR materials used for roof or pavement have been developed and researched widely [10–12]. Pisello *et al.* [10] carried out an experimental characterization and optimization of a new membrane for building roofs with the aim of contributing to the reduction of the peak ambient temperatures and improvement of the intense UHI phenomenon during summer. Additionally, the in-field and in-lab measurements of several low-cost natural gravel coverings have also been implemented to counter the UHI phenomenon by Pisello *et al.* [11]. Gobakis *et al.* [12] developed a number of inorganic coatings both for buildings and urban environments, and the materials were characterized using X-ray diffraction (XRD) and differential thermal analysis (DTA) to verify their composition, and the optical properties of these materials were analyzed by measuring the surface temperature while exposed to the outdoor environment.

Currently, retro reflective (RR) materials used for building exterior walls to mitigate the UHI effect are being researched globally [13–17]. RR envelopes could help to reduce the energy consumption of buildings and the UHI effect, because a part of the solar radiation is sent back towards the incoming direction. Specifically, RR envelopes can strongly reduce the mutual radiative effect among buildings located in close proximity [18]. Rossi *et al.* [13] chose RR and diffusive reflective materials and tested their reflection directivity properties. The tested RR materials show a strong RR behavior for low incident angles of sunlight; however, RR materials show a weak RR behavior for higher incident angles, and the radiation is mainly specularly reflected. Additionally, UHI mitigation was evaluated by an experimental model while applying these RR or diffusive reflective materials to building envelopes. Compared to the diffusive reflective envelope, the cooling potential of a high-intensity prismatic RR envelope facing south is about 1.5% better at a latitude of 30° when evaluated by an analytical model. The benefit to urban canyons through applying new RR cool materials on the building envelopes was also investigated by Rossi *et al.* [14]. It showed that RR materials have a high cooling potential with respect to traditional white diffusive reflective coatings in urban canyons and can thus improve urban climate conditions during the summer period. Yuan *et al.* [15] proposed a method to determine the retro-reflectance of RR materials and developed a type of RR material and investigated its durability and RR performance by evaluating changes in retro-reflectance for a long time period exposed to the outdoor environment [16]. In addition, the influence of several envelopes with different reflection directional properties on the albedo of urban canyons was simulated and analyzed. It showed that the albedo of simulated urban canyons with RR envelopes is the largest, about 6% larger than those with diffusive reflective envelopes and about 9% larger than those with mirror reflective envelopes [16]. Qin *et al.* [17] evaluated the effect of RR and diffusive surfaces on temperatures of inner and outer walls using simulations set in the outdoor environments. It showed that the RR wall can keep the building blocks cooler than the diffusive wall during sunny weather in the summer period.

The studies above show that the HR or RR building envelope materials have the potential to mitigate UHI effects and reduce cooling loads in the summer due to their high solar reflectivity. However, it can increase the heating load and is not conducive to energy conservation in winter [19,20].

In major cities (Tokyo, Nagoya, Osaka) of Japan, temperatures have been rising. For example, the air temperature has risen 2.1 °C for Osaka in the past 100 years, which is higher than the national average temperature increase of 1.0 °C. This 1.1 °C difference is thought to be due to UHI effect [21]. According to a research report, it is known that the global contribution from buildings towards energy consumption, both residential and commercial, has steadily increased to between 20% and 40% in developed countries and has exceeded the other major sectors: industrial and transportation [22]. Buildings in the urban area are a major contributor to the UHI phenomenon. Research on the anthropogenic heat emissions showed that the exhaust heat from buildings in Japan accounted for approximately half of the anthropogenic heat in the city [23]. Thus, to reduce energy consumption in buildings plays an important role in countering the UHI effect.

Many studies and countermeasures to mitigate the UHI effects have also been implemented widely in Japan [24–27]. From 2010, HR roofing sheets were installed on the roofs of 70 schools in

Osaka, Japan, to mitigate the UHI effect and reduce building energy consumption. The solar reflectivity of HR roofing sheets installed on roofs was investigated over a long period of time. In order to evaluate the effect of HR roofing sheets on the energy conservation of buildings, this study aims to calculate and compare the thermal load of buildings before and after HR roofing sheet installation on their roofs. Additionally, to minimize the thermal load of buildings, this study considers applying thermal insulation together with the HR roofing sheets to the roof.

