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

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ABSTRACT

Recently, urban heat island is remarkable at almost metropolises in Japan, and countermeasures for the phenomenon are urgently demanded. As one of the measures, paving with water retentive material on streets or road is potential to diminish sensible heat flux and reduce air temperature by absorbing latent heat of water retained in the material. In the process of promotion of the water retentive material, it is necessary that the method of performance evaluation of the material is established. In this study, evaporation performance of water retentive material is evaluated with field measurement in the condition simulated the pavement with the material. Heat budget measurement on the surface of material in moisture state is evaluated, and the evaporation efficiency of the material is measured. The evaluation accuracy is verified by comparison with the results of weighing. In addition, heat and moisture transport properties of the water retentive material are evaluation in order to investigate the evaporation behavior in detail and apply to the numerical analysis with heat and moisture conservation equations.

Introduction

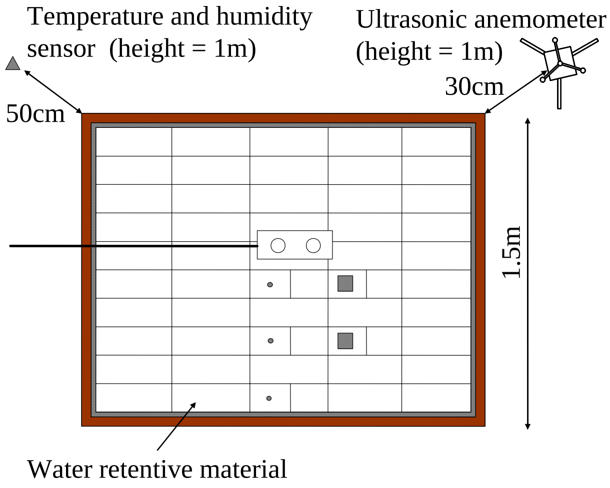
Recently, urban heat island is remarkable at almost metropolises in Japan, and countermeasures for the phenomenon are urgently demanded. As one of the measures, paving with water retentive material on streets or road is potential to diminish sensible heat flux and reduce air temperature by absorbing latent heat of water retained in the material. In the process of promotion of the water retentive material, it is necessary that the method of performance evaluation of the material is established. Narita et al. suggests a method that convective mass transfer coefficient is measured by evaporation rate from wet filter paper and sensitive heat flux is measured by means of analogy between heat and mass transfer and applies it for evaluating the performance of water retentive pavement in field experiment (Narita et al. 2004). It is necessary for evaluating inside water content distribution of the material to analyze the diffusion equations of heat and moisture transfers simultaneously because of interaction between them. Fundamental theory for simultaneous analysis of heat and moisture transfer has been constructed for concrete, but case study applying the theory for water retentive material is scarcely found.

In this study, evaporation performance of water retentive material is evaluated outdoors in the condition simulated the pavement with the material. Heat budget measurement on the surface of material in moisture state is evaluated, and the evaporation efficiency of the material is measured. The evaluation accuracy is verified by comparison with the results of weighing. In addition, heat and moisture transport properties of the water retentive material are evaluation in order to investigate the evaporation behavior in detail and apply to the numerical analysis with heat and moisture conservation equations.

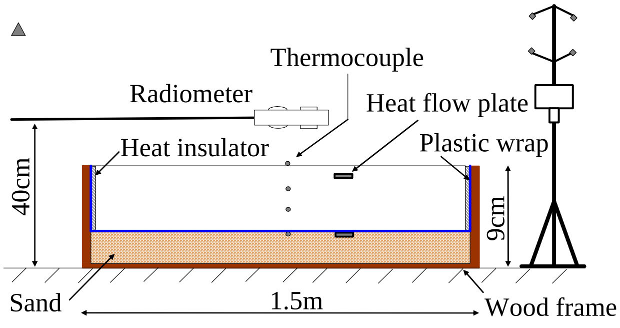
Performance Evaluation by Field Measurement

Outline of Measurement

Field measurement of evaporation efficiency of water retentive material is performed at open space on roof of Bldg. A5 in Osaka Prefecture University. Model sample size of measured object is 1.5 x 1.5 m^2, and consists of two sizes of water retentive block (300 x 150 x 50mm^3, 150 x 150 x 50mm^3). Figure 1 shows the schematic drawing of the measurement situation of model sample and measuring devices. Model sample consists of wood frame, sand and water retentive blocks. Sand layer is laid in depth of 20mm underneath blocks layer by assuming pavement. Styrene foam is inserted between wood frame and blocks for thermal insulation. Data is logged every 20 seconds, and averaging time is 10 minutes. Two heat flow plates for measuring heat conduction flux into the inside water retentive material are installed at 12mm in depth from the surface and the bottom surface of the material. The former plate is put between two blocks of 12mm in depth and 38mm, and is coated with silicon grease for reduction of thermal resistance. Temperature profile in depth direction of water retentive material is measured by installing copper-constantan thermocouples at 0mm (on the top surface), 15mm, 35mm and



(a) Top view



(b) Front view

Figure 1. Measurement situation

50mm (on the bottom surface).

