A Study on Passive Cooling Methods by Evaporation and Solar Reflection on Rooftops in a Temperate Climate Region

Suk-Jin Jung¹ and Seong-Hwan Yoon^{*2}

¹ Ph.D. Student, School of Architecture, Pusan National University, Korea

² Associate Professor, School of Architecture, Pusan National University, Korea

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Abstract

A number of studies have been carried out on the passive cooling of the outer surface of buildings for the purpose of conserving energy without resorting to fossil fuels, while simultaneously improving the indoor thermal comfort. In addition, the heat island phenomenon has been regarded as a problem. Thus, it is necessary to strive to reduce the thermal load of buildings on the urban environment. In this study, an outdoor experiment was conducted using test specimens with a focus on passive cooling on rooftop surfaces in summertime to clarify the cooling effect of various types of passive rooftop cooling. The influence of rooftop cooling on the indoor heat load, and the heat load of the atmospheric side were also clarified. A total of 10 types of data were collected; case 1 is an AR surface, Cases 2~5 are watered AR surfaces, Cases 6 and 7 are ceramic tiles, with and without water coating or white paint respectively, and finally, Cases 8 and 9 are perforated bricks, with and without a coat of white paint respectively. (1) Results of data analysis for Cases 6~10 show that because these types can reduce the load on the air during the day, they are effective. For Cases 7 and 9 and during the day, the heat island effect is suppressed. For Cases 6~9, the tropical night phenomenon can be prevented. (2) In order to reduce the cooling load in summer, the roof slab insulation to reduce heat load in the atmosphere is essential in order to employ an effective passive cooling method. (3) For the insulation standards of the next generation of solar radiation and the evaporation coefficients of 0.5 or 2 and more, 0.1 or 2 can be applied.

Keywords: reflection; evaporation; thermal environment; heat load; temperature; air temperature; rooftop; field experiment; air-conditioning load

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1. Introduction

A number of studies have been carried out on the passive cooling of the outer surface of buildings for the purpose of conserving energy without resorting to fossil fuels, while simultaneously improving the indoor thermal comfort. In addition to this, the heat island phenomenon has been regarded as a problem (Ichinose *et al.*, 1999). Thus, it is necessary to strive to reduce the thermal load of buildings on the urban environment. It is particularly important to examine thermal properties of finishing materials on rooftop surfaces, where the incoming direct solar radiation is considerable.

Based on this, Jayasinghe (2003), Ishikawa (2008) etc. have analysed the indoor energy load or the thermal environment changes that are focused on

cool rooftops where paints or aluminum foils of high reflection rates have been applied. Takahashi (2003), Choi (2006) etc. quantified changes in the indoor temperature by spraying water on the rooftops, and measuring the results. Theodosiou (2003), Yamasaki (2006), Castleton (2010) etc. analysed the effectiveness of reducing the cooling load through the evaporation effects of plants, by measurement and simulation. However, these previous studies were focused on a specific cooling method, and it is hard to find any study cases that compare various passive cooling methods. Also, most of the studies are limited to the building's indoor problems such as indoor load or thermal comfort, and it is hard to find any studies related to the aspect of heat islands in cities, which is a big issue nowadays.

For these reasons, an experiment was carried out with various finishing materials, to compare the effect of the absorption factor of solar radiation and evapotranspiration. Additionally, numerical simulations were carried out and the effect of indoor energy saving, and the relaxation effect of heat islands in cities were analysed. In the outdoor experiment, various test

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^{*}Contact Author: Seong-Hwan Yoon, Associate Professor, School of Architecture, Pusan National University, Jangjeondong, Busan 609-735, Korea
Tel: +82-51-510-1479 Fax: +82-51-514-2230
E-mail: yoon@pusan.ac.kr

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Table 1. Outline of the Test Pieces

CASE No.	Exterior materials of the roof and measuring point of temperature	Cooling Method
1	 Experimental area (300 * 300)	None
2		Sprinkling * at 8:00 (About 0.5 mm)
3		Sprinkling * at 12:00 (About 0.5 mm)
4		Sprinkling * at 16:00 (About 0.5 mm)
5		Sprinkling * at 8:00, 12:00, and 16:00 (Each about 0.5 mm)
6	 Ceramic tile (300 * 300, t=45)	Ceramic tile without water
7		Ceramic tile with water
8	 Brick (300 * 300, t=100, Opening ratio : 20%)	Perforated brick without white painting
9		Perforated brick with white painting
10	 Artificial turf (300 * 300, t=20)	Artificial turf

* Sprinkling was periodically performed from 3 September to 4 September.

