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STUDY ON HEAT ISLAND MITIGATION ON INTERLOCKING BLOCK PAVEMENT

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Note: The following is the notation used in this paper: (.) for decimals and ( ) for thousands.

Summary

Many cities in Japan are very hot in summer. On warm summer days, the air temperature in a city can be 3°C to 4°C higher than in surrounding areas. Such cities are called "urban heat islands." Measures to mitigate this "urban heat island effect" tend to address three factors: land cover, anthropogenic heat, and topographic features that affect wind.

Roads and parking lots are usually paved with black asphalt, which absorbs most of the sunlight that falls on it. The sunlight is converted into thermal energy, and when these pavements heat up, they heat the ambient air. Various pavement surfaces have been proposed toward mitigating the urban heat island effect. This study examined the thermal characteristics of interlocking block (IL block) pavement by analyzing the surface heat budget, net radiation, surface temperature, subsurface temperature, conduction heat flux and other characteristics.

Compared with asphalt pavement, IL block pavement was found to have a lower pavement temperature in daytime and to decrease the sensible heat flux that heats the ambient air. IL block pavement is expected to be effective at mitigating the urban heat island effect.

1. INTRODUCTION

In recent years, large cities in Japan have been experiencing a strong heat island effect, a phenomenon whereby temperatures in a city are higher than those in its suburbs. Specifically, summer daytime temperatures become higher and the number of "tropical nights" increases. The heat island effect has emerged because:

1. Artificial land cover (urban structures, roadway pavement) in cities has increased, which has lead to reduced water evaporation and transpiration, thus reducing the latent heat flux.
2. Exhaust heat from automobiles and air conditioners has increased, which increases the heat flux to the atmosphere.
3. Narrowly spaced high-rise buildings hinder the dispersion of air that has been warmed by sensible heat flux.

Mitigating the heat island effect requires modifying ground surfaces covered with concrete and asphalt. Achieving this requires developing new roadway paving techniques, as well as expanding parks and other green spaces and planting street trees. In Japan, pavements that are expected to mitigate the heat island effect include water-retentive pavement, reflective pavement, permeable pavement and soil pavement. In the United States, increasing attention has been paid to the external surfaces of buildings and to roadways, for similar reasons. Hashem Akabari, et al of the Heat Island Group at the Lawrence Berkeley National Laboratory have proposed light white-colored concrete pavement, whose higher albedo (solar reflectance) helps moderate the maximum daytime temperature of roadway surfaces. Calling it "cool pavement," the group has been studying white-colored concrete pavement as a means of mitigating the heat island effect. One light-colored concrete pavement is interlocking block (IL block) pavement.

This paper investigates the extent to which IL block pavement can reduce the intensity of sensible heat flux, and thereby reduce the heat island effect. Toward this, the authors installed test pavements, took related measurements on IL block and asphalt pavement specimens and analyzed the results to clarify differences in heat budget between the specimens.

2. PAVEMENT SPECIMEN MEASUREMENTS

Comparative measurement of heat budget between IL block and asphalt pavement specimens was conducted in Osaka, a Japanese city known to be a severe heat island. The types of pavement used were permeable IL block pavement, and normal and permeable asphalt pavements for control. The permeable IL block pavement specimen was of a rectangular type, with each block measuring 100 mm x 200 mm x 80 mm. The specimen had a permeability coefficient of 1×10^{-2} cm/sec or more, which meets the relevant Japanese standard. Figure 1 shows the IL block specimen which was installed with Type-T thermocouple. The normal asphalt pavement specimen was dense-graded asphalt with a maximum grain diameter of 13 mm. The permeable asphalt pavement specimen was an open-graded asphalt mixture with a permeability coefficient of 1×10^{-2} cm/sec or more.



Figure 1. IL block specimen installed with Type-T thermocouple.