Relation between Wind Speed and Convective Heat Transfer Coefficient

The relation between wind speed and convective heat transfer coefficient on the measuring surface is evaluated in the process of measurement of evaporation efficiency. In the dry condition of water retentive material, net radiation Rn and conductive heat flux G on the material surface are measured, and sensible heat flux H is calculated by the residual of heat budget as following eq. (1).

$$H = Rn - G \tag{1}$$

In the equation, it is assumed that latent heat flux does not exist. Convective heat transfer coefficient α is calculated by following eq.(2).

$$\alpha = \frac{H}{T_{\mathrm{sur}} - T_{\mathrm{air}}} \tag{2}$$

where T_{sur} is the surface temperature of the material, and T_{air} is air temperature. The heat transfer coefficient is related with horizontal wind speed U as shown in fig. 2. The following relation between wind speed and heat transfer coefficient (3) is derived by measuring several times.

$$\alpha = 4.86U + 6.02 \tag{3}$$

Calculation of Evaporation Efficiency

The calculation of evaporation efficiency is shown in following procedure. First sensible heat flux H is calculated based on eqs. (2) and (3) with measured wind speed and temperatures of surface and air, and then latent heat flux lE is calculated by residual of heat budget as

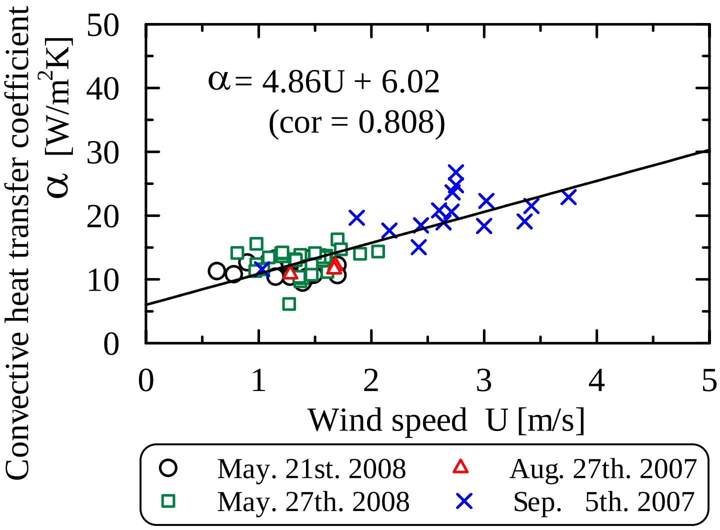
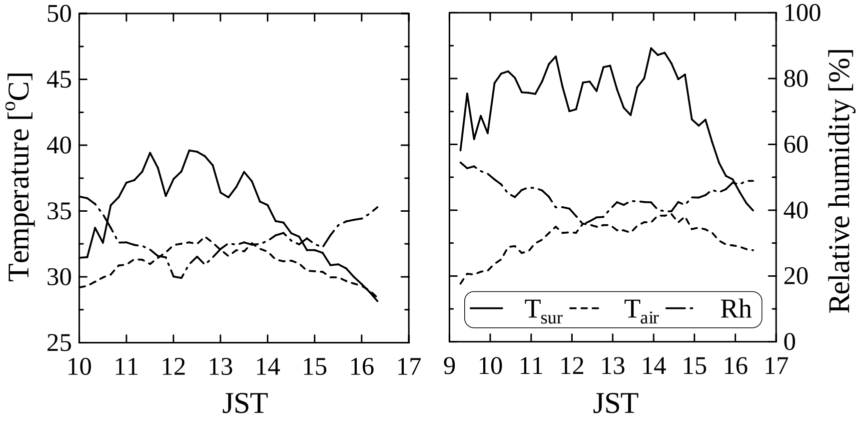
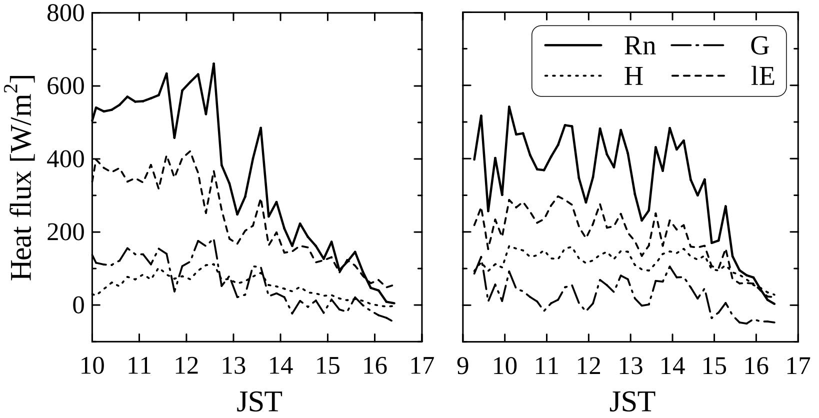