2. Methodology

2.1. Subject School and HR Roofing Sheet

The subject school was chosen from 70 schools in Osaka. The roof appearance of the subject school covered with HR roofing sheets is shown in Figure 1. The ground plan of the top floor (the 4th floor) of the school building with a floor area of about 683 m^2 is shown in Figure 2. Structures of the roof, floor, exterior wall, and interior wall are shown in Table 1.

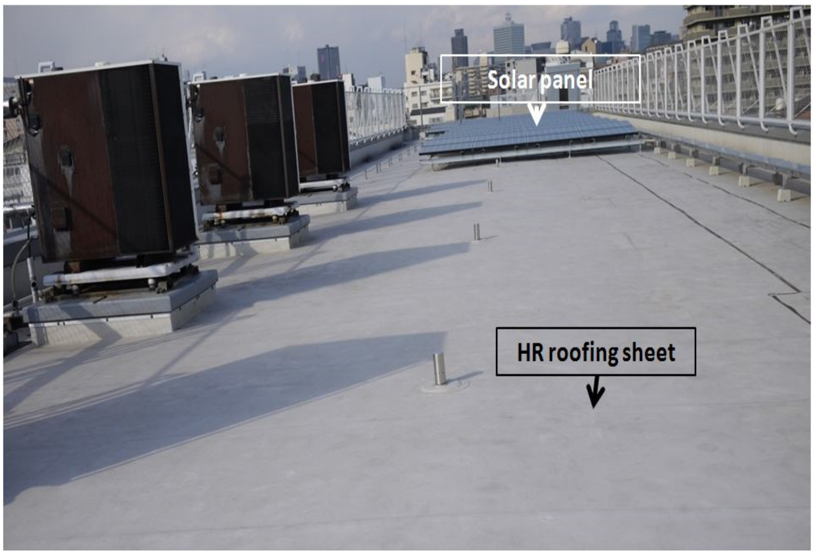

Figure 1. The roof appearance of the subject school coated with HR roofing sheets.

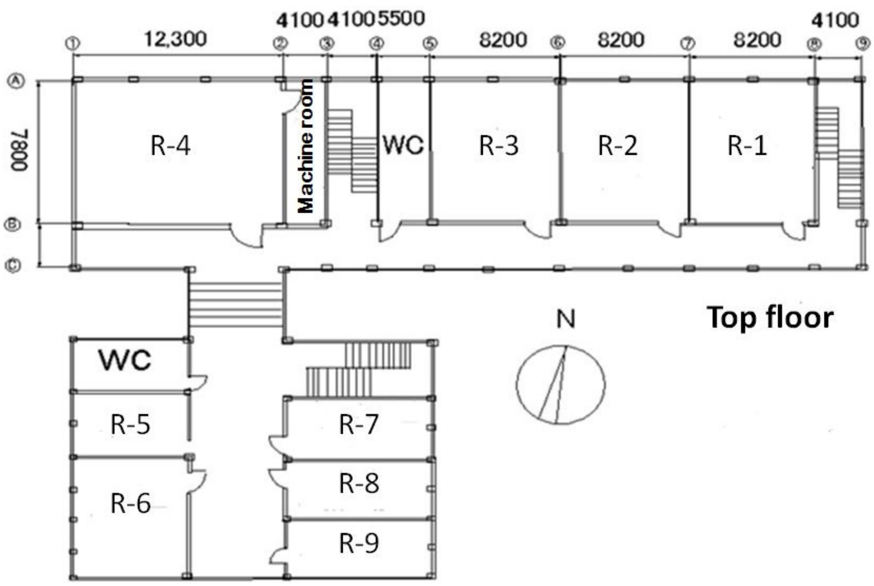

Figure 2. Ground plan of the top floor of the subject school with a floor area of about 683 m^2.

Table 1. Structures of roof, floor, exterior wall, and interior wall of school building.