** The ceramic tile was sunken in the water for 2 hours, and it was set on the roof at 8:00 of 2 September.
(Initial water content : 30%)

pieces were installed on an existing rooftop to examine the change in the surface temperature on a clear, summer day. Next, numerical calculation was carried out assuming different states of insulation in order to clarify the influence of rooftop surface cooling on the thermal load both indoors and outdoors in summertime.

2. Experimental Outline

2.1 Research building of experimental blocks

The experiment was conducted on the rooftop of the Main Research Building at the Building Research Institute. The building used as a subject was a 7-story RC building; the rooftop finish was asphalt roofing.

Table 1. shows the outline of the test specimens.

Two cases were assumed; one with the test section of asphalt roofing (AR, hereafter) only, and another with that of water-permeable tile (ceramic), perforated bricks (red bricks) and artificial turf (polyethylene resin). The test specimens were installed directly onto the rooftop slab. Based on the unit of 300*300mm, a 300mm interval was placed between individual test specimens to prevent any influence on the adjacent section. Experimental data in this thesis was analysed based on the one dimensional method. The validity of the test specimen was checked by preliminary tests.¹⁾

From the three environmental aspects of "latent heat of evaporation, "ventilation and "solar reflection, three types of passive cooling methods were applied:

(a) watered AR surface (Cases 2~5)

(b) ceramic tiles with and without water content (Cases 6 and 7)

(c) perforated bricks with and without a coat of white paint (Cases 8 and 9)

In the case of (a), to compare the cooling effect at the time of sprinkling, a 0.5mm sprinkling was performed once a day, in the morning, noon or evening (8:00, 12:00 or 16:00) or three times a day (morning, noon and evening). In the preliminary test, when the amount of sprinkling exceeded 0.5mm, the AR surface overflowed. Thus, the authors set the one-time

sprinkling amount to 0.5mm. In the cases of (b), after soaking the ceramic tiles for two hours, they were placed, with a 30% volume water content, in the test section, in the evening (18:00, September 2). In the cases of (c), white paint was applied to the surface.

The temperature (T_{II}) at the upper test piece in (b) and (c) corresponds to the rooftop surface temperature when the test specimen is used as a rooftop finish.

However, in this study, T_{II} was expressed as the upper test specimen temperature in order to distinguish it from Cases 1~5, in which no test specimen was installed. T_I in Case 1 was regarded as the non-measured rooftop surface temperature. The fact was then considered that T_I , T_{II} , and T_{III} had decreased compared to the surface temperature in other cases of different surface finishes and of a similar insulation structure as the cooling effect. The total measurement period was one week, from September 1 to 7, 2003. The main measurement items were the rooftop surface temperature (Tab. 1, T_I), the upper test specimen temperature (Tab. 1, T_{II}), the lower test specimen temperature (Tab. 1, T_{III}), the outside temperature, and solar radiation. The outdoor temperature was measured by an Assmann's aspiration psychrometer (approximately 1.2m in height).

For other temperature measurements, the Type-E thermocouple was used and the results were recorded at 10-minute intervals. For general meteorological data such as wind direction, wind velocity and rainfall, the measured values from the nearest local weather station were utilized. During the measurement, the indoor temperature under the roof was maintained at 24°C by air conditioning.

2.2 Result of the experiment

Fig.1. shows the meteorological conditions during the test period. On fair days from September 3~6, the amount of solar radiation exceeded 800W/m² and the highest daytime temperature was 30°C. On September 3, a 5mm rainfall was recorded between 16:00 and 17:00. Using the actual measured data of September

Fig.1. Weather Condition

3 (the highest temp: 34.5°C) and September 4 after a rainfall, the cooling effect for each case was examined.