Figure 2. Relation between wind speed and convective heat transfer coefficient

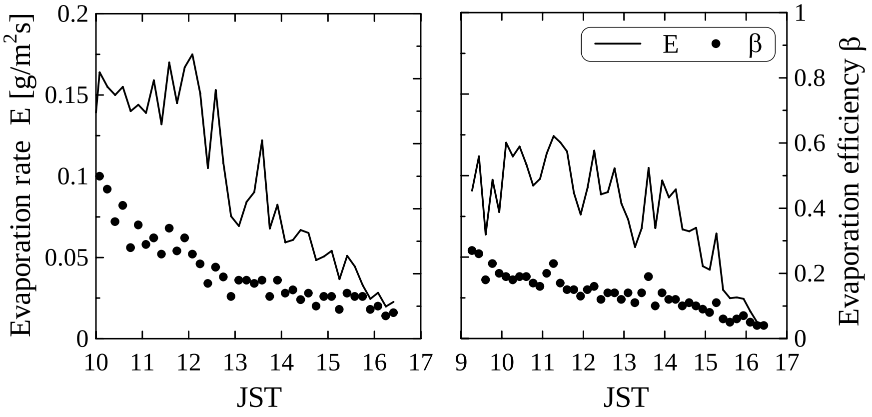
following equation.



(a) Temperature and relative humidity

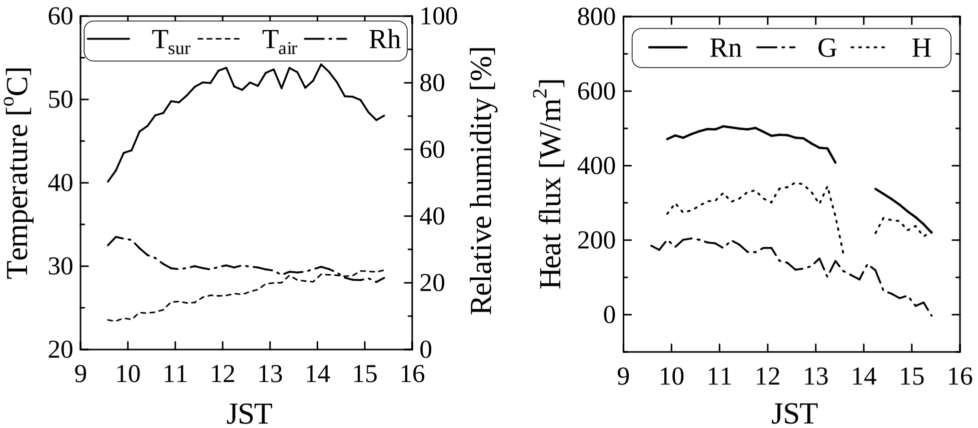


(b) Heat budget



(c) Evaporation speed and efficiency

Figure 3. Measured results on wet conditions on Sep. 11 2007 (left, full wet) and Jul. 31 2008 (right, after drying for one day)



(a) Temperature and humidity (b) Heat budget

Figure 4. Measured results on dry condition (May 27 2008)

$$lE = Rn - H - G \tag{4}$$

Next evaporation rate E is evaluated by dividing the latent heat flux by latent heat of water l.

$$E = \frac{lE}{l} \tag{5}$$

The evaporation efficiency β is defined as the ratio of the evaporation rate on the object surface to that on the water surface, and can be obtained from following equation.

$$\beta = \frac{E}{k\left[q_{\mathrm{sat}}(T_{\mathrm{sur}}) - q_{\mathrm{air}}\right]} \tag{6}$$

where $q_{\mathrm{sat}}(T_{\mathrm{sur}})$: saturation specific humidity on water surface based on surface temperature, q_{air} : specific humidity of air and k : convective mass transfer coefficient. The convective mass transfer coefficient is obtained from the analogy between heat and mass transfer.

