Thermal Characteristics of Porous Pavement and Its effect On Urban Environment

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ABSTRACT: The variability of surface heat flux depends strongly on the material heat absorption and rate of heat storage. Heat fluxes at the air/ground interface , the temperature in the surface and sub-surface of the various pavement were observed and analysed on summer days. It was found that the surface and subsurface temperatures of different pavement materials are significantly different from each other. Temperature at the porous and nonporous asphalt pavement at the peak hour was more than 52°C, which was 22°C higher than air temperature. Temperature of other porous and nonporous pavement such as concrete, porous concrete and porous block also reached at 50°C. However temperature at the ceramic pavement is much lower than that of other surfaces and almost the same as that of the grass surface. A unidimensional model coupling with subsurface heat and moisture transfer was developed to study the thermal characteristics of porous pavement under fine meteorological conditions. Subsurface heat and moisture transfer revealed that pore volumes inside the porous pavement is very important for the transport of water vapour. Large pores inside the porous asphalt, porous concrete or porous blocks reduce the capillary pressure, consequently hinder the evaporation from the surface. Ceramic pavement materials absorb a large amount of water from the underlying soil layers due to small pores, which is turned to evaporation and released to the atmosphere.

KeyWords: Porous Pavement, Non-porous Pavement, Urban Environment, Thermal Charateristics, Observation.

1 INTRODUCTION

Characterization of porous pavement on the thermal level is done for the purpose of understanding, modelling, and in some cases controlling the behaviour and the properties of the macroscopic medium. The concept of what is ' macroscopic' is spontaneous one and it usually means a sample of the medium on which observation were performed in the field [3]. Thermal characteristics of ground surface is an important factor in the surface energy balance. It represents the energy flux available for the transport of sensible and latent heat to the atmosphere above and the conducting heat to the soil below. Thermal processes at the ground surface depends thermal characteristics of the ground surface materials such as surface emission , reflectivity , thermal conductivity and also evaporation process at the surface.

Analysis of the response of the surface to atmospheric conditions is complicated due to non-linearities of the governing equations, the inhomogenity of the underlying soil and hysteresis of the moisture retention [1]. To properly describe the interaction between porous pavement and urban atmospheric boundary layer, one must adequately describe heat and moisture movement at porous surfaces and within the soil below, since the soil layer represents both a source and sink of heat and moisture to and from the atmosphere [2]. The purpose of this study is to investigate the heating processes inside the various porous and nonporous pavements based on the observational data and a

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numerical model .In an effort to simulate these complicated characteristics a unidimensional model for the heat flow characteristics under the surfaces covered by porous and non-porous materials has been developed.

2 OBSERVATIONAL WORK AND DATA COLLECTION

A series of climatological observations were conducted throughout the year from August , 1994 to July, 1995 by the Public Housing Corporation office at Kuki , 70 km north of Tokyo (36^{o}N, 139^{o}36') . These observation were aimed primarily to investigate the heating processes inside various pavements. There were ten types of sample paved surfaces prepared for the observation of surface temperature and temperature at different depths under the surface together with ground conduction heat flux. Additionally ground surface albedo, atmospheric conditions such as atmospheric temperature, air relative humidity and wind velocity, downward total solar radiation, infrared radiation were also measured. Although measurment were carried out throughout one year, due to the limit of this paper only results of observation on August 9, 1994 are presented. During this period, large-scale forcing appeared to be weak and cloud cover was low. Four adjoing sample surface materials with contrasting thermal properties were selected-porous block pavement, fresh dark non-porus asphalt, grass(3.0 cm long) and ceramic porous pavement. The surface temperature were obtained by two way; directly by thermoflow and componently by copper-constantan thermocouples stuck on the studied surfaces. The ambient atmospheric temperature was measured using platinum wire thermometer electrostatical capacitance type with a accuracy of ±0.02^{o}C. During the observation the relative humidity and wind speed were measured using psychrometers and supersonic cup anemometer(drag agains cups causes rotation on the axis perpendicular to wind) repectively with the accuracy of ±0.01% and 0.01m/s. The meteorological data was recorded in every 10 minutes interval. To illustrate this, hourly observations data are presented in Figure 1; maximum ambient air temperature reached approximately 35^{o}C, while the wind speed and percentage of relative humidity were minimum. These conditions are believed to be representative summer days in this area..

