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CONTROL OF ROAD SURFACE TEMPERATURE AND THERMAL ENERGY STORAGE USING A BORE-HOLE HEAT EXCHANGE SYSTEM

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SYNOPSIS

A Bore-hole Heat Exchange System (BHES) has been introduced to control pavement temperature in a car park at Fukui University. The BHES consists of a bore-hole and an asphalt surfaced pavement covering twelve concrete panels that have heat exchanger loops incorporated. The bore-hole is 70 m in length and comprises an inner and an outer pipe. A heat carrier liquid circulates between the pavement and the bore-hole. Efficiency and performance of the BHES are experimentally and theoretically evaluated from the viewpoint of seasonal thermal energy storage.

It is shown that the BHES can suppress the rise of the car park pavement surface temperature in summer and melt the snow on the car park surface in winter using terrestrial heat.

INTRODUCTION

From the viewpoint of the conservation of the global environment, solar energy and wind-power are attractive heat energy sources that can be utilized semi-permanently. Since these natural energy sources are not constant and the available energy level depends on weather conditions, technical development is still insufficient for utilizing them effectively. A bore-hole heat exchange system (BHES) is a technique to extract ground heat and to re-inject surplus heat energy back into the ground.

Eliminating snow from street and roads is a significant concern in many regions of the world and a variety of countermeasures have been adopted according to local conditions.

Applying warm groundwater to the road surface using a sprinkler system embedded permanently in the roadway is a technique widely used in Japan. This system becomes inadequate, however, once there is a heavy accumulation of snow. It may also lead to deleterious lowering of the groundwater table. Fukui is located on the Japan Sea side of the main island and experiences heavy snowfalls in spite of its mild winters. Solar energy is the most easily available natural energy source, but unfortunately, in winter the duration of sunshine in regions on the Japan Sea side is extremely short and changeable. Consequently, availability of solar energy for heat storage may be low. However, since Fukui is in the southern part of the heavy snow region, ground temperatures remains fairly warm, even in winter. Winter temperatures at 3 m below the ground surface are never lower than 12℃. For this reason, in snowfall affected regions westward from the Fukui area, terrestrial heat may be more effective than using solar energy directly.

A Bore-hole Heat Exchange System (BHES), shown in Fig.1, was built to prevent ice films and snow accumulation at a car park on the campus of Fukui University. The BHES consists of a long bore-hole with coaxial pipe heat exchanger and a pavement containing a heat exchanger loop. The pavement acts as a solar collector, while the bore-hole works as a heat exchanger with the ground. The ground serves as a heat source for warming up the pavement in winter and is recharged in summer by the solar heat absorbed from the road surface. Summer-time cooling of the road surface may be beneficial to the road itself to prevent rutting and may also mitigate local warming associated with radiation from hot asphalt surfaces.

The BHES was originally developed for thermal energy storage in rock, but many cities in Japan have been built on alluvial aquifers with a shallow groundwater table. Existing BHES sites in Japan have used shallow bore-holes, usually in the range of 20～40 m [1],[2]. Deep bore-holes such as that utilized in this study are much deeper, with depths ranging from 70 to 200 m [3],[4]. The effect of groundwater flow on the performance of this BHES will be an interesting theme in a future study.

This study aims at evaluating the snow melting performance of a deep BHES in winter as well as the cooling of the pavement in summer.

STRUCTURE OF THE BHES AND MEASUREMENT TECHNIQUES

Structure and Heat Flow of BHES

The BHES consists of a long bore-hole heat exchanger coupled to a surface heat exchanger embedded just below the surface of an asphalt paved road. The latter is called the pavement heat exchanger in this paper. A polypropylene-glycol water mixture (thermal conductivity : 0.53 (W/mK)) is circulated in the pavement heat exchanger loop and bore-hole pipe by a 0.3 kW pump operating continuously.

(1) Bore-hole heat exchanger : The bore-hole is 70 m in length and comprises an inner and an outer pipe made of polyethylene. The inner pipe is 56 mm outside diameter with a 3 mm wall thickness. The outer is 90 mm outside diameter with 4 mm wall thickness.