	A: Before Installation of HR Roofing Sheets	B: After Installation of HR Roofing Sheets
Roof	In order from indoor to outdoor: Rock wool (12 mm) + Gypsum board (9 mm) + Hollow layer + Ordinary concrete (150 mm) + mortar (15 mm) + Asphalt (10 mm) + Light concrete (60 mm)	In order from indoor to outdoor: A + HR roofing sheets (3 mm)
Floor	In order from top to bottom: Plastic tile (3 mm) + Mortar (15 mm) + Ordinary concrete (150 mm) + Hollow layer + Gypsum board (9 mm) + Rock wool (12 mm)	
Exterior wall	In order from indoor to outdoor: Mortar (20 mm) + Ordinary concrete (150 mm) + Mortar (20 mm) + Tile (8 mm)	
Interior wall	Mortar (20 mm) + Ordinary concrete (120 mm) + Mortar (20 mm)	

HR roofing sheets have high solar reflectivity in the near-infrared (NIR) range regardless of the solar reflectivity in the visible (VIS) range. The solar reflectivity of the HR roofing sheet sample in different wavelengths was measured using a spectrophotometer in the laboratory. The solar reflectivity for the wavelength range from 400 nm to 780 nm (Visible range) is approximately 0.5, approximately 0.58 for the range from 780 nm to 1700 nm (Near-infrared range), and approximately 0.54 for the range from 400 nm to 1700 nm.

2.2. Measurement of Solar Reflectivity in the Field

For the purpose of evaluating the durability of the HR roofing sheets installed on the rooftop, the long-term change in the solar reflectivity of the HR roofing sheets over about 780 days was investigated using a portable spectrophotometer. In addition, to examine the effect of surface dirt on its solar reflectivity, the HR roofing sheet surfaces were cleaned with distilled water after about 780 days, and the solar reflectivity was measured. The measurement result is shown in Figure 3.

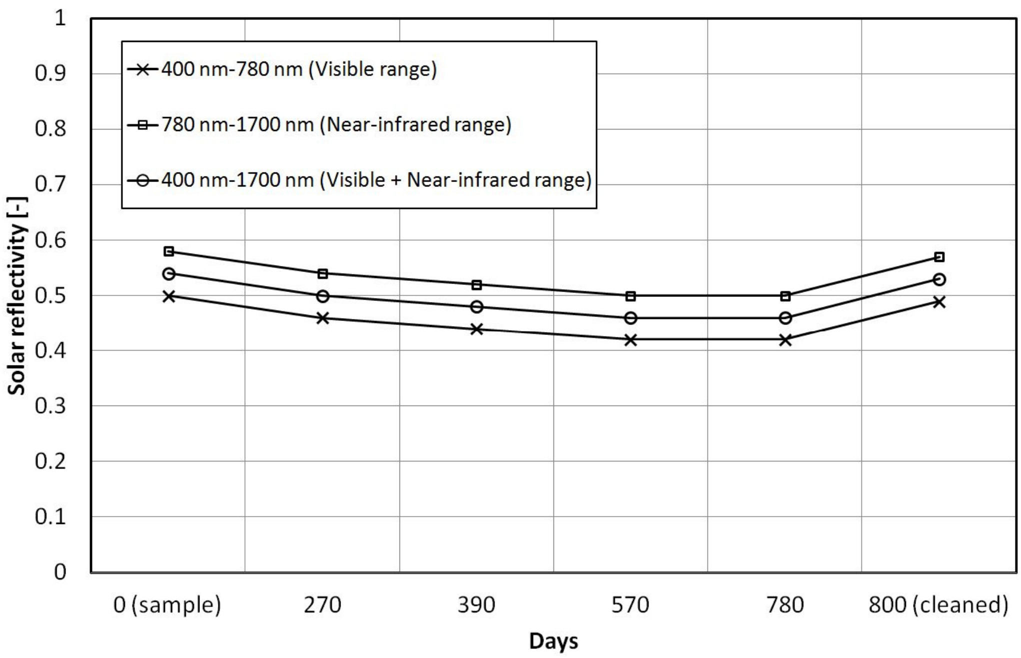

Figure 3. Change in the solar reflectivity of the HR roofing sheets over a long period of time, about 780 days.