Fig.2. (a) shows the change in the rooftop surface temperature T_I in Cases 1~5. Although a cooling effect on the surface temperature of several degrees was observed immediately after sprinkling in Cases 2~5, the effect was temporary.

The decrease in the upper test specimen temperature (T_{II}) can contribute to a reduction in the convective sensible heat on the atmosphere. Thus, by comparing the upper test specimen temperature (T_{II}) to the rooftop surface temperature, the surface temperature difference was regarded as the cooling effect on the atmosphere.

Fig.2. (b) shows the change in the surface temperature and the upper test specimen temperature in Cases 6~9. First, the temperature difference ΔT

was compared between T_I in Case 1 and T_{II} in the other cases. Cases 6 and 8 showed a low surface temperature in the afternoon in comparison to Case 1.

Meanwhile, Cases 7 and 9 showed a large decrease in the surface temperature towards the middle of the day. ΔT reached its maximum before and after 14:00 when the highest daytime temperature occurred, recording -5.3°C in Case 6, -12.9°C in Case 7, -5.2°C in Case 8 and 9.1°C in Case 9. After sunset, the differences between Cases 6~9 were very small. By 5:00 when the lowest daytime temperature occurred, ΔT were somewhere around -2.5 in all cases. Next, from the temperature difference ΔT in T_{II} between Cases 6 and 7 and between Cases 8 and 9, the effects of water content and white-paint coating were examined. In the comparison of surface temperature between the cases of water-permeable tiles with and without water content, a maximum temperature difference of 8.9°C was recorded. Comparing the cases with or without a white-paint coating, the maximum temperature difference was 7.4°C. On September 4, there was no major difference in the surface temperature during daytime in Cases 6 and 7.

This was presumably because the amount of water content had been recovered to a significant extent in both cases because of the rainfall on the evening of September 3. Thus, it became clear that, when using water-permeable materials, the cooling effect for the

Fig.2. Temperature Change of Outdoor Air, Surface Temperature of Rooftop, Top & Bottom Temperature of the Test Specimens

next day and later could be expected not only from human-induced sprinkling but also from natural precipitation in a temperate climate region.

The lower test specimen temperature (T_{III}) in each case is believed to contribute to the overall heat transfer into the room, while as a boundary condition for the rooftop slab, there is a time delay due to the heat transmission of the rooftop slab. Therefore, by comparing the lower test specimen temperature (T_{III}) to the rooftop surface temperature in Case 1, the surface temperature difference was regarded as an index for the cooling effect on the indoor side. Fig.2.

(c) shows the change in the surface temperature and the lower test specimen temperature in Case 1 and Cases 6~9. As a general trend, the daily change in T_{III} in each case was observed to be 1~3 hours late in comparison to the change in the amount of solar radiation. Looking at T_I in Case 1 and ΔT (the temperature difference in T_{III} in the case), the difference was almost none at night. Yet, a relatively large cooling effect was obtained towards the middle of the day in Cases 6~10. ΔT reached its maximum around 14:00 when the daytime temperature also reached its maximum, recording (a) -20.3°C in Case 7, (b) $-13.8 \sim -15.1^\circ\text{C}$ in Cases 6, 8 and 9 and (c) -9.5°C in Case 10. (a) In Case 7, in which the greatest effect was observed, T_{III} was controlled in correspondence to the air temperature, blocking off most of the radiation heat. Similarly to the change in T_{II} in Fig.2. (b), such effect lasted until September 4 because of natural precipitation. (b) The effects in Cases 6, 8 and 9 are believed to stem mainly from the heat capacity and heat resistance of the test specimen. In the case of the lower test specimen temperature, the difference with or without a white-paint coating was about 1.3°C maximum, which is not a particularly large number.

The reason for this is that the test was conducted under weak wind conditions that day; thus, in the end, the effect of removing heat from the radiation by the ventilation of perforated bricks was small. (c) In the case of artificial turf, although the cooling effect on the atmosphere could not be obtained, that on the indoor side was expected.