(2) Pavement heat exchanger : The pavement including steel heat exchanger loop is made of concrete and the pavement area is 60 m^2 (5 m×12 m). The test road consists of an asphalt layer 0.03 m thick

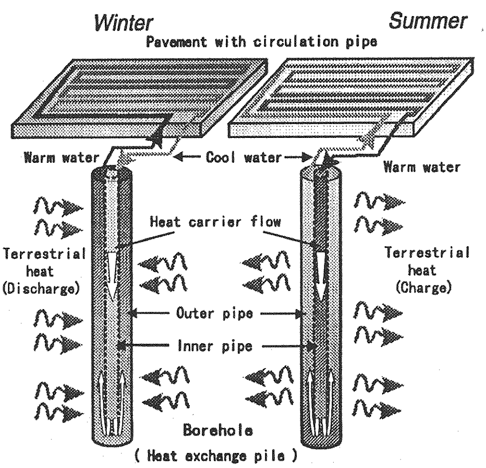

Fig.1 Heat transport system of BHES

overlaying 0.16 m thick concrete panels. The size of the panels is 2.5 m×2 m. The galvanised steel heat pipe is 15 mm outside diameter and is installed at mid-depth in each concrete panel with space of 0.1 m.

In winter, the liquid is circulated downward through the inner pipe and upward through the outer. In this process, it absorbs terrestrial heat from the ground surrounding the bore-hole and releases the heat via the heat exchanger loop to the pavement. In this way the pavement is warmed up enough to melt snow. In summer, the liquid absorbs the solar energy from the pavement and transfers it to the bore-hole from whence it is stored in the earth. The pavement temperature is lowered in the process.

Measurement Techniques

In order to monitor the thermal behavior of the BHES, thermocouples are placed in the asphalt, bore-hole heat exchange liquid, concrete panels and at various levels along the heat exchanger pipes. In addition, liquid temperatures are measured at the inlet and outlet ends of the steel heat exchanger loop in the concrete panels. Four thermocouples are placed in the asphalt at depths of 0.005 m, 0.01 m, 0.02 m and 0.03 m below the upper surface. The water temperature in the bore-hole is measured at levels of 0 m, 2 m, 18 m, 36 m, 53 m and 68 m below the top of the inner and outer pipes. Data is automatically measured via a data logger and stored in a computer file every 30 minutes. Meteorological data is also collected, both near the experimental site and from the meteorological observatory in Fukui. Snow depth is measured by a scale and monitored automatically by a video camera.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Heat Transfer between Bore-hole and Ground

A field test is carried out to evaluate the amount of thermal energy (discharged energy) extracted from the ground through the wall of the bore-hole. In this experiment, iced water is continuously supplied to the bore-hole heat exchanger and the circulation flow rate, Q, ranges from 5 ℓ/min to 60 ℓ/min. The

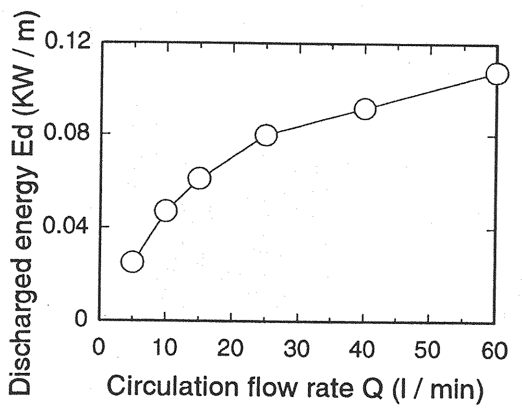

Fig.2 Relationship between discharged energy and circulation flow rate

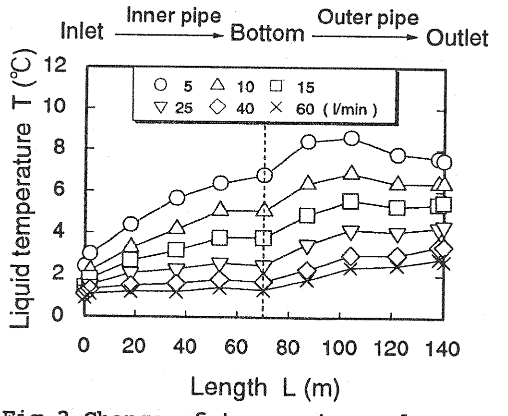

Fig.3 Change of temperature along inner and outer pipe

tests ware conducted in the order Q = 60, 40, 25, 10 and 5 ℓ/min. The water temperature at the outlet of the bore-hole attains a quasi-steady condition within one to two hours after the change of flow rate.