In Figures 2(a-d) are temperature distributions in surface material, inside the surface material and subsurface of covered surface materials by porous block, asphalt, grass and ceramic August 9, 1994 at 6:00, 12:00, 18:00 and 0:00.In Figure 2(a) are temperature distributions in all sample surfaces at 6 a.m just after sunrise. Inspite the difference in the covering materials, the temperature distribution is higher for the porous block and lower for the ceramic surfaces, this difference is 4^{o}C at 50 cm below the sample surface.

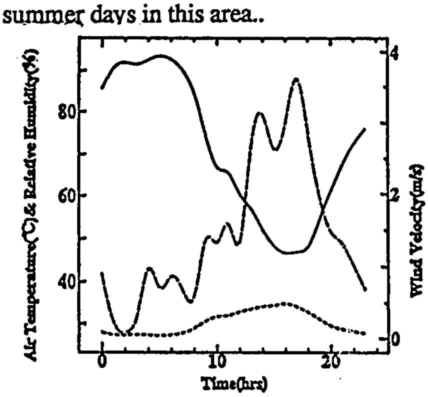

Fig.1 Climatological Data on August 9, 1994

The vertical subsurface temperature for the natural surface grass was measured upto 30cm below the surface. Grading the sample surfaces on account of vertical profile of temperature distribution at 6:00 are as porous block, nonporous asphalt, grass and ceramic. Under the surfaces, temperature decreases from large depth towards the surfaces, which indicates heat released to the atmosphere. In Fig.2(b) vertical profile of temperature distribution at 12:00 noon. From this figure it is clear that temperature of all sample surfaces is higher than the subsurface, because this time all surface absorb solar energy and stored heat energy to the subsurfaces. The surface temperature of nonporous asphalt is higher than the other surfaces and lower for the grass. The subsurface temperature difference at 50 cm depth is 3.75^{o}C. At this depth highest temperature observed for the porous block and lowest for the ceramic. This is due to the effect of water content and thermal conductivity of surface and subsurface materials of the porous pavement. In Fig.2(c) is data at 18:00 just before the sunset and Fig.2(d) are data at 0:00. From the Figures 2(a-d) it is found that the subsurface temperature under the ceramic surface is lower and porous block surface is higher, because of the effect of thermal conducivity. Since thermal conductivity of ceramic block is small, it is heated only on the surface and the stored heat is also smaller than other surfaces. The temperature of the grass surface is less than that of other surfaces due to evapo-transpiration from grass and the distribution of temperature under the grass is very different from that under other surfaces. The surface temperature of asphalt and porous block decreases to less than 40^{o}C and grass surface temperature decreases to less than air temperature. Vertical temperatures distribution difference at depth 50 cm was observed 5.6^{o}C at 18:00, 4.5^{o}C at 0:00.