Fig.3. shows the time change in the surface temperature immediately before and after sprinkling. The change was proportional to the solar radiation at the time of sprinkling in the order of Morning (sprinkling) < Evening < Noon. On the other hand, the duration of the continuous effect was longer in the order of Noon (sprinkling) < Evening < Morning.

The duration is normally two hours or less with this type of sprinkling. Thus, to expect a continuous effect during daytime, one needs to use water-permeable materials.

From Fig.4., based on the discussion results above, the differences between T_I in Case 1 and T_{II} and T_{III} in other cases were obtained, and the decreases in surface

temperature by day and night were then grouped. In G1 (Case 2~5), the decrease in the surface temperature was 1°C or lower for the entire day; a cooling effect on the atmosphere and the indoor side cannot be particularly expected. In G2 (Cases 6 and 8) and G3 (Cases 7 and 9), the decrease in the surface temperature of $3\sim 4^\circ\text{C}$ was observed for the entire day; a reduction in the heat load in the atmosphere can thus be expected. Especially in G3, the surface temperature dropped by more than 8°C during daytime. In G4 (Cases 6~10), a decrease of 8°C or higher in the daytime surface temperature was observed; a cooling effect on the indoor side can thus be expected. One can deduce the following from these analysis results: Cases 6~10 are effective in reducing the air-conditioning load during daytime; Cases 7 and 9 are effective in inhibiting the heat island phenomenon during daytime; and Cases 6~9 are effective in preventing the tropical night phenomenon.

Fig.3. Lapse Time of Cooling Effect after Sprinkling

Fig.4. Cooling Effects during Daytime and Nighttime

3. Calculation Outline

To evaluate the influence of the rooftop surface cooling on the indoor heat load, a dynamic heat load calculation was conducted by the thermal circuit

network method (Ishida *et al.*, 1987). Furthermore, to evaluate the influence of the rooftop surface cooling on the atmospheric heat load, an unsteady heat conduction calculation of a one dimensional multi-mass system on the roof was conducted using the backward relaxation method, which made it possible to predict more detailed data such as a cross-sectional temperature distribution. For the evaporation and reflection of solar radiation on a building's outer surface, the new sol-air temperature was used, taking evaporation into consideration. Details of the SAT* are given in the following:

$$Q_A = Q_R - Q_V - Q_{IE} \quad \text{Eq. (1)}$$

Since $Q_R = Q_S - Q_I$ Eq.(1) can be rewritten as follows:

$$\lambda(\partial\theta/\partial z) = Q_S - Q_I - Q_V - Q_{IE} \quad \text{Eq. (2)}$$

Here,

$$Q_V = \alpha_c (\theta_s - \theta_a) \quad \text{Eq. (3)}$$

$$Q_S = (1 - \theta_a) \quad \text{Eq. (4)}$$

and if $\varepsilon\sigma(T_a^4 - T_s^4) = \varepsilon\alpha_r(\theta_a - \theta_s)$,

$$Q_I = \varepsilon\sigma T_s^4 - (1 - K^*CC)^* B_r^* \varepsilon\sigma T_a^4 - K^*CC\varepsilon\sigma T_s^4$$

$$= (1 - K^*CC)[(1 - B_r)^* \varepsilon\sigma T_a^4 - \varepsilon^* \alpha_r(\theta_a - \theta_s)] \quad \text{Eq. (5)}$$

Also, the saturation vapor pressure f_s is expressed by the one-dimensional approximate equation

($f_s = a^*q_s + b$) of θ_s ,

$$Q_{IE} = w^*I^*\alpha_w(f_s - f_a) = a^*w^*\alpha_w(\theta_s - \theta_a) + w^*I^*\alpha_w(a^*\theta_a + b - f_a) \quad \text{Eq. (6)}$$

Organizing Equations (2)~(6), the following equation can be obtained:

$$-\lambda(\partial\theta/\partial z) = \alpha_t[(\theta_a + \theta_e^*) - \theta_s]$$

