Evaporation Performance Analysis for Water-Retentive Material, Based on Outdoor Heat-Budget and Transport Properties

Shin’ichi Kinoshita*1, Atsumasa Yoshida and Naoki Okuno,

*1Osaka Prefecture University, Sakai, Osaka, Japan

Corresponding author email: kinosita@me.osakafu-u.ac.jp

ABSTRACT

Recently, the urban heat island (UHI) effect has been remarkable in most metropolitan areas in Japan, and countermeasures for this phenomenon are urgently demanded. One such measure is paving streets and roads with a water-retentive material that has the potential to diminish sensible heat flux and reduce air temperatures by absorbing latent heat from the water retained in the material. In the process of promoting this water-retentive material, it is necessary to establish a method for evaluating it. In this study, the evaporation performance of the water-retentive material was evaluated with a field measurement under a condition that simulated the pavement with the material. The heat-budget measurement on the surface of the material in a moist state was evaluated, and the evaporation efficiency of the material was measured. The accuracy of the evaluation was verified by comparing it with the results of weighing. In addition, the heat and moisture transport properties of the water-retentive material were evaluated in order to carefully investigate its evaporation performance and a numerical analysis using heat and moisture conservation equations was employed.

Potential cost savings were also determined through energy simulation using IES(ve). With the application of PerfectCool on pavements surrounding a development, a potential electrical yearly savings of 3.46% can be derived, with a highest possible monthly savings of 4.88%. On a typical hot day, the possible reduction of chiller load can be up to 7.69%.

Introduction

Recently, the urban heat island (UHI) effect has been remarkable in most metropolitan areas in Japan, and countermeasures for this phenomenon are urgently demanded. One of the measures, paving streets or roads with a water-retentive material, has the potential to diminish sensible heat flux and reduce air temperatures by absorbing latent heat from the water retained in the material. In the process of promoting this water-retentive material, it is necessary to establish a method for evaluating it. Narita et al. (2004) suggested a method whereby a convective mass transfer coefficient is calculated from the evaporation rate of wet filter paper, and sensitive heat flux is calculated by means of an analogy between heat and mass transfer, and these are applied to an evaluation of the performance of water-retentive pavement in a field experiment. To evaluate the distribution of water within the material, it is necessary to analyze the diffusion equations for heat and moisture transfers simultaneously because of interaction between them. A basic theory for the simultaneous analysis of heat and moisture transfers has been designed for concrete, but few case studies have applied this theory to a water-retentive material.

In this study, the evaporation performance of a water-retentive material was evaluated outdoors under a condition that simulated the pavement with this material. The heat-budget measurements on the surface of the material in a moist state were evaluated, and the evaporation efficiency of the material was measured. The accuracy of the evaluation was verified by comparing it with the results of weighing. In addition, the heat and moisture transport properties of the water-retentive material were evaluated carefully to investigate its evaporation performance and a numerical analysis using heat and moisture conservation equations was employed.

Performance Evaluation by Field Measurement

Outline of Measurement

Field measurement of the evaporation efficiency of the water-retentive material was performed in an open space on the roof of Bldg. A5 in Osaka Prefecture University. The model size of the measured object was 1.5 x 1.5 m2, and consisted of two sizes of water-retentive block (300 x 150 x 50mm3 and 150 x 150 x 50mm3). Figure 1 shows the schematic of the measurement setup for the model and measuring devices. The model consisted of a wood frame, sand, and water-retentive blocks. The sand layer was laid at a depth of 20 mm beneath the layer of blocks to create a pavement. Styrene foam was inserted between wood frame and blocks for thermal insulation. Data were logged every 20 seconds, and average time was calculated at 10 minutes. Two heat-flow plates for measuring heat conduction flux inside the water-retentive material were installed at 12 mm from the top and bottom surfaces of the material. The former plate was put between two blocks with a depth of 12 mm and 38 mm, and was coated with silicon grease to reduce thermal resistance. The temperature profile within the water-retentive material was measured by installing copper-constantan thermocouples at 0 mm (on the top surface) and at 15 mm, 35 mm, and 50 mm (on the bottom surface).
Figure 1. Measurement situation
Relationship between Wind Speed and Convective Heat Transfer Coefficient