Measured Results

Evaporation efficiency Figure 3 shows the experimental results on Sep. 11th 2007 and Jul. 31st 2008. The results in Sep. 11th are obtained in the measurement after immersing the water retentive material in water for one day, and those in Jul. 31st are in the measurement after drying the material by leaving outdoors from the daytime before one day. The bottom surface of material in the former is wrapped with plastic film, and moisture on the surface is impermeable. That in the latter is directly contacted with sand layer, and moisture is permeable. In both cases, latent heat flux occupies most of heat budget. Figure 4 shows the results with water retentive material in dry condition. The left hand side shows the surface temperature and air temperature and humidity, and the right hand side shows the heat budget. In comparison between the results

Table 1. Estimated error

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

in wet and dry conditions, it is found that the surface temperature in wet case becomes lower than that in dry case. The ratio of latent heat flux to net radiation in Jul. 31st (only data of $Rn > 300\mathrm{W/m}^2$) is smaller than that in Sep. 11th. On the other hand, the ratio of sensible heat flux in Jul. 31st is twice larger. Although the net radiation in the morning of Sep. 11th is higher than that of Jul. 31st, the surface temperature in Sep.11th is lower about 5 deg. C. This is caused by difference of latent heat flux between them, and differences in evaporation rate and evaporation efficiency are also found.

Thus, it is revealed that the effect of surface temperature decreases by water retention and the evaporation efficiency deteriorate as water retentive material becomes drier. In order to draw out the temperature decrease effect to the maximum, it is necessary to sustain the evaporation by water supply and to construct simultaneously water supply system in utilization of water retentive material.

Accuracy of measurement Accuracy of the evaporation measurement from residual of heat budget is evaluated by comparison with that of weighing. Table 1 shows the result of estimated error. It is necessary to estimate the evaporation during preparation and clearance of experiment. In the measurement of 2008, the amount is estimated by weight change of a water retentive block during the period. In that of 2007, as the block for the estimation does not exist, it is assumed that the evaporation during preparation of item c) in Table 1 is equal to the evaporation in the same time interval from the start of heat budget measurement. The measurement in 2007 seems to be more accurate by judging from only estimated error g) in Table 1, but the proportion of estimated evaporation during preparation is relatively large. Considering that the preparation is started from 7 a.m., it is potential that the estimated value is overestimated. Although uncertain item exists, the accuracy of measurement with heat budget is about 10 %, and it is revealed that the method is relatively accurate.

Numerical Analysis of Heat and Moisture Transfer

Properties Evaluation and Numerical Conditions

Numerical analysis is made for transfer of heat and moisture corresponding to the field measurement. Fundamental equations consist of one dimensional conservation equations of heat and moisture as follows.

$$\rho_w \left(\frac{\partial \psi}{\partial \mu} \right) \frac{\partial \mu}{\partial t} = \frac{\partial}{\partial x} \left[\lambda'_\mu \left(\frac{\partial \mu}{\partial x} - g \right) \right] + \frac{\partial}{\partial x} \left(\lambda'_T \frac{\partial \mu}{\partial t} \right) \tag{7}$$

$$c\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left[l\lambda'_{\mu g} \left(\frac{\partial \mu}{\partial x} - g \right) \right] + \frac{\partial}{\partial x} \left[\left(\lambda + l\lambda'_{Tg} \right) \frac{\partial T}{\partial x} \right] \tag{8}$$

The origin is located on material surface and x axis is located in downward of the depth direction. In eqs. (7) and (8), ρ_w: water density, ρ: density, ψ: volume moisture content, μ: moisture chemical potential, λ: thermal conductivity, λ'_μ: hydraulic conductivity related to chemical potential gradient, λ'_T: hydraulic conductivity related to temperature gradient, $\lambda'_{\mu g}$: hydraulic conductivity in gas phase related to chemical potential gradient, λ'_{Tg}: hydraulic conductivity in gas phase related to temperature gradient, c: specific heat, T: temperature and g: gravity.