The pavements were designed for light traffic and were composed of the following layers from top to bottom. The permeable IL block pavement consisted of 8 cm of permeable IL block, 2 cm of cushion sand, 50 mm of permeable bituminous-stabilization, 10 cm of crusher-run and 10 cm of filter. The normal asphalt pavement consisted of 50 mm of normal asphalt mixture, 50 mm of bituminous-stabilization and 120 mm of crusher-run. The permeable asphalt pavement consisted of 50 mm of permeable asphalt mixture, 5 cm of permeable bituminous-stabilization, 120 mm of crusher-run and 100 mm of filter. Each pavement installed at the experiment site is 2 m x 2 m.

The following parameters were measured: air temperature, relative humidity, global solar radiation on the horizontal plane, infrared radiation flux, wind direction, wind velocity, rainfall and the specimen's surface and internal temperatures and heat flux. Solar reflectance (albedo) was calculated based on the results of solar irradiance measurement using shortwave and long-wave radiometers. Amounts of evaporation from the specimens were also measured by using test pieces.

Surface temperature was measured using infrared thermometer and Type-T thermocouple (with the latter fixed to the surface by adhesive tape). The infrared thermometer was installed 150 mm above each specimen at an angle of 30° relative to the north edge to minimize the effect of shadows cast by the thermometers themselves. The area measured corresponded to an oval with a semimajor axis of about 240 mm and a semiminor axis of about 90 mm. For daytime surface temperatures, the infrared thermocouple measurements tended to be lower than the Type-T thermocouple measurements for all specimens. The primary reason for this could be that the observed surface may have been shadowed by surface roughness, shadows that would be determined by the sizes of the aggregate. The shadows would be notable because the infrared thermometer was on the north edge of the block. To a lesser degree, it may be possible that the Type-T thermocouple was warmed by solar radiation. Based on this, the authors of this study decided to use the measurements obtained with the infrared thermometer, while being aware of the need for further review on appropriate methods of measuring surface temperature.

The shortwave and long-wave radiometers were installed 300 mm above the specimens. Measurements were taken at 10 sec intervals for 10 minutes between 10:00 and 14:00, which is when the sun was relatively high. Albedo was calculated from the data collected during the hours when the solar radiation input was stable.

Evaporation was measured by weighing test pieces on three consecutive days, from 08:00 on August 3, 2005, after sprinkling them with water corresponding to 10 mm of rainfall between 17:00 and 18:00 on August 2, 2005. A total of six test pieces were used: three permeable IL blocks, and three permeable asphalt pieces (consisting of the same material that was used as the surface layer for the permeable asphalt pavement specimen). IL block piece measured one block, and permeable asphalt piece measured 150 mm in diameter and 50 mm in height. Three each of the permeable IL blocks and asphalt pieces were placed on each of the pavement specimens. Measured masses of three specimens were averaged for each type of the test specimen for subsequent analysis. The normal asphalt pavement test pieces were not measured in this experiment, as they had a low void ratio, allowing little water to permeate. Measurements were taken every hour between 08:00 and 12:00 and every two hours between 14:00 and 18:00 on the first day, every two hours between 08:00 and 18:00 on the second day, and at 08:00 and 13:00 on the third day.

3. SPECIMEN MEASUREMENT RESULTS

On the specimen pavements, surface temperatures were measured in the middle of the summer of 2005 for the three days from August 3 using the infrared thermometer. The results are shown in Figure 2. The normal asphalt pavement specimen recorded the highest temperature, about 60°C, of

the three specimen types. The permeable asphalt pavement specimen was 2°C to 3°C cooler than the normal asphalt pavement specimen. The permeable IL block pavement specimen was about 20°C cooler in maximum temperature and about 4°C cooler during the night than the other two specimens.