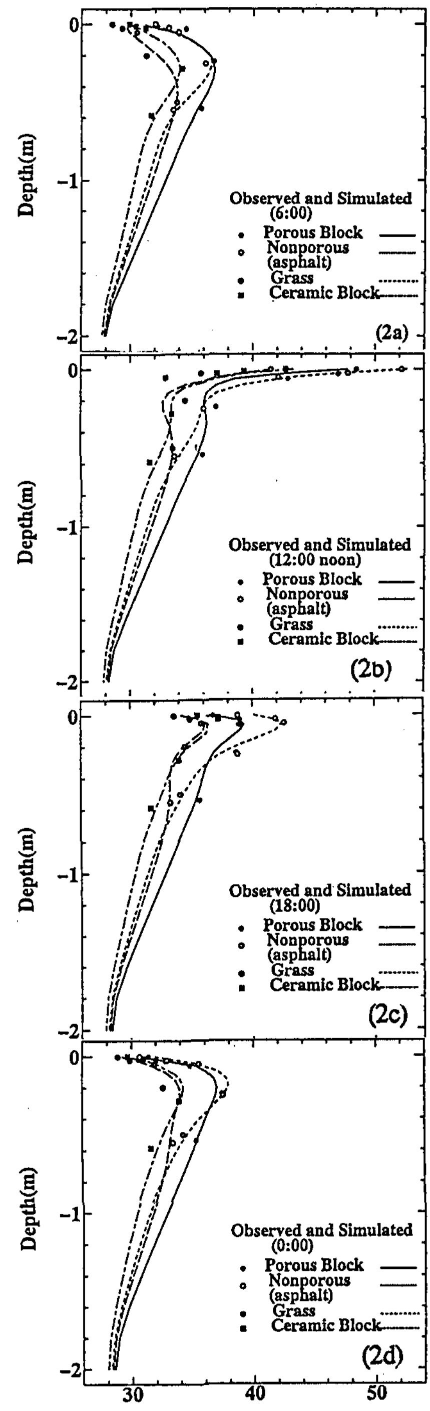

Figure 2 Vertical distribution of temperature under different surfaces.

Compared with Figures 2(b), 2(c) and 2(d) we can see that temperature difference between the three figures is the amount of heat released to the atmosphere. Among the porous pavement it is observed that the surface temperature of porous block is higher because of pore size, its large pore size reduce the capillary pressure, consequently hinder the evaporation from the surface and surface is heated, on the other hand ceramic pavement absorb large amount of water from the underlying soil layers due to the small pore, which is turn to the evaporation and released to the atmosphere. Heat flux from the surface to atmosphere directly is in the form of sensible heat , indirectly in the form of latent heat and longwave radiation. The sensible heat warms air directly and air absorbs longwave radiation and increases its temperature and latent heat directed just reverse of the sensible heat. Longwave radiation from different surfaces and its absorption due to air is computed with different value of surface temperature.

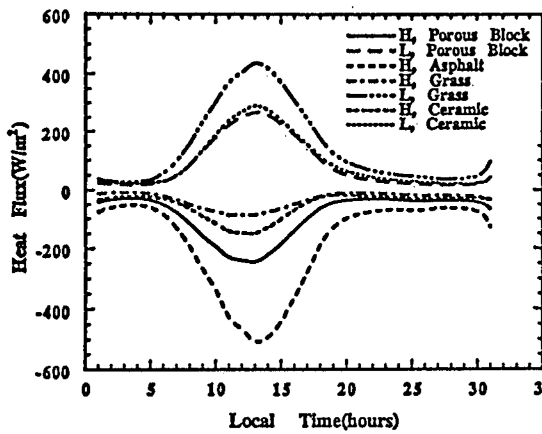

Fig.3 Diurnal Latent and Sensible Heat Flux from Surface

The computed sensible and latent heat flux are presented in Figure 3. In Figure 3 L is for latent heat flux and H for sensible heat flux. The data of air is standard data of mid-latitude in summar. At noon, temperature of asphalt surface is 52.1°C, grass is 41.2°C, porus-bl. is 48.5°C and por. ceramic is 42.7°C, the difference of longwave radiation from four surfaces is very significant and much larger than artificial heat.