Fig.2 presents the relationship between circulation flow rate, Q, and discharged energy per unit length, E_d, which is calculated by the following equation.

$$E_d = (\rho C) Q (T_{out} - T_{in}) / L \quad (1)$$

where (ρC) = the volumetric heat capacity (= 4140 kJ/m^3K); Q = circulation flow rate (m^3/hour); T_{out} = liquid temperature at the outlet of the bore-hole; T_{in} = liquid temperature at the inlet of the bore-hole; and L = the bore-hole length.

Because temperature drop is also affected by flow rate, the value of E_d is not-simply linearly proportional to Q. E_d for Q = 40 ℓ/min is 10% larger than that for Q = 25 ℓ/min.

The temperature profiles along the inner and outer pipes under quasi-steady conditions are given for different circulation flow rates, Q, in Fig.3. Depths 0 m, 70 m and 140 m on the x-axis correspond to the inlet, bottom, and outlet of the bore-hole, respectively. When Q is large, the liquid temperature rises only in the outer pipe. In the case of small Q, however, when the liquid goes down the inner pipe, initially its temperature begins to rise steeply but thereafter it rises more gradually towards the bottom of the bore-hole. Because of thermal short circuit effects between the opposing flows, the temperature falls between the middle and the outlet of the outer pipe.

After this experiment was completed, Q was kept 40 ℓ/min between November and March, and at 25 ℓ/min during all other periods of operation.

Snow Melting and Control of Pavement Temperature in Winter by a BHES

Photo.1 shows the effectiveness of the BHES snow-melting system in the car park at Fukui University on February 1, 1996. It is seen that the BHES has a satisfactory ability for melting the snow.

Fig.4 presents the vertical temperature profile in the asphalt at 6 A.M. and 2 P.M. on February 1, 1996. T_{pt} and T_{pc} are the asphalt temperature with the heat exchanger loop (test pavement) and without the heat exchanger loop (control pavement), respectively. There is no difference in the temperature profile of the control pavement at 6 A.M. and 2 P.M. because of snow accumulation. The absolute temperature-gradient of the test pavement, $|dT_{pt}/dz|$, is larger than that of the

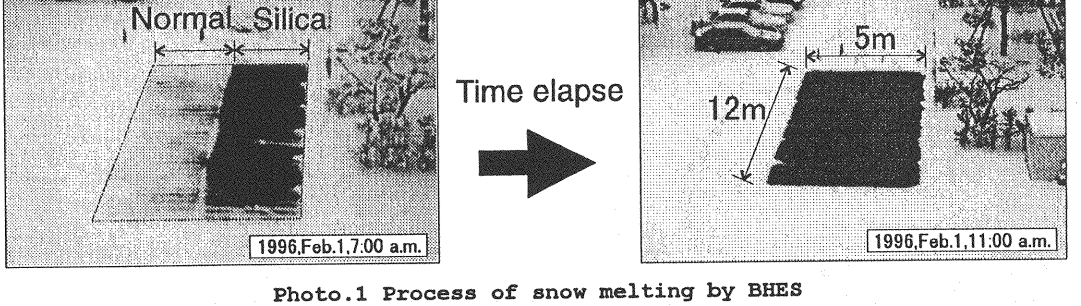

Photo.1 Process of snow melting by BHES

control pavement, $|dT_{pc}/dz|$, at 6 A.M. because of the heat flux across the heat exchanger loop. As the snow on the test pavement has already disappeared at around 8 A.M., T_{pt} is much higher than T_{pc} and $|dT_{pt}/dz|$ becomes small in the daytime.