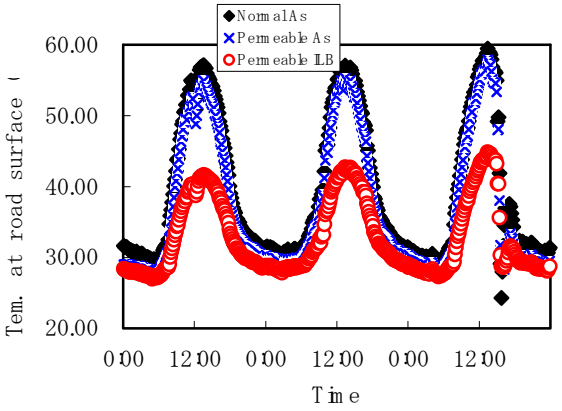


Figure 2. Temperature at each pavement surface (3/8/2005-5/8/2005).

Table 1. Albedo at surface (Dry Condition).

TYPES	ALBEDO
Permeable ILB Pavement	0.40
Normal Asphalt Pavement	0.08
Permeable Asphalt Pavement	0.07

Table 1 shows the albedos of the pavement specimens when they were dry. Due to the light color of the cement, the permeable IL block pavement specimen had a relatively high albedo of 0.40. The normal and permeable asphalt pavement specimens had albedos of 0.08 and 0.07, respectively, which are about a fifth of the albedo of the permeable IL block pavement specimen. Figure 3 shows the relationship between the maximum surface temperatures and the albedos of the specimens. The maximum surface temperature tends to drop as the albedo increases. Its high albedo seems to have played a part in the permeable IL block pavement specimen's the lower surface temperature relative to the asphalt pavement specimens.

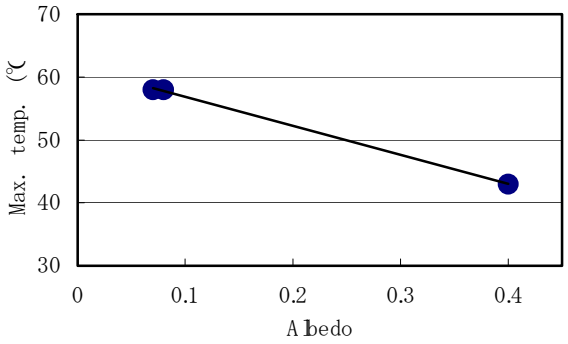


Figure 3. Relation between albedo and máximum temperatura at pavement surfaces.

Figure 3 shows the amounts of evaporation calculated based on the mass measurements, which were terminated at about 15:00 on August 5 due to a rainfall of 7 mm. On the first day of the measurement, there was a noted difference in evaporation between the two types of test pieces. On the second day of the measurement, the difference was extremely small. Evaporation measurements were conducted three times in the summers of 2004 and 2005, including this particular measurement. They all show similar tendencies.

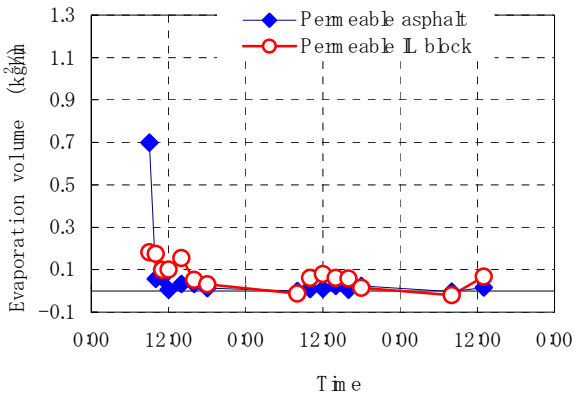


Figure 4. Evaporation volumen calculated from measurement resut (3/8/2005-5/8/2005).

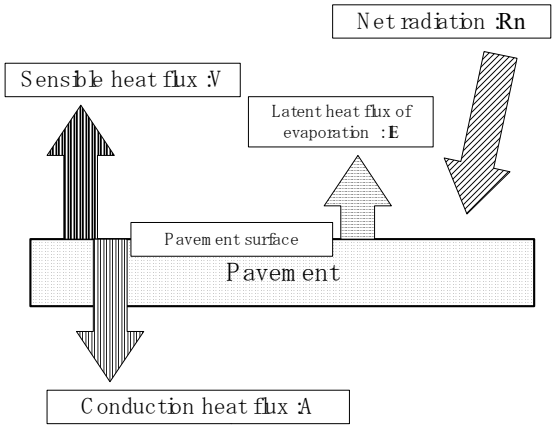


Figure 5. Heat balance at the pavement surface.