Thermal conductivity of water retentive material in moisture state is measured with unsteady hot-wire method based on JIS R 2616 (JISC. 2001) in several conditions of moisture content φ, and is represented as a linear function dependent on moisture content.

$$\lambda = 0.085\varphi + 0.911 \tag{9}$$

Hydraulic conductivities in gas and liquid phases related to chemical potential gradient and those related to temperature gradient can be estimated by means of moisture permeability λ' and water permeability K. Moisture permeability is measured by the following. Several kinds of moisture permeable cup containing saturated solution of salt, such as NaCl and $MgCl_2$, and setting a specimen of the water retentive material are prepared and are located in a thermohygrostat. Permeability is calculated from weight change of the whole of the cup and temperature and humidity in the thermohygrostat, which is based on JIS A 1324 (JISC. 1995).

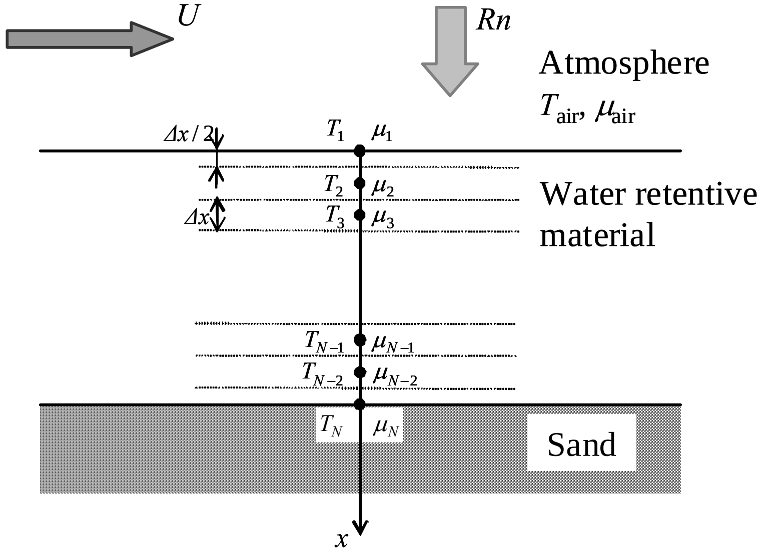


Figure 5. Numerical model

The value of moisture permeability obtained is 1.96 x 10^{-11} kg/msPa, which is considered to be constant to humidity from the result of the measurement. Water permeability is evaluated with a falling head permeability test, and the value obtained is 6.12 x 10^{-8} m/s. The water retention curve is necessary for evaluation of $\partial \psi / \partial \mu$ in the left hand side of eq. (7). Generally, the curve can be obtained by measurement of equilibrium moisture content, but enough data for numerical analysis cannot be obtained in this study. Therefore, the model suggested by van Genuchten (van Genuchten, 1980) is applied for the water retention curve, and the model parameters for loam (Carsel et al, 1988) are 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 are