The relationship between wind speed and the convective heat transfer coefficient on the measuring surface was evaluated by measuring evaporation efficiency. In the dry condition of the water-retentive material, net radiation ($R_n$) and conductive heat flux ($G$) on the material’s surface were measured, and sensible heat flux ($H$) was calculated by the residual of the heat budget, as follows in equation (1):

$$ H = R_n - G $$  \hspace{1cm} (1)

In the equation, it was assumed that latent heat flux did not exist. The convective heat transfer coefficient was calculated as follows in equation (2):

$$ \alpha = \frac{H}{T_{\text{sur}} - T_{\text{air}}} $$  \hspace{1cm} (2)

Where $T_{\text{sur}}$ is the surface temperature of the material, and $T_{\text{air}}$ is the air temperature. The heat transfer coefficient is related to horizontal wind speed ($U$), as shown in Figure 2. The following relation between wind speed and heat transfer coefficient (3) was derived by measuring several times:

$$ \alpha = 4.86U + 6.02 $$  \hspace{1cm} (3)

Calculation of Evaporation Efficiency

The calculation of evaporation efficiency was made with the following procedure. First sensible heat flux ($H$) was calculated based on equations (2) and (3). Wind speed, the surface and air temperatures, and then latent heat flux ($lE$) were calculated by the residual of heat budget, as in the following equation:

$$ lE = R_n - H - G $$  \hspace{1cm} (4)

Figure 2. Relationship between wind speed and the convective heat transfer coefficient

- 224 -
Figure 3. Results for wet conditions on September 11, 2007 (left, full wet), and July 31, 2008 (right, after drying for one day)
Next, evaporation rate \((E)\) was evaluated by dividing the latent heat flux by the latent heat of water \((l)\):

\[
E = \frac{IE}{l}
\]  

The evaporation efficiency \((\beta)\) was defined as the ratio of the evaporation rate on the object’s surface to that on the water’s surface, and can be obtained from following equation:

\[
\beta = \frac{E}{k[q_{sair}(T_{sur}) - q_{air}]}
\]  

Where \(q_{sair}(T_{sur})\): saturation specific humidity on the water’s surface, based on the surface temperature \(q_{air}\): specific humidity of the air and \(k\): the convective mass transfer coefficient. The convective mass transfer coefficient was obtained from the analogy between heat and mass transfers.

Results

Evaporation efficiency. Figure 3 shows the experimental results for September 11, 2007 and July 31, 2008. The results for September 11 were obtained after immersing the water-retentive material in water for one day, and those for July 31 were obtained after drying the material by leaving it outdoors during the daytime before one day. The bottom surface of the material in the former case was wrapped with plastic film, and thus the surface was impermeable for moisture. In the latter case, the material was in direct contact with the sand layer, and is the surface was permeable for moisture. In both cases, latent heat flux accounted for most of the heat budget. Figure 4 shows the results for the water-retentive material in dry conditions. The left-hand side shows the surface temperature, air temperature, and humidity, and the right-hand side shows the heat budget. Comparing the results for wet and dry conditions, it is evident that the surface temperature in the wet case is lower than that in the dry case. The ratio of latent heat flux to net radiation on July 31 (only data for \(Rn > 300\,\text{W/m}^2\) was smaller than that for September 11. On the other hand, the ratio of sensible heat flux on July 31 was twice as large. Although the net radiation on the morning of September 11 was higher than that on July 31, the surface temperature on September 11 was lower by about 5° C. This was caused by the difference in latent heat flux for each case. Differences in evaporation rates and evaporation efficiency also were found.