The result showed that the solar reflectivity decreased about 0.08 after 780 days of exposure in the outdoor environment for all three wavelength ranges. However, the solar reflectivity almost recovered to the initial value when the surface was cleaned with distilled water. Thus, the dirt accumulated on the surface is considered as the main cause of the decrease the solar reflectivity. This also indicates that there is no surface degradation over the 780 day period.

2.3. Thermal Load Calculation

In this research, the software "New HASP/ACLD-β" is used to calculate the thermal loads of buildings, as EnergyPlus is used in U.S. Parameters in the New HASP/ACLD-β calculation program, such as the solar reflectivity of exterior walls, the structure of building walls, the operating condition of air conditioning, and can be manipulated easily [28]. The following input data needed, similar to EnergyPlus, includes hourly data such as air temperature, solar radiation, cloud cover, and building data such as solar radiation absorption, long-wave emissivity of outer walls, distance to and height of neighboring buildings, and the schedule of indoor activities and occupancy. For a full list, see [28].

For this study, monthly thermal load and annual thermal load (annual cooling and heating loads) of the subject school before and after the construction of the HR roofing sheets were calculated using the New HASP/ACLD-β. Conditions of the thermal load calculation are shown in Table 2.

Table 2. The conditions of the thermal load calculation.

External condition	Standard weather data: Expanded AMeDAS Weather Data of Japan			
	Location: Osaka, Japan			
Orientation and area of window	Orientation of window: Northwest 15 degrees Window area: 3.2 m × 1.8 m = 5.76 m^2			
Fresh air	Infiltration		Amount of fresh air into room ($25\ m^3$/h-person; Weekday 8:00–17:00)	
	0.5 times/h		1.4 times/h	
Internal heat generation	Body (heat generation: 108 W/person)		Lighting (efficiency: 0.9)	OA equipment (Sensible heat)
	Number of persons: 36		10 W/m^2	5.8 W/m^2
Air conditioning service	Weekday 8:00–17:00			
Temperature and Humidity settings		Heating season (Dec–March)	Cooling season (June–Sept)	Middle season (April–May; Oct–Nov)
	Temperature (°C)	22	28	25
	Humidity (%)	40	60	50
Roof solar reflectivity	Standard (no HR roofing sheets): 0.1 for the range (400–1700 nm)		With HR roofing sheets: 0.54 for the range (400–1700 nm)	

3. Results and Discussion

Monthly thermal and annual thermal loads (annual cooling and heating loads) before and after construction of the HR roofing sheets in the subject school were calculated and shown in Figures 4 and 5 respectively.

The result showed the following:

- The thermal load from May to October (note that September is summer vacation for the school) decreased when the roof was covered with the HR roofing sheets (Case B). Among these months, July had the largest reduction of monthly cooling load, about 30 MJ/m^2/month.
- Compared to the case without the HR roofing sheets (Case A), annual total thermal loads decreased about 25 MJ/m^2/year, and the cooling load decreased about 112 MJ/m^2/year with the HR roofing sheets (Case B). However, annual heating load increased about 87 MJ/m^2/year with HR roofing sheets (Case B).