Here, however, α_t and θ_e will be

$$\alpha_t = (1 - K^*CC)^* \varepsilon^* \alpha_r + \alpha_c + a^*w^*I^*\alpha_w$$

$$\theta_e^* = [(1 - \rho)J_s - (1 - K^*CC)(1 - B_r)^* \varepsilon\sigma T_a^4 - w^*I^*\alpha_w(b - f_a)]/\alpha_t$$

In this study, $(\theta_a + \theta_e^*)$ is handled as the sol-air temperature, taking evaporation into consideration (SAT*, hereafter). Fig.5. shows the results for which SAT* was calculated, using the hottest day. The maximum air-conditioning load was generated (August 5) from the standard weather data of Tokyo.

SAT* dynamically changes depending on the solar reflectance (ρ , hereafter) rather than the evaporation rate (w , hereafter). If the value is identical, the SAT* with a value of ρ that is greater than that of w takes precedence. Here, based on the concept of the above SAT*, the equivalent solar reflectance is proposed (ρ^* , hereafter) to evaluate the effects of evaporation and the reflection of solar radiation. If equivalent outside air temperatures with evaporation in mind are equal, the effects of evaporation and solar reflection are considered to be equal. In the following, a numerical analysis was conducted with ρ^* as the main parameter.

Figs.6. and 7. show the floor plan of the building and the rooftop slab structure in the indoor heat load

calculation. For the subject, an office building was envisioned; the plan for the room was created based on standard office simulations of AIJ (Architectural Institute of Japan). The rooftop surface temperatures can vary considerably depending not only on the surface finish but also on the insulated state of the rooftop slab. For this reason, a calculation was performed for the case with no insulation (thermal resistance: $0.51\text{m}^2\text{K/W}$) on the rooftop slab.

(a) Relationship between ρ and SAT* ($w=0.0$)

(b) Relationship between w and SAT* ($\rho=0.1$)

Fig.5. Relationship between ρ, w and Outdoor Air Temperature

Fig.6. Floor Plan of the Building for the Calculation

Then, after changing the thickness of the insulation material in five stages, a calculation was conducted for the case of internal insulation (thermal resistance: $0.87\sim 5.88\text{m}^2\text{K/W}$) on the rooftop slab. Table 2. shows various input conditions used to calculate the indoor heat load. Air conditioning was set to operate between 8:00 and 18:00 and the fixed temperatures

*The case with thermal insulation material: Extrusion method polystyrene form 3 sorts
 =10/20/30/50/100/150mm
 (Convective heat transfer coefficient=0.03W/m²K, Heat capacity=25.1kJ/m³K)

Fig.7. Rooftop Slab Structure for the Calculation

for air conditioning and heating were set at 26°C and 22°C respectively. Inside the building, the heat generation of 25W/m² from lighting and equipment was established. The convection heat-transfer rate on the indoor side and outdoor side was 11.1 and 25.0W/m²K respectively.

Table 2. Input Conditions for the Calculation

Data kinds	Input conditions		
Weather data	Standard weather data of the average year of the SHASE		
Room outline and indoor conditions	Size	Area	108 m ²
		Story height	3.6m
	Conditions of air-conditioning	Setup temp. for cooling	26°C
		Setup temp	22°C
		Air-conditioning time	8am-6pm
		Ventilation rate	1.0 ACH
Thermal boundary data	Indoor heat generation	Lighting	20W/m ²
		Instrument	5w/m ²
		Person	0.2person/m ²
	Convective heat transfer coefficient	Indoor side	11.1W/m ² K
		Outdoor side	25.0W/m ² K
	Others	Indoor heat capacity	12.6KJ/m ³ K
	Rooftop	Equivalent solar reflectance *	0.1~0.9
		Thermal resistance	0.51~5.88m ² KW
		Thermal emittance	0.9
	Exterior wall	Solar reflectance	0.1
		Thermal emittance	0.9
	Window	Thermal resistance	2.11 m ² KW
		Solar permeability coefficient	0.29
		Solar shading coefficient	0.125

4. Result of the Calculation

Fig.8. shows the integrating value of air-conditioning load on the hottest day in Tokyo with atmosphere $\rho^*=0.1\sim0.9$ under different insulated states of the rooftop slab. Fig.9. shows the convective heat flux from the rooftop during the daytime under the same conditions. When the rooftop is insulated, the air-conditioning load decreases (Fig.8.). The thermal resistance level of the rooftop slab was particularly conspicuous in its drop rate between no insulation and the standard for the next-generation energy-saving level of Japan (2.29m²K/W). Even for the building without insulation, the effect of air-conditioning load reduction corresponding to that in the next-generation energy-saving level could be obtained by implementing a rooftop cooling of $\rho^*=0.9$.