Fig.5 shows the time variation of representative temperatures associated with the BHES and pavement, as well as snowfall intensity data for February 1, 1996. In Fig.5, T_i is the liquid temperature at the pavement heat exchanger inlet, T_o is the liquid temperature at the outlet, T_{pt} is the surface temperature (depth 0.01 m, mid-point between heat exchanger tubes) for the test pavement, T_{pc} is the corresponding temperature for the control pavement (depth 0.01 m) , T_a is the atmospheric temperature measured over the pavement and h is the snowfall intensity. T_a is continually below 0 ℃ except around 2 P.M.. T_{pc} remains approximately 0℃ over the whole day because of the snow accumulation. T_{pt}, however, remains near 1℃ at night and then begins to rise around 8 A.M., because of solar radiation, and reaches a maximum (8.2℃) at 2 P.M. after the snow has melted. Afterward, the fresh snowfall lowers T_{pt} to about 1℃ again. T_o is always higher than T_i because the heat exchange liquid absorbs terrestrial heat while flowing through the bore-hole heat exchanger. The difference between T_i and T_o is significant at night but diminishes in the daytime (especially after the snow melts and the black surface of the asphalt appears). After 2 P.M., the snowfall was continuous and heavy (h = 0.01~0.03 m/hour), as mentioned above, and the snow depth on the control pavement increased from 0.19 m (at 2 P.M.) to 0.32 m (at 10 P.M.). On the test pavement, however, snow accumulation was not observed till 6 P.M. and, eventually, at 10 P.M., the maximum snow depth was reached. It was only 0.01 m.

Fig.6 shows the variation in time of the heat flux density, E_r, released from the pavement heat exchanger loop. When the circulation discharge, Q, increases, E_r increases, already shown in Fig.2. The data for Q = 10 ℓ/min was measured under the same condition as the climate when we took the data for Q = 40 ℓ/min. For Q = 40 ℓ/min, E_r ranges from 0.06 to 0.15 kW/m^2 and is relatively large at night or during snow fall events.