3. THEORY AND MODEL DEVELOPMENT

Now, we try to estimate the thermal behaviour of surface materials, which indicates the warming of lower atmosphere. In order to solve this problem, a mathematical model is employed to simulate the thermal phenomena of surface covered by porous, grass and non-porous materials. The governing equations for mass and heat transfer under porous and non-porus pavement are as follows. The equation of mass transfer inside the porous pavement was derived by [1].

$$\left[\left(1-\frac{\rho_\upsilon}{\rho_\ell}\right)\frac{\partial\theta}{\partial\psi}+\frac{\theta_a}{\rho_\ell}\frac{\partial\rho_\upsilon}{\partial\psi}\right]\frac{\partial\psi}{\partial t}+\left[\left(1-\frac{\rho_\upsilon}{\rho_\ell}\right)\frac{\partial\theta}{\partial T}+\frac{\theta_a}{\rho_\ell}\frac{\partial\rho_\upsilon}{\partial T}\right]\frac{\partial T}{\partial t}$$

$$=\nabla\left[\left(K+D_{\psi\upsilon}\right)\nabla\psi+\left(D_{T\upsilon}+D_{Ta}\right)\nabla T\right]+\frac{\partial K}{\partial z} \qquad (1)$$

The corresponding equation for heat transfer is

$$\left[C+L\theta_a\frac{\partial\rho_\upsilon}{\partial T}-\left(\rho_\ell W+\rho_\upsilon L\right)\frac{\partial\theta}{\partial T}\right]\frac{\partial T}{\partial z}+\left[L\theta_a\frac{\partial\rho_\upsilon}{\partial\psi}-\left(\rho_\ell W+\rho_\upsilon L\right)\frac{\partial\theta}{\partial\psi}\right]\frac{\partial\psi}{\partial t}$$

$$=\nabla\left[\lambda\nabla T+\rho_\ell\left(LD_{\psi\upsilon}+gTD_{Ta}\right)\nabla\psi\right]-C_\ell q_m\nabla T \qquad (2)$$

Where C is the total volumetric heat capacity of the soil and is estimated by

$$C = C_d + C_\ell \rho_\ell \theta + c_p \rho_\upsilon \theta_a$$

The vapour density ρv is given by

$$\rho_\upsilon(\psi, T) = \rho_0(T) exp\left(\psi g / R T_k \right) \qquad (3)$$

Where θ is the volumetric liquid water content, θa is the volumetric air content, ρ_υ is the density of water and t is the time, C_d is the heat capacity of dry soil, c_p is the specific heat of vapour at constant pressure, W is the differential heat of wetting. ρ_0 is the saturation vapor density at temperature T, R is the gas constant for water vapor, Tk is the absolute temperature, q_m is the moisture flux, ρ_ℓ is the liquid water density, $D_{\psi\upsilon}$ is the matric potential diffusivity of water vapour, $D_{T\upsilon}$ is the temperature diffusivity of vapour and D_{Ta} is the transfort coefficient for absorbed liquid flow due to thermal gradient, T is the soil temperature, Ψ is the matric potential, K is the hydraulic conductivity and k is the unit vector opposite of gravity. C_ℓ is the heat capacity of liquid water.

at $0 \le z \le l$, the heat conservation equation for non-porous pavement is [4]

$$\rho c \frac{\partial T}{\partial t} = K_1 \frac{\partial^2 T}{\partial z^2} \qquad (4)$$

Where z is the depth from the surface, l is the surface materials depth, ρc , K_1 are the heat capacity and thermal conductivity of surface covering materials respectively. The surface mass flux is

$$q_m = e \qquad (5)$$

The boundary condition of intersurface between surface cover and soil is the continuation of temperature and heat flux, the surface boundary condition is as follows:

$$-K \frac{\partial T}{\partial t} = S(1 - \alpha) + R_{Ln} + H - Le - Cl(T - T_0)e \qquad (6)$$

Where first term of the R.H.S S is the total solar radiation flux, α is the surface albedo, in second term R_{Ln} is the net longwave radiation, third term H is the tubulent sensible heat and fourth term is the turbulent latent heat, T_0 is the reference temperature as the datum of for zero enthalpy [1] the fifth term is the sensible heat carried from the porous surfaces to the atmosphere by the evaporated water vapor. For non-porous materials such as asphalt, the fourth and fifth term of equation (6) is absent since no evaporation can occur at these surfaces.and e is the evaporation rate.