By comparison, as the thermal resistance value of the rooftop increases, the convective heat flux from the rooftop during daytime increases (Fig.9.).

Fig.8. Air-Conditioning Load during the Day (Tokyo, the Hottest Day)

Fig.9. Convective Heat Flux to the Atmosphere during the Daytime (Tokyo, the Hottest Day, 10:00~15:00)

However, the increase rate was merely 2~3%, a small figure compared to the air-conditioning load.

Fig.10. shows the relationship between the daytime and nighttime rooftop surface temperatures and the heat flux to the indoor side and the outdoor side air on the hottest day in Tokyo.

In the daytime, there was a correlation between the ρ^* value and the rooftop surface temperature; as the ρ^* value increased by 0.2, the surface temperature decreased by 5.3~5.5°C (Fig.10. (a)).

The rooftop surface temperature changed significantly depending on the ρ^* value rather than on the insulated state of the rooftop slab. When $\rho^*=0.1$, the rooftop surface temperature was 21.0°C higher than the outdoor temperature. As the surface temperature increased, the heat flux to the indoor side and the atmosphere also increased. Yet, by strengthening the insulation, the heat transfer could be controlled to a low level.

Similarly, at nighttime, as the ρ^* value increased, the rooftop surface temperature decreased (Fig.10. (b)). It is believed that the increase in the ρ^* value helped the effect of inhibiting the daytime thermal storage.

Similarly to the daytime, as the surface temperature increased, the heat flux to the indoor side and the atmosphere also increased. Yet, when the surface temperature reached below the outdoor air temperature, the heat flux value to the atmosphere side became

negative. Thus, the heat flux to the atmosphere was negative when the ρ^* value was 0.7 or greater, regardless of the insulated state of the rooftop slab. The above findings clarified that the rooftop surface temperature was closely related to both the heat load to the atmosphere and the indoor heat load. This suggests that observed values of the rooftop surface temperature in Fig.4. played a significant role in measuring the thermal performance of the rooftop slab.

Fig.10. Average Rooftop Temperature During the Daytime and the Nighttime, and Heat Flux to Indoor and the Atmosphere (Tokyo, the Hottest Day, Daytime: 10:00~15:00, Nighttime: 22:00~Following 3:00)

Fig.11. shows the daily integrating value of the air-conditioning load on the hottest day when w and ρ changed to 0.1 and 0.9 respectively. It became clear that even when the rooftop slab was not insulated, an energy-saving performance similar to that in the next-generation insulation standard of Japan (thermal resistance=2.29m²K/W) could be obtained from ρ :0.5 or greater (w =0.0) and w :0.1 or greater (ρ =0.1). It also became clear that, with ρ :0.5, an effect of air-conditioning load reduction similar to that with w :0.1 could be obtained. Also, it was confirmed that, regardless of the insulated state of the rooftop slab, with an increase in ρ , w would contribute to the reduction in the indoor air-conditioning load.

Up to this point, the cooling effect of the rooftop surface in summertime has been examined. In winter, it

is believed that the reverse effect such as a heating load increase occurs. Therefore, an annual load calculation was performed, targeting the regions that have different climate conditions, and a yearlong evaluation was conducted.

Fig.11. Daily Integrating Air-Condition Load and w , ρ (Tokyo, the Hottest Day)

Fig.12. shows the integrating value of the region-by-region annual air-conditioning load on the non-insulated rooftop slab when ρ^* :0.1, 0.5, and 0.9.