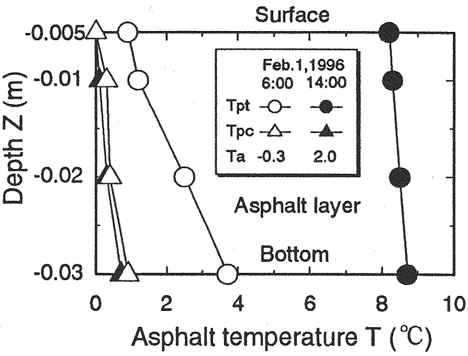

Fig.4 Vertical temperature profile in asphalt layer

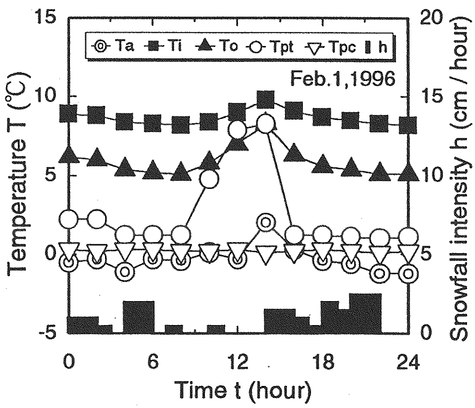

Fig.5 Typical diurnal variation of temperatures and snowfall intensity

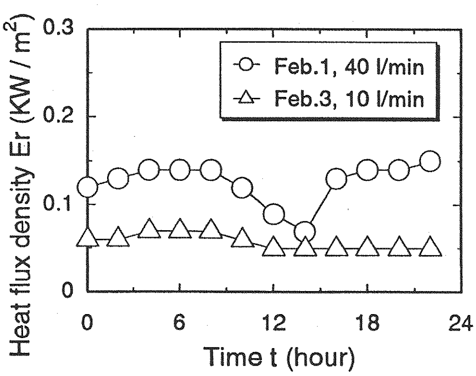

Fig.6 Heat flux density released from heat exchanger loop

Control of Pavement Temperature in Summer by BHES

During the summer, the device is also used to control pavement temperature. Fig.7 shows the vertical temperature profile in the asphalt at 6 A.M. and 2 P.M. on July 17, 1996. Temperatures in the test section are lower than in the control section and the difference between them reaches 13℃ to 20℃ at 2 P.M.. The test section profile is uniform at 6 A.M., i.e. $dT_{pt}/dz = 0$, but dT_{pc}/dz is slightly negative at the same time. A weak upward heat flow occurs in the control pavement. From this difference, it is seen that the heat exchanger loop in the pavement acts as a heat sink even during the night-time in summer.

Fig.8 shows the time variation of representative temperatures such as T_i, T_o, T_{pt}, T_{pc} and T_a on July 17, 1996. T_a varies from 25.5℃ to 34.6℃. It is of interest that T_{pc} (control pavement) is always higher than T_a even at night. This is known to contribute to the urban heat island phenomenon. T_i is higher than T_o over the whole day because of the heat transfer from the bore-hole into the ground. For both sections the maximum pavement temperature appears at 2 P.M.. However, T_{pc} (control pavement) reaches 70℃ while T_{pt} (test pavement) does not exceed 50 ℃. This level of decrease of surface temperature may be useful in reducing pavement rutting problems.

Fig.9 shows the absorbed heat flux density, E_g, associated with the heat transfer from the pavement towards the pavement exchanger loop. The solar energy absorption-efficiency, E_f, defined as the ratio of E_g to the sum of the net short wave and incoming long wave radiation, is also shown. E_g and E_f have a positive correlation each other. They are small during the night-time and large in the daytime. E_f ranges from 0.1 to 0.25, which is small compared with normal solar collectors.

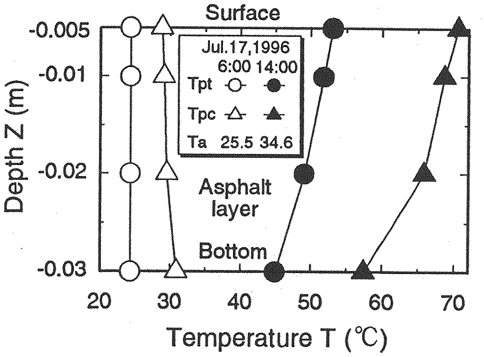

Fig.7 Vertical temperature profile in asphalt layer

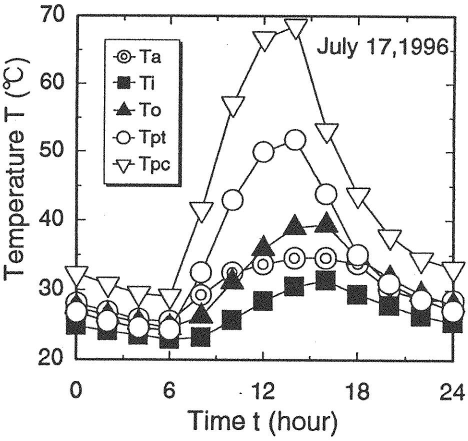

Fig.8 Typical diurnal variation of temperatures

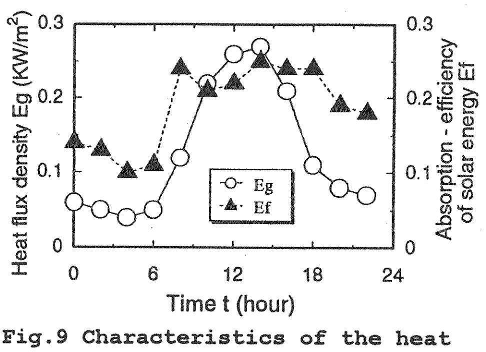

Fig.9 Characteristics of the heat transfer between pavement and exchanger loop

Thermal Energy Budget and Snow Melting Performance of BHES

Fig.10 presents the monthly thermal energy budget, E, for the bore-hole heat exchanger. A plus sign means charging from bore-hole heat exchanger to ground and a minus sign means extraction of terrestrial heat. Unfortunately, the data for April was lost because of equipment problems. In order to warm up the pavement and melt the snow, E is negative from November to March. Over an annual cycle, the system is capable of injecting approximately twice as much energy in summer as will be extracted in the following winter. This means that in Fukui, it should be possible to design a Bore-hole Heat Exchange System that can reliably provide sufficient heat for snow melting purposes.