4. HEAT BUDGET CALCULATION

4.1 Equation of specimen surface heat budget

Figure 5 diagrams the heat budget of a pavement surface. The heat budget can be represented by equations (1) to (4) on the assumption that evaporation takes place only at the pavement surface. The latent heat of vaporization (*IE*) is based on the weight measurements of the test pieces.

$$Rn = A + V + lE \quad \textbf{(1)}$$

$$A = -\lambda \frac{\partial T}{\partial z} \Big|_{z=0} \quad \textbf{(2)}$$

$$V = \alpha(Ts - Ta) \quad \textbf{(3)}$$

$$lE = l \cdot \beta \cdot \alpha_w (Xs - Xa) = l \cdot \beta \cdot \alpha / Cp \cdot (Xs - Xa) \quad \textbf{(4)}$$

where:

Rn: net radiation (W/m^2), *A*: conduction heat flux (W/m^2), *V*: sensible heat flux (W/m^2), *IE*: latent heat flux (W/m^2), λ: heat conductivity (W/mK), α: convective heat transfer coefficient (W/m^{2}K), *Ts*: surface temperature (°C), *Ta*: air temperature (°C), β: evaporative efficiency (-), *Cp*: specific heat of air (J/kgK), *Xs*: saturated humidity (kg/kg), *Xa*: air absolute humidity (kg/kg).

4.2 Estimation of heat conductivity and volumetric thermal capacity

Heat conductivity in pavement can be expressed using the one-dimensional of heat conduction equation (5) shown below.

$$\frac{\partial T}{\partial t} \Big|_m = \frac{\lambda}{c} \frac{\partial T^2}{\partial^2} \quad (5)$$

where:

c: thermal capacity (J/m^3K).

Using the heat flux and temperature data measured on the pavement specimens, attempts were made to estimate the heat conductivity (λ) and the thermal capacity (c). Equations (6) and (7) are derived from equations (2) and (5) using finite differences.

$$A = -\lambda \frac{\Delta T}{\Delta z} = \frac{\lambda}{\Delta z}(T_s - T_1) \tag{6}$$

$$\lambda \frac{1}{\frac{\Delta z_1}{2} + \frac{\Delta z_2}{2}} \left(\frac{T_{m-1} - T_m}{\Delta z_1} - \frac{T_m - T_{m+1}}{\Delta z_2}\right) = c \frac{(T_m - T_m^*)}{\Delta t} \tag{7}$$

where:

Δz: distance (m) between Ts and T_1, $\Delta z1$: distance (m) between T_{m-1} and T_m, $\Delta z2$: distance (m) between T_m and T_{m+1}.

Figure 6 plots the results of substituting actual measurements for temperature and heat flux into Equation (6). The vertical axis represents conduction heat flux while the horizontal axis represents the temperature difference between the upper and lower faces of the heat flux plate divided by the distance between these faces. The slope of the approximated straight line can be regarded as the heat conductivity (λ). Figure 7 plots the results for when heat conductivity (λ) from Figure 6 is used in Equation (7). The slope of the approximated straight line can be regarded as the thermal capacity (c). Table 2 shows the heat conductivity (λ) and thermal capacity (c), estimated as above, for the pavement specimens.

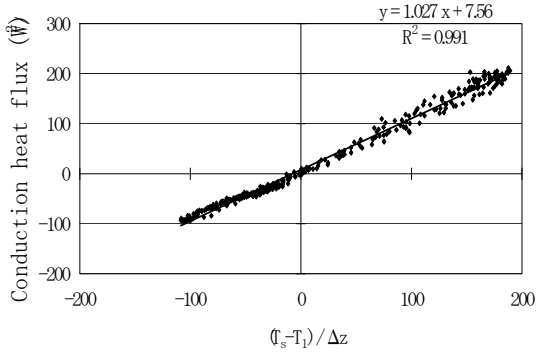


Figure 6. Presumption of heat conductivity (Normal asphalt).