Thus, it was revealed that surface temperatures decrease when water is retained, and evaporation efficiency deteriorates as water-retentive material becomes drier. In order to maximize the decrease in temperature, it is necessary to sustain evaporation of the water supply and to both construct a water supply system and make use of a water-retentive material.

Accuracy of measurement. The accuracy of the evaporation from the residual heat budget was evaluated by comparing it with that of weighing. Table 1 shows the estimated error. It is necessary to estimate the evaporation that occurred during preparation and clearance of the experiment. In the measurement from 2008, the amount was estimated based on the change in weight of a water-retentive block during the evaluation period. In measurement from 2007, because the block for the estimation did not exist, it was assumed that the evaporation during preparation of item (c) in Table 1 was equal to the evaporation in the same time interval from the start of the heat budget measurement. The measurement in 2007 seems to be more accurate, judging from the estimated error \((g)\) in Table 1, but the proportion of the estimated evaporation during preparation was relatively large. Considering that the preparation started at 7 a.m., it is possible the value was overestimated. Although uncertainty exists, the accuracy of heat budget measurement is about 10%, and the method has been shown to be relatively accurate.
Numerical Analysis of Heat and Moisture Transfers

Properties Evaluation and Numerical Conditions

A numerical analysis was made for transfer of heat and moisture corresponding to the field measurement. The basic equations consisted of one-dimensional conservation equations for heat and moisture, as follows.

\[
\rho \frac{\partial \psi}{\partial t} + \frac{\partial \mu}{\partial t} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial \mu}{\partial x} - g \right) + \frac{\partial}{\partial x} \left( \lambda' \frac{\partial \mu}{\partial x} \right)
\]

(7)

\[
\rho_c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left[ \lambda_{\text{re}} \left( \frac{\partial \mu}{\partial x} - g \right) \right] + \frac{\partial}{\partial x} \left( \lambda + \lambda'_{\text{re}} \frac{\partial T}{\partial x} \right)
\]

(8)

The origin was located on the material’s surface and the x axis was located below. In equations (7) and (8), \( \rho_c \): water density, \( \rho \): density, \( \psi \): volume moisture content, \( \mu \): moisture chemical potential, \( \lambda \): thermal conductivity, \( \lambda' \): hydraulic conductivity related to chemical potential gradient, \( \lambda'_{\text{re}} \): hydraulic conductivity related to temperature gradient, \( \lambda'_{\text{re}} \): hydraulic conductivity in gas phase related to chemical potential gradient, \( \lambda'_{\text{re}} \): hydraulic conductivity in gas phase related to temperature gradient, \( c \): specific heat, \( T \): temperature and \( g \): gravity.

The thermal conductivity of the water-retentive material in a moist state was measured with the unsteady hot-wire method, based on JIS R 2616 (JISC. 2001) under several conditions of moisture content \( \varphi \), and is represented as a linear function dependent on moisture content.

\[
\lambda = 0.085\varphi + 0.911
\]

(9)

Hydraulic conductivity in gas and liquid states is related to the chemical potential gradient, and those related to temperature gradient can be estimated by means of moisture permeability (\( \lambda' \)) and water permeability (\( K \)). Moisture permeability was measured by the following means. Several kinds of permeable cups containing saturated solutions of salt, such as NaCl and MgCl\(_2\), and with a specimen of the water-retentive material were prepared and were located in a thermostatic bath. Permeability was calculated from the weight change of the whole of the cup and temperature and humidity in the thermostatic bath, which is based on JIS A 1324 (JISC. 1995). The value of moisture permeability obtained was 1.96 x 10\(^{-11}\) kg/msPa, which was considered to be consistent with humidity from the measurement. Water permeability was evaluated with a falling head permeability test, and the value obtained was 6.12 x 10\(^{-8}\) m/s. The water-retention curve is necessary for evaluation of \( \mu \psi \frac{\partial \mu}{\partial t} \) in the left-hand side of equation (7). Generally, the curve can be obtained by measurement of the equilibrium moisture content, but enough data for the numerical analysis could not be obtained for this study. Therefore, the model suggested by van Genuchten (1980) was applied for the water-retention curve, and the model parameters for loam (Carsel et al. 1988) were substituted for those of water-retentive material.

