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

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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

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. Theodosisiou (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
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.

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
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 $\Delta T$ 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. $\Delta T$ 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, $\Delta T$ were somewhere around -2.5 in all cases. Next, from the temperature difference $\Delta T$ 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
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 \( T_{lm} \) 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 \( T_{lm} \) 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 \( T_{lm} \) in each case was observed to be 1~3 hours late in comparison to the change in the amount of solar radiation. Looking at \( T_1 \) in Case 1 and \( \Delta T \) (the temperature difference in \( T_{lm} \) 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. \( \Delta T \) reached its maximum around 14:00 when the daytime temperature also reached its maximum, recording (a) \(-20.3^\circ C\) in Case 7, (b) \(-13.8 \sim -15.1^\circ C\) in Cases 6, 8 and 9 and (c) \(-9.5^\circ C\) in Case 10. (a) In Case 7, in which the greatest effect was observed, \( T_{lm} \) was controlled in correspondence to the air temperature, blocking off most of the radiation heat. Similarly to the change in \( T_2 \) 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.

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:

\[ Q_A = Q_E - Q_r - Q_{IE} \]  
Eq. (1)

Since \( Q_S = Q_A - Q_e \), Eq.(1) can be rewritten as follows:

\[ \lambda(\partial \theta/\partial z) = Q_S - Q_r - Q_e + Q_{IE} \]  
Eq. (2)

Here,

\[ Q_S = \alpha_r (\theta_s - \theta_r) \]  
Eq. (3)

\[ Q_r = (1 - \theta_s) \]  
Eq. (4)

and if \( \epsilon(\theta_s^4 - \theta_r^4) = \epsilon\alpha_r (\theta_s - \theta_r) \),

\[ Q_r = \epsilon\sigma (\theta_s^4 - (1-K'CC)B'_\rho \sigma T_s^4 - K'CC\sigma T_r^4) \]

\[ \theta_r = [(1-K'CC)(1-B'_\rho)\sigma T_s^4 - \epsilon \alpha_r (\theta_s - \theta_r)] \]  
Eq. (5)

Also, the saturation vapor pressure \( f_s \) is expressed by 
the one-dimensional approximate equation 
\( (fs = a\theta_s + b) \) of \( \theta_s \),

\[ Q_{IE} = w^* T \alpha_w (f_s - f) = w^* T \alpha_w (\theta_s - \theta_r) + 
\quad w^* T \alpha_w (a\theta_s + b - f) \]  
Eq. (6)

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

\[ -\lambda(\partial \theta/\partial z) = \alpha_r (\theta_s + \theta_r) - \theta_r \]

Here, however, \( \alpha_r \) and \( \theta_r \) will be

\[ \alpha_r = (1-K'CC)\epsilon \alpha_r + \alpha_r + w^* T \alpha_w \]

\[ \theta_r = [(1-K'CC)(1-B'_\rho)\sigma T_s^4 - w^* T \alpha_w (a\theta_s + b - f)]/\alpha_r \]

In this study, \( (\theta_s + \theta_r) \) 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 (\( \rho \), hereafter) rather than the evaporation 
rate (\( w \), hereafter). If the value is identical, the SAT* 
with a value of \( \rho \) that is greater than that of \( w \) takes 
precedence. Here, based on the concept of the above 
SAT*, the equivalent solar reflectance is proposed (\( \rho^* \), 
hereafter) to evaluate the effects of evaporation and 
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 \( \rho \) 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: 0.51m²K/W) on the rooftop slab.

Then, after changing the thickness of the insulation 
material in five stages, a calculation was conducted 
for the case of internal insulation (thermal resistance: 
0.87–5.88m²K/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
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.

4. Result of the Calculation

Fig.8 shows the integrating value of air-conditioning load on the hottest day in Tokyo with atmosphere $\rho^*$=0.1~0.9 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.). 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 $\rho^*$ value and the rooftop surface temperature; as the $\rho^*$ 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 $\rho^*$ 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. Yet, when the surface temperature reached below the outdoor air temperature, the heat flux value to the atmosphere side became

Table 2. Input Conditions for the Calculation

| Data kinds          | Input conditions                          |
|---------------------|------------------------------------------|
| Weather data        | Standard weather data of the average year of the SHASE |
| Size                | Area 108 m²                               |
|                     | 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                 |
| Indoor heat generation | Lighting 20W/m²                        |
|                     | Instrument 5w/m²                         |
|                     | Person 0.2person/m²                     |
| Convective heat transfer | Indoor side 11.1W/m²K         |
|                     | Outdoor side 25.0W/m²K                   |
| Others              | Indoor heat capacity 12.6KJ/m³K           |
| Thermal boundary data | Equivalent solar reflectance 0.1~0.9  |
|                     | Thermal resistance 0.51~5.88m²/KW         |
|                     | Thermal emittance 0.9                     |
|                     | Exterior wall                            |
|                     | Solar reflectance 0.1                     |
|                     | Thermal emittance 0.9                     |
|                     | Thermal resistance 2.11 m²K/W            |
| Window              | Solar permeability 0.29                  |
|                     | Solar shading coefficient 0.125           |

The rooftop surface temperature changed significantly depending on the $\rho^*$ 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 $\rho^*$ value increased, the rooftop surface temperature decreased (Fig.10. (b)). It is believed that the increase in the $\rho^*$ 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 $\rho^*$ 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.

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.

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, $\rho$ (Tokyo, the Hottest Day)](image1)

![Fig.12. Annual Air-Conditioning Load of Several Regions in Japan (RC Structure, Roof Slab: No Thermal Insulation)](image2)

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\(_c\): convective heat transfer [W/m\(^2\)]
5) Q\(_r\): radiant 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\(_w\): latent heat transfer [W/m\(^2\)]
9) Q\(_c\): conductive heat transfer [W/m\(^2\)]
10) a\(_c\): convective heat transfer coefficient [W/(m\(^2\)K)]
11) a\(_r\): radiant heat transfer coefficient [W/(m\(^2\)K)]
12) a\(_m\): moisture transfer coefficient [W/(m\(^2\)K\(^2\))]\(^{-1}\)
13) \(\rho\): reflectance [-]
14) \(\varepsilon\): emittance [-]
15) \(\sigma\): Stefan-Boltzmann constant [W/(m\(^2\)K\(^4\))]\(^{-1}\)
16) B\(_e\): ratio of emission [-]
17) S\(_c\): solar radiation [W/m\(^2\)]
18) T\(_\infty\): absolute temperature [K]
19) \(\Theta\): temperature [°C]
20) K\(_a\): 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) \(\lambda\): 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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