The lower boundary condition is at large depth, temperature is constant and equals to 27.5°C and depth is considered for simulation 2m. The comparison of simulated and observed temperature distributions at different surfaces with various depth at different times in day is shown in Figure 2 and in Figure 4. In Figure 3 depicts the simulated sensible and latent heat flux for the porous block, asphalt, grass and ceramic. It is found that latent heat flux is higher from grass and lower from porous block, sensible heat flux is higher from asphalt and lower from grass which represents warming condition of the surface. In the Figure 3 negative sign for sensible heat flux is heat released to the atmosphere.

3 CONCLUDING REMARKS AND FUTURE WORK

A study of the thermal transfer to the underground of the porous pavement can not handled properly without the coupling of moisture and heat transfer. Because of evaporation from porous surface and evapotranspiration from grass surface, the temperature of the surface smaller than non-porous surface. The non-porous surface materials can absorb a large amount of the incoming net radiation, which increases its surface temperature and causes the variation of urban environment. An evidence can be made that porous pavement is more reliable than the nonporous pavement for balancing the urban thermal environment from the point of evaporation.

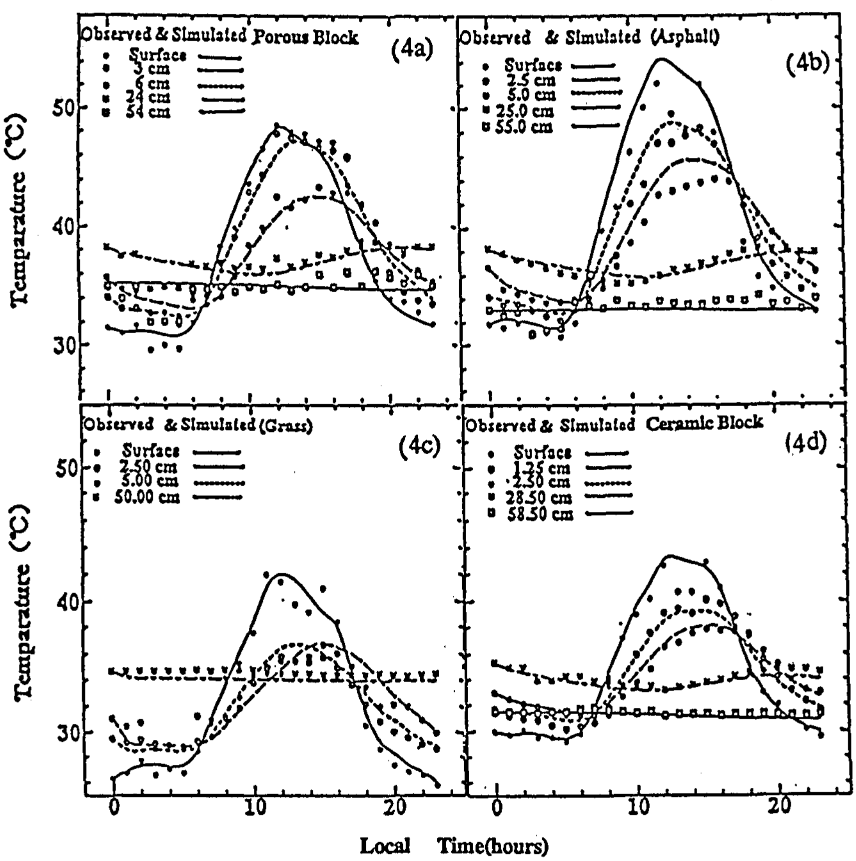

Figure 4 Diurnal Surface and under surface temperature on August 9,1994

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