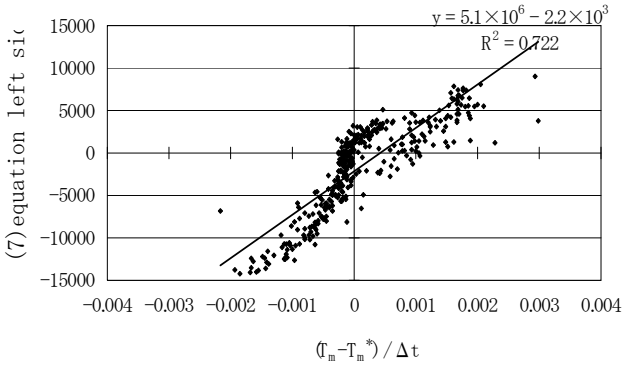


Figure 7. Presumption of thermal capacity (Normal asphalt).

Table 2. Heat conductivity and thermal capacity of each pavement (presumed value).

TYPES OF PAVEMENT	HEAT CONDUCTIVITY (W/M x K)	THERMAL CAPACITY ($MJ/K.m^3$)
Permeable IL block	1.47	2.9
Normal asphalt	1.03	5.1
Permeable asphalt	0.90	0.9

Table 3. Estimated result of evaporative efficiency (In case of surface temperature to be unknown).

TYPES OF	EVAPORATIVE EFFICIENCY

PAVEMENTS	FIRST DAY (8/3)	SECOND DAY (8/4)	THIRD DAY (8/5)
Permeable IL block	0.079	0.046	0.068
Permeable asphalt	0.009	0.005	0.005

4.3 Estimation of evaporative efficiency

To analyze heat budget, Takebayashi et al. reviewed three methods. In the first, the sensible heat flux is derived as a residual of the heat budget equation. In the second, the convective heat transfer coefficient is unknown. In the third, the roadway surface temperature is unknown. In the current study, the heat budget was analyzed using roadway surface temperature (*Ts*) as an unknown. Equation (8) is derived from equations (1), (3) and (6).

$$T_s = \frac{Rn - lE + \alpha \cdot T_a + \frac{\lambda}{\Delta z} \cdot T_1}{\alpha + \frac{\lambda}{\Delta z}} \qquad \textbf{(8)}$$

In Equation (8), *Ts* was obtained by convergent calculation, as it was also included in *Rn* and *IE* as a component. The heat conductivity (λ) and thermal capacity (c) are adopted from Table 2 (estimated from measurements). Convective heat transfer coefficient (α) was calculated, with the surfaces of the pavement specimens classified as rough and using the Jurges Equation below, in which actual measurements of wind velocity were used.

$$\alpha = 6.1 + 4.2U \qquad (U \le 5) \qquad \textbf{(9)}$$

$$\alpha = 7.5U^{0.78} \qquad (U \ge 5) \qquad \textbf{(10)}$$

where:

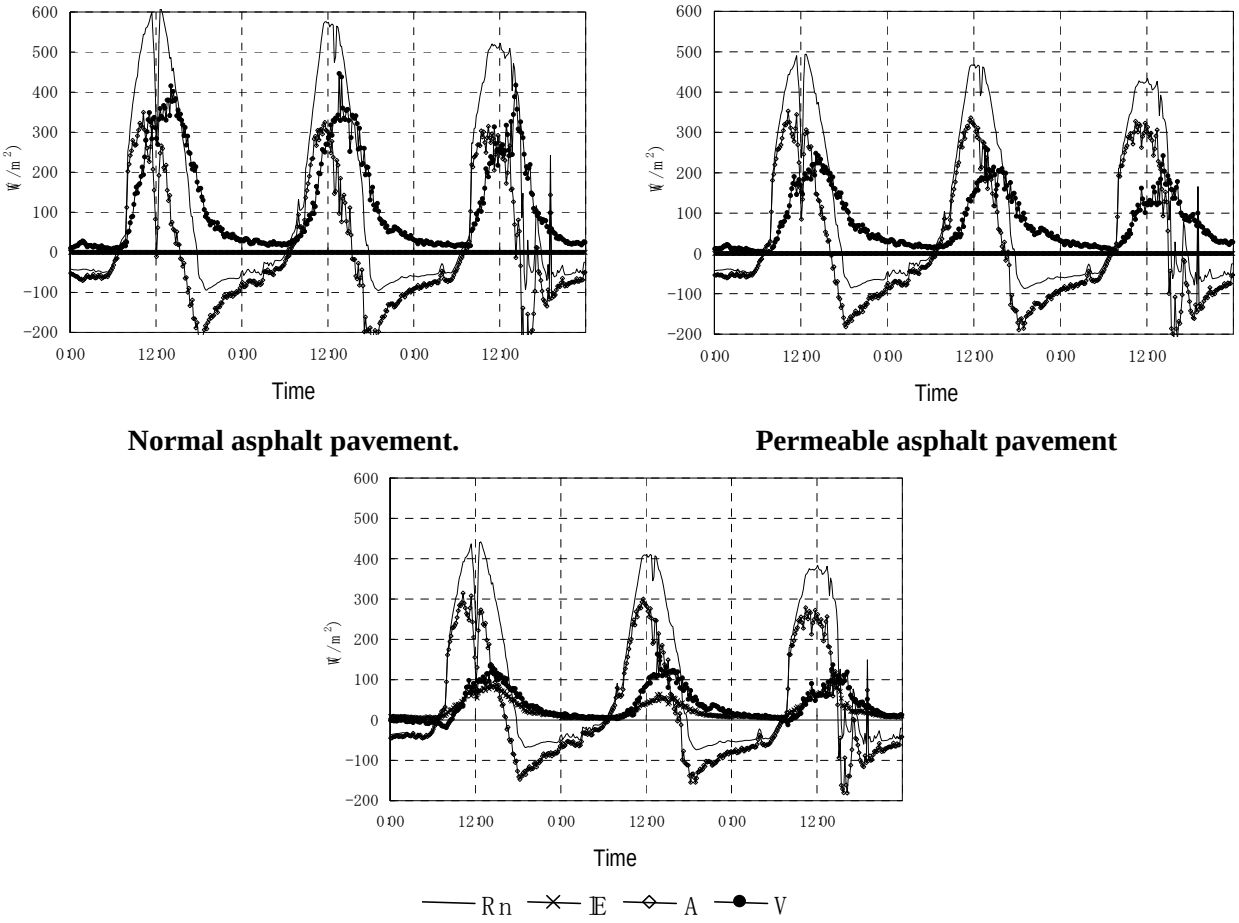
U: wind velocity (m/s).

Subsequently, evaporation efficiency (β) was estimated such that the estimation would be consistent with the measured weights of the test pieces. The results are shown in Table 3.

4.4 Results of surface heat budget calculation

Figure 8 shows the results of surface heat budget calculation on the pavement specimens. Figure 9 shows the calculated and measured surface temperatures of the normal asphalt pavement specimen. As the calculations and measurements are roughly equal, the surface heat budget calculations are regarded as reasonably accurate.

The specimens' net radiation, sensible heat flux, latent heat flux and conduction heat flux were calculated by inputting measured values into the heat budget equation given above[3)]. The maximum and average sensible heat fluxes (V) of the specimens (sensible heat flux is considered to be a direct cause of the heat island effect) obtained from calculation are shown in Figure 10. As shown in the figure, the sensible heat flux for the permeable IL block pavement specimen was less than those for the normal and permeable asphalt pavement specimens by 270 W/m^2 at maximum and 80 W/m^2 on average. It can therefore be concluded that permeable IL block pavement is effective at mitigating the heat island effect. This potential mitigating effect is attributed to the high albedo and evaporative efficiency of this pavement type. The permeable asphalt pavement specimen, because of its negligible evaporation rate, achieved a significant sensible heat flux that was roughly equal to that generated by the normal asphalt pavement specimen. It can therefore be concluded that permeable asphalt pavement would not be effective at mitigating the heat island effect.