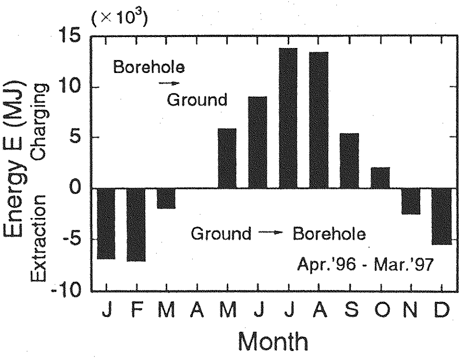

Fig.10 monthly thermal energy budget

The snow melting performance of the BHES can be conveniently described by two terms, P_{melt}, and COP_w, defined by

$$P_{melt} = E_{dis} / E_{in} \quad (2)$$

$$COP_w = E_{dis} / E_p \quad (3)$$

where E_{dis} = the total energy discharged from the ground during the period November to March; E_{in} = the seasonal total of internal energy of the liquid at the inlet of the bore-hole exchanger during the period November to March; and E_p = the seasonal total electrical energy consumed by the circulation pump during the period November to March. The value of P_{melt} is 0.12 and COP_w is 6.2.

CONCLUSIONS

A Bore-hole Heat Exchange System (BHES) has been applied to prevent winter time icing and snow accumulation in a car park at Fukui university. In summer, the system is used to control the pavement temperature of the car park. The main conclusions from the field experiment are as follows:

(1) The amount of terrestrial energy extracted from a coaxial pipe type bore-hole heat exchanger increases as the circulation flow rate increases.
(2) The BHES is effective, in summer, for cooling the pavement and, in winter, for de-icing and melting the snow at a car park of Fukui University.
(3) The BHES can lower the pavement temperature as much as 20℃ in summer and this decrease in the temperature helps to reduce pavement rutting problems.
(4) The amount of thermal energy accumulated from May to October (annual charged energy) is approximately twice as large as that from November to March (annual discharged energy).

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APPENDIX - NOTATION

The following symbols are used in this paper:

COP_w	=	efficiency of snow melting performance (E_{dis}/E_p);
$\|dT_{pc}/dz\|$	=	absolute temperature-gradient of control pavement;
$\|dT_{pt}/dz\|$	=	absolute temperature-gradient of test pavement;
E	=	thermal energy budget for bore-hole heat exchanger;
E_d	=	discharged energy per unit length of bore-hole heat exchanger;
E_{dis}	=	total discharged energy from November to March;
E_f	=	solar energy absorption-efficiency;
E_g	=	absorbed heat flux density associated with heat transfer from pavement towards pavement heat exchanger loop;
E_{in}	=	total internal energy of liquid at inlet of bore-hole exchanger from November to March;
E_r	=	heat flux density released from pavement heat exchanger loop;
E_p	=	total electric power of pump from November to March;
L	=	the bore-hole length;
P_{melt}	=	efficiency of snow melting performance (E_{dis}/E_{in});
Q	=	circulation flow rate (ℓ/min);
T_a	=	atmospheric temperature;
T_i	=	liquid temperature at pavement heat exchanger inlet;
T_{in}	=	liquid temperature at the inlet of the bore-hole;
T_o	=	liquid temperature at pavement heat exchanger outlet;
T_{out}	=	liquid temperature at the outlet of the bore-hole;
T_{pc}	=	asphalt temperature without the heat exchanger loop (control pavement);
T_{pt}	=	asphalt temperature with the heat exchanger loop (test pavement); and
(ρC)	=	volumetric heat capacity.

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