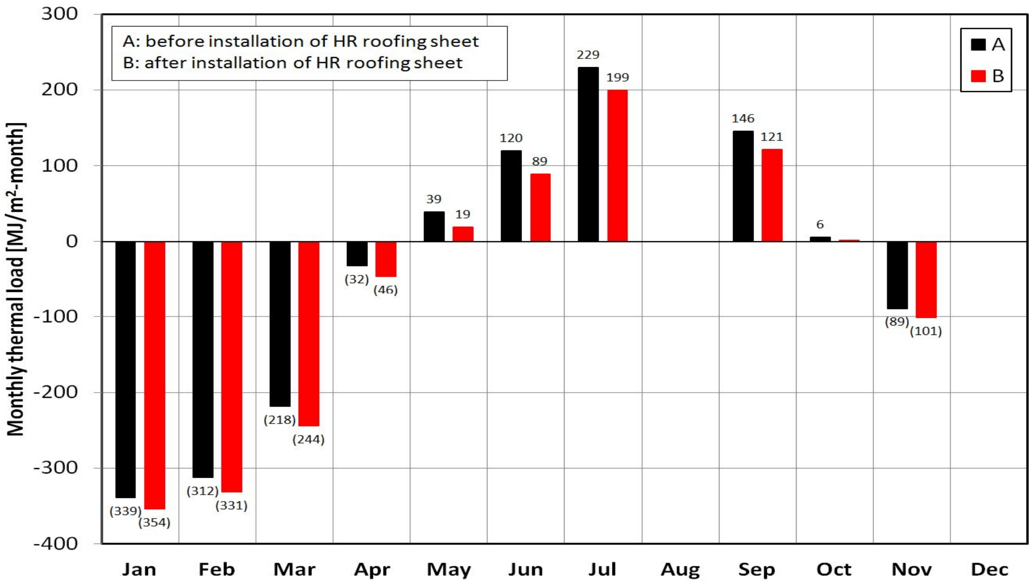

Figure 4. Monthly thermal load of the subject school (A: before installation of the HR roofing sheets; B: after installation of the HR roofing sheets).

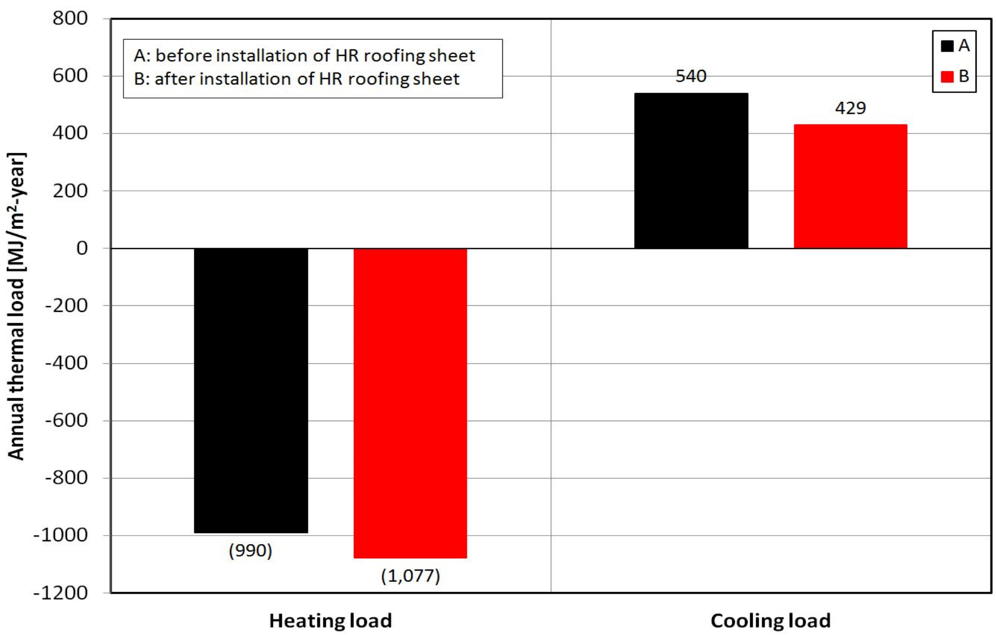

Figure 5. Annual cooling and heating loads of the subject school (A: before installation of the HR roofing sheets; B: after installation of the HR roofing sheets).

4. Retrofitting the Roof to Reduce Thermal Loads

In order to minimize the total thermal load and heating load, the analysis next considers applying thermal insulation to the roof of the subject school together with the HR roofing sheets. Added insulation thickness for four cases (B1: 25 mm; B2: 50 mm; B3: 75 mm; B4: 100 mm) are assumed to be combined with the HR roofing sheets.

Monthly thermal and annual thermal loads (annual cooling and annual heating loads) for the four cases were calculated. These are compared to the previous two and shown in Figures 6 and 7.