Figure 5 shows the numerical model. The differential equations (7) and (8) are discretized by means of the central difference of second order precision for diffusion terms. Spatial grids were located within the material at uniform intervals. The grid size was 1 mm. The Euler method was used for time marching, and the time interval was 10 millisecond(s). The boundary condition of the top surface was specified from the heat budget and moisture evaporation rate obtained by field measurements. At the bottom surface, the temperature was the measured value, and moisture transfer did not occur because the material was impermeable. The initial condition of the temperature profile is given by linear interpolation of the measured value at the beginning time of the field measurement, and that of the moisture chemical potential profile is uniformly given as the value corresponding to the bulk water content of the water-retentive material before measurement.

### Table 1. Estimated error

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Sep. 11, 2007</th>
<th>Jul. 31, 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Evaporation with weighing method</td>
<td>g</td>
<td>7634.6</td>
<td>7188.5</td>
</tr>
<tr>
<td>b. Evaporation calculated with heat budget</td>
<td>g</td>
<td>5240.1</td>
<td>4643.1</td>
</tr>
<tr>
<td>c. Evaporation during preparation</td>
<td>g</td>
<td>2385.6</td>
<td>1157.9</td>
</tr>
<tr>
<td>d. Sand water absorption</td>
<td>g</td>
<td>0.0</td>
<td>145.0</td>
</tr>
<tr>
<td>e. Evaporation during clearance</td>
<td>g</td>
<td>No data</td>
<td>217.6</td>
</tr>
<tr>
<td>f. Difference (a-b-c-d-e)</td>
<td>g</td>
<td>8.9</td>
<td>1024.8</td>
</tr>
<tr>
<td>g. Estimated error (f/a)</td>
<td>%</td>
<td>0.12</td>
<td>14.26</td>
</tr>
</tbody>
</table>
Figure 5. Numerical model

Figure 6. Moisture content profile in the depth direction

Figure 7. Comparison between experimental and numerical results
Numerical Results

Figures 6 and 7 show the numerical results for the measured values on September 11, 2007. Figure 6 shows the temporal change of the moisture content profile within the material every hour. As shown in this figure, the material begins to dry from the top surface, and the internal moisture content gradually decreases with the progress of surface drying. The evaporation rate is the greatest for one hour from the beginning of the measurement, and decreases with the lapse of time. As shown in Figure 7, evaporation efficiency decreases with the decrease of the evaporation rate. These results qualitatively agree with those of the field measurements. The bulk water content in the numerical result was 12.9wt%, which relatively agrees with the experimental result of 11.6wt%.

Comparing the calculated surface temperature with the measured one, as shown in Figure 7, it is evident that temporal changes of temperature can be qualitatively evaluated, but the calculated value is about 5°C lower than the measured value. This reason is that the latent heat flux on the top surface was overestimated and the sensible heat flux and conductive heat flux were underestimated, as shown in Figure 8. Thus, the numerical model used in this study can express the internal moisture transfer of water-retentive material, but must be improved to express heat transfer.

Summary

1. The surface temperature of water-retentive material decreases with water retention, and evaporation efficiency deteriorates as water-retentive material becomes drier. Evaporation efficiency can be used in the performance evaluation of water-retentive material.

2. The accuracy of the evaporation from the residual heat budget was evaluated by comparing it with that of weighing. As the result, the accuracy of measurement was about 10%, and the method has been shown to be relatively accurate.

3. Numerical analysis using simultaneous heat and moisture transfer equations can express the internal moisture transfer of water-retentive material, but must be improved to express heat transfer because the latent heat flux caused by evaporation on the material’s surface has been overestimated.
References


(Received Feb 9, 2012, Accepted Oct 10, 2012)