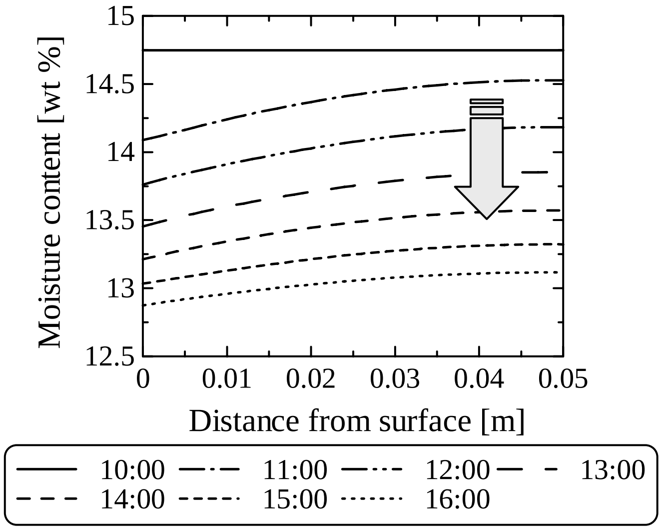


Figure 6. Moisture content profile in depth direction

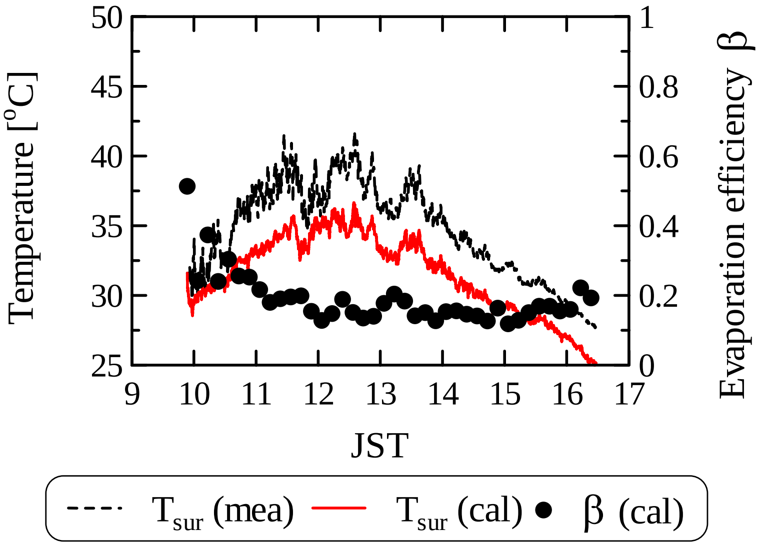


Figure 7. Comparison between experimental and numerical results

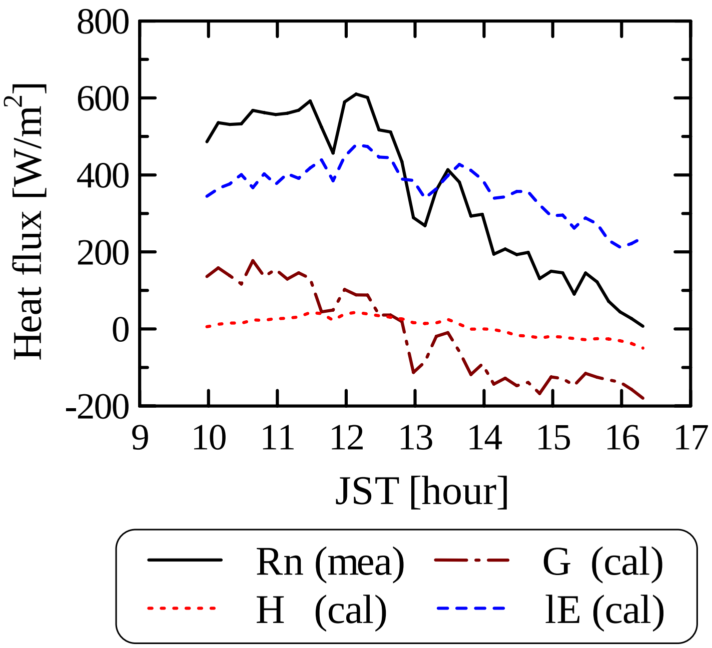


Figure 8. Numerical result of heat budget

located in depth direction with uniform interval. Grid size is 1mm. Euler method is used for time marching, and the time interval is 10ms. Boundary condition of top surface is specified from heat budget and moisture evaporation rate obtained by field measurement. At the bottom surface, temperature is the measured value, and moisture transfer is impermeable. Initial condition of temperature profile is given by linear interpolation of measured value at beginning time of field measurement, and that of moisture chemical potential profile is uniformly given as the value corresponding to bulk water content of the water retentive material before measurement.

Numerical Results

Figure 6 and 7 show the numerical results with the measured values in Sep. 11th 2007. Figure 6 is the temporal change of moisture content profile in depth direction every one 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. Evaporation rate is the largest during one hour from the beginning of measurement, and decreases with the lapse of time. As shown in figure 7, evaporation efficiency decreases with the decrease of evaporation rate. These results qualitatively agree with those of field measurement. Bulk water content in numerical result is 12.9wt%, which relatively agrees with experimental result of 11.6wt%.

Compared calculated surface temperature with measured one, as shown in figure 7, temporal change of temperature can be qualitatively evaluated, but calculated value is about 5deg.C lower than measured value. This reason is that the latent heat flux at top surface is overestimated and sensible heat flux and conductive heat flux are underestimated, as shown in figure 8. Thus, the numerical model using in this study can express internal moisture transfer of the water retentive material, but remains scope for improvement in heat transfer.

Summay

1. The effect of surface temperature of water retentive material decreases by water retention and the evaporation efficiency deteriorate as water retentive material becomes drier. Evaporation efficiency can be applied for the performance evaluation of water retentive material.

2. Accuracy of the evaporation measurement from residual of heat budget is evaluated by comparison with that of weighing. As the result, the accuracy of measurement is about 10 %, and the method is relatively accurate.

3. Numerical analysis using simultaneous heat and moisture transfer equations can express internal moisture transfer of the water retentive material, but remains scope for improvement in heat transfer because of overestimation of latent heat flux by evaporation on the material surface.

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