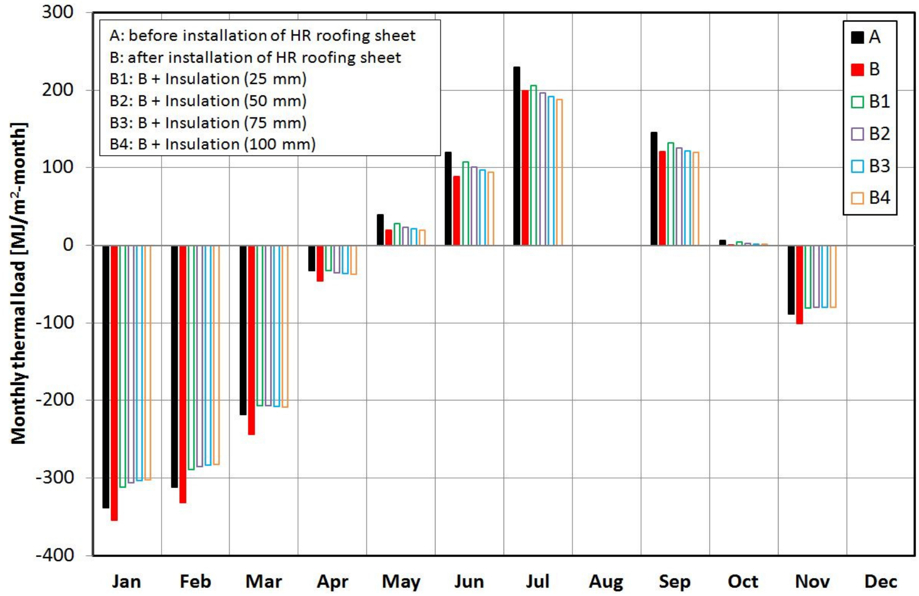

Figure 6. Monthly thermal load of the subject school (A: before installation of the HR roofing sheets; B: after installation of the HR roofing sheets; B1: B + Insulation (25 mm); B2: B + Insulation (50 mm); B3: B + Insulation (75 mm); B4: B + Insulation (100 mm)).

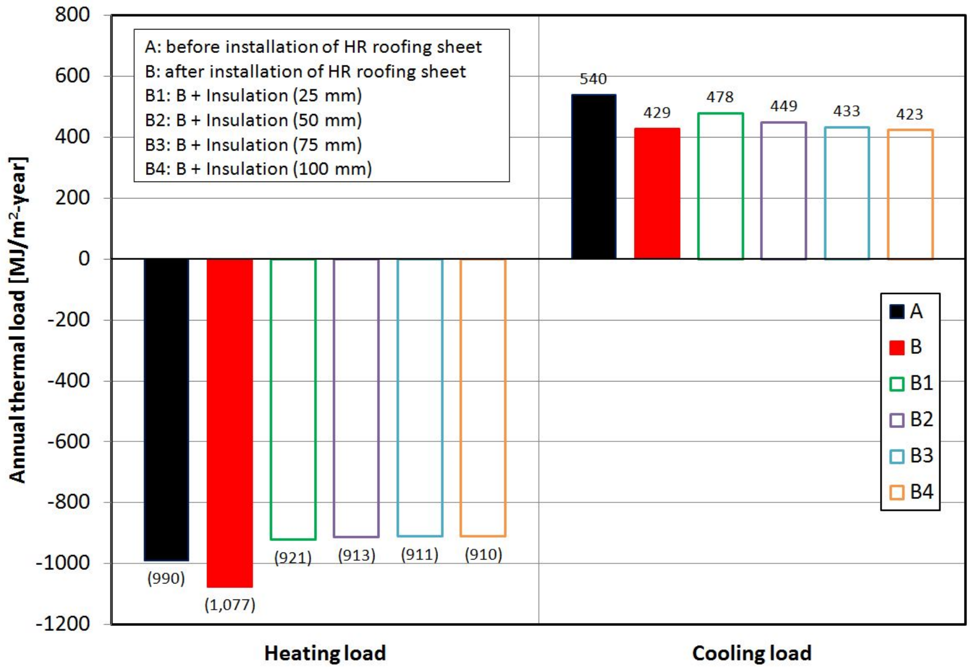

Figure 7. Annual thermal load of the subject school (A: before installation of the HR roofing sheets; B: after installation of the HR roofing sheets; B1: B + Insulation (25 mm); B2: B + Insulation (50 mm); B3: B + Insulation (75 mm); B4: B + Insulation (100 mm)).