As ρ^* increased, the cooling load reduced and the heating load increased. This problem of the heating load increase can be resolved by passive actions such as watering only in summertime using water-retentive materials on the rooftop. However, the details will be a future task. In Tokyo, the cooling load, which had been reduced due to the rise in ρ^* , was offset by the increase in the heating load and showed no change as the annual air-conditioning load.

However, the problem of the peak electric power in summer was one of the major tasks in terms of energy issues. Thus, it is believed that, in regions south of Tokyo, one should strive to decrease the surface temperature on the rooftop surface.

Fig.12. Annual Air-Conditioning Load of Several Regions in Japan (RC Structure, Roof Slab: No Thermal Insulation)

5. Conclusion

In this study, an outdoor experiment was conducted using test specimens with a focus on the passive cooling on the rooftop surface in summertime to clarify the cooling effect of various types of passive cooling. Influence of the rooftop cooling on the indoor heat load

and the influence of the heat load on the atmospheric side were also clarified. The findings are as follows:

1. A total of 10 types of experimental data were collected; Case 1 is an AR surface, Cases 2~5 are watered AR surfaces, Cases 6 and 7 are ceramic tiles, with and without a water coat or white paint respectively, Cases 8 and 9 are perforated bricks, with and without a coat of white paint respectively, and finally, Case 10 is an artificial turf (polyethylene resin). Results of data analysis for Cases 6~10 show that because these types can reduce the load on the air during the day, they are effective. For Cases 7 and 9, during the day, the heat island effect is suppressed. For Cases 6~9, the tropical night phenomenon can be prevented. For Cases 2~5, the decrease in the surface temperature was 1°C or lower for the entire day; a cooling effect on the atmosphere and the indoor side cannot be expected.

2. It was discovered that, even when the insulation work on the rooftop slab is incomplete, an energy-saving performance similar to that in the next-generation insulation standards could be achieved with a solar reflectance of 0.5 or greater and an evaporation rate of 0.1 or greater.

3. From the calculated findings of the region-by-region annual air-conditioning load, it was noted that regions where the cooling of the rooftop surface would be effective throughout the year are the regions south of Tokyo.

Symbols

- 1) subscript a: atmosphere
- 2) subscript s: surface
- 3) subscript t: physical quantity at thickness t
- 4) Q_R : radiant heat transfer [W/m^2]
- 5) Q_S : heat transfer by short wave radiation [W/m^2]
- 6) Q_L : heat transfer by long wave radiation [W/m^2]
- 7) Q_V : sensible heat transfer [W/m^2]
- 8) Q_E : latent heat transfer [W/m^2]
- 9) Q_A : conductive heat transfer [W/m^2]
- 10) α_c : convective heat transfer coefficient [$W/(m^2K)$]
- 11) α_r : radiant heat transfer coefficient [$W/(m^2K)$]
- 12) α_w : moisture transfer coefficient [$W/(m^2h(kg/kg))$]
- 13) ρ : reflectance [-]
- 14) ε : emittance [-]
- 15) σ : Stefan-Boltzmann constant [$W/(m^2K^4)$]
- 16) B_r : ratio of emission [-]
- 17) J_s : solar radiation [W/m^2]
- 18) T : absolute temperature [K]
- 19) θ : temperature [°C]
- 20) K : height coefficient of clouds [=0.62]
- 21) CC : amount of clouds [-]
- 22) a, b : coefficient of one-dimensional approximate equation of saturation vapour pressure [-]
- 23) w : evaporation efficiency [-]
- 24) f : vapour pressure [kg/kg]
- 25) l : latent heat of evaporation of water [=2512kJ/kg]
- 26) λ : thermal conductivity [$W/(mK)$]

Note

- ¹ A preliminary experimental study was carried out using a 300*300mm size ceramic tile and a 1000*1000mm size ceramic tile, and it was noted that the temperatures were almost the same with a slight temperature difference of 0.2°C. Also, it was noted, that the temperature difference between the center point of the test specimen (300*300mm) and two compensational temperature measurement points, which were 150mm away from the center point of the test body, was within -0.2~+0.1°C.

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