Normal asphalt pavement. **Permeable asphalt pavement**

Permeable Interlocking Block Pavement.

Figure 8. Calculation result of surface heat budget at each pavements (3/8/2005-5/8/2005).

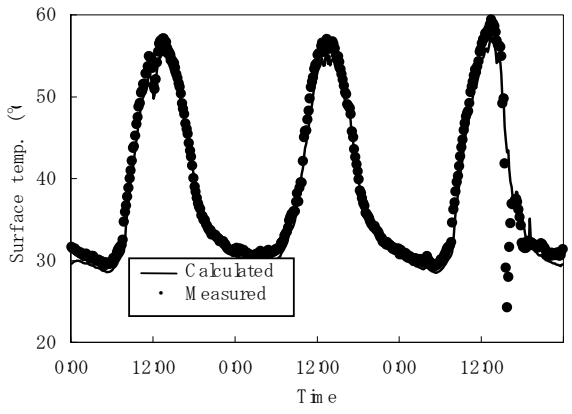


Figure 9. Calculation result and measurement result of surface temperature (3/8/2005-5/8/2005).

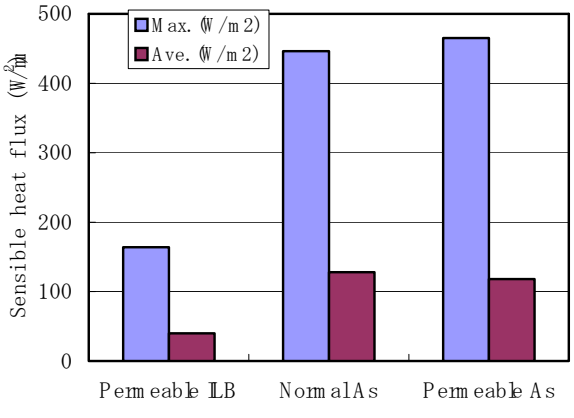


Figure 10. Calculation results of sensible heat flux at each pavement.

5. CONCLUSIONS

This study investigated the differences in sensible heat flux from the surface of permeable IL block pavement versus normal and permeable asphalt pavements, toward determining whether permeable IL block pavement may be able to mitigate the heat island effect. The findings are summarized as follows.

1. Due primarily to its high albedo, the permeable IL block pavement specimen demonstrated lower surface temperature than the asphalt pavement specimens. The difference was about 20°C for daytime maximum temperature and about 4°C for nighttime temperature.
2. The calculated surface heat budget showed that the permeable IL block pavement specimen achieved a lower sensible heat flux than the normal and permeable asphalt pavement specimens. The difference was 270 W/m2 at maximum and 80 W/m2 on average.
3. It can be concluded that permeable IL clock pavement may be effective at mitigating the heat island effect.

6. REFERENCES

H. TAKEBAYASHI, M. MORIYAMA, 2007,"Surface Heat Budget on Green Roof and High Reflection Roof for Mitigation of Urban Heat Island ," Building and Environment, 42, p. 2971-2979.

H. TAKEBAYASHI, M. MORIYAMA, M. NISHIOKA, T. KIMISHIMA, M. NABESHIMA, M. KAGATA, T. HONDA, 2008,"Study on Urban Heat Island Mitigation Effect based on Surface Heat Budget on Environmental Consideration Type Pavements," J. Environ. Eng., AIJ, Vol.73, No.623, p. 77-83.

JAPAN INTERLOCKING BLOCK PAVEMENT ENGINEERING ASSOCIATION, 2000,"The Outline of the Design and Construction Manual for Interlocking Block Pavement", p. 69.

LAWRENCE BERKELEY NATIONAL LABORATORY: http://eetd.lbl.gov/heatIsland.