The results showed the following:

- Compared to Case A, the total thermal load of Case B1 decreased about 130 MJ/m^2/year (cooling load decreased about 62 MJ/m^2/year and heating load decreased about 68 MJ/m^2/year), the total thermal load decreased about 168 MJ/m^2/year (cooling load decreased about 77 MJ/m^2/year and heating load decreased about 91 MJ/m^2/year) for Case B2, the total thermal load decreased about 186 MJ/m^2/year (cooling load decreased about 107 MJ/m^2/year and heating load decreased about 79 $MJ/m^2/year$) for Case B3, and the total thermal load decreased about 196 $MJ/m^2/year$ (cooling load decreased about 117 $MJ/m^2/year$ and heating load decreased about 79 $MJ/m^2/year$) for Case B4.

- The heating load decreased as the insulation thickness increased from 25 mm to 100 mm. However, the effect of the insulation thickness on the heating load was not significant when the insulation thickness increased above 50 mm.
- Compared to Case B (HR roofing sheets and no insulation), the cooling load of Case B1 (25 mm) and Case B2 (50 mm) increased, and the cooling load of Case B3 (75 mm) and Case B4 (100 mm) was almost the same as Case B.

The result indicated that the appropriate combination of HR roofing sheets and thermal insulation of roof is more effective in reducing the thermal load, which is directly related to the energy conservation of buildings, compared to HR roofing sheets alone or an added thermal insulation of the roof alone.

5. Conclusions and Future Research

This paper presented a countermeasure of a cool building roof to oppose the UHI phenomenon and save on the energy consumption of buildings in Osaka. The analysis is divided into two parts. First is the investigation of solar reflectivity of HR roofing sheets installed on the school roof over a long period of time. The other is a thermal load calculation of the subject school building. The thermal load calculation includes i) a comparison of building thermal loads with and without HR roofing sheets; ii) a proposal of roof retrofitting with HR roofing sheets with added thermal insulation to minimize the annual thermal loads.

For the investigation of solar reflectivity, the solar reflectivity of HR roofing sheets installed on the roof was measured using a portable spectrophotometer, and the measurement result showed that the solar reflectivity decreased about 0.08 for the three different wavelength ranges after 780 days exposure. However, the solar reflectivity almost recovered to the initial value when the surface dirt was cleaned with distilled water. This indicated that there was no significant degradation on the surface of HR roofing sheets over about 780 days.

For the thermal loads of the subject school, the annual total thermal loads of the school building were found to decrease about 25 $MJ/m^2/year$, and the cooling load to decrease about 112 MJ/m^2-year after installation of the HR roofing sheets. However, the annual heating load increased about 87 $MJ/m^2/year$ with HR roofing sheets.

For the retrofitting of the school roof, if the thermal insulation could be added together with the HR roofing sheets, the total thermal load of the subject school can be minimized through a thermal load calculation. Thus, for the location of Osaka (34.7°N), Japan, if the solar reflectivity of a building roof is increased to 0.5 with HR sheets, a combination of insulation thickness of about 50–75 mm with the HR roof sheets is an optimal combination to reduce the thermal load for this school.

For future research, in order to compare the actual energy consumption of buildings with and without an HR envelope, it is necessary to monitor the energy consumption of a building, including its air-conditioning. Additionally, the effect of an HR roof on UHI mitigation must also be examined using simulation and field measurement.

At present, the HR roofing sheets are only installed on the roofs of some schools and are not being used for individual building roofs due to the high cost of HR roofing sheets. Thus, in order to apply the HR roofing sheets more widely, the development of low-cost HR materials will be an important issue in future research. If such diffusive HR materials are used on exterior facades, their reflection directional characteristics should also be better analyzed to prevent "light pollution" in the future.

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Conflicts of Interest: The authors declare no conflict of interest.

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