Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 2(4):130-136

Laboratory Study on Solar Collector of Thermal Conductive Asphalt Concrete

Shaopeng Wu[1+], Mingyu Chen[2], Hong Wang[2], and Yuan Zhang[2]

Abstract: It is current interest to make good use of asphalt pavements and airport runways as environmentally friendly solar collectors for the heating and cooling of adjacent buildings as well as to keep the pavements ice-free directly. The process of extracting heat energy from asphalt pavements was investigated in this study. Water flowing through copper tubes inserted within small laboratory prepared asphalt concrete slabs was used as heat exchanger. The rise in water temperature as a result of flow through the asphalt concrete slab was used as the indicator of the efficiency of heat exchange. Thermal conductive fillers were utilized to improve the thermal conductivity of asphalt concrete and thus resulting in an improved efficiency of asphalt collector. Experimental results showed that the heat energy obtained from solar irradiation can be enhanced by means of Conductive Asphalt Concrete (CAC). The circulating water has a cooling effect on decreasing the high temperature within asphalt concrete and thus reducing its risk of permanent deformation. Focus is on mixture design to prepare an effective heat exchanger that is capable to extract a maximum heat from asphalt pavements.

Key words: *Conductive asphalt concrete; Efficiency; Solar energy temperature distribution.*

Introduction

Asphalt pavements have gained more and more attention in recent years as an interesting new renewable energy source [1]. The sun provides a cheap and abundant source of clean and renewable energy. Solar cells have been used to capture this energy and use it. A more useful form of “cell” can be asphalt pavements, which serves as solar collector and has been developed for the heating and cooling of adjacent buildings as well as to keep the pavement ice-free directly [2]. Asphalt pavements can be heated up to 70°C by solar irradiation during summer season because it’s excellent heat-absorbing property. The heat retained in the asphalt pavement can still provide energy after sunset, whereas traditional solar cells fail to do so. Due to the excellent heat-absorbing property and wide use in parking lots, tarmacs, and roadways, application of the thermal energy potential from asphalt pavement by means of solar collectors appears some potential [3].

Besides the advantages mentioned above, asphalt collector also has its limitation on the poor energy exchange efficiency. Several researches have been conducted to investigate the energy efficiency using laboratory measurements and numerical simulations. Bijsterveld et al. [1] conducted finite element simulations to investigate the effects of heat exchanger system that embedded inside asphalt pavement on the temperature distributions and stress/strains inside the pavement. They concluded on the basis of results obtained from the models that locating the heat exchanger tubes at shallow depths would allow extraction of more energy but would result in higher stresses in the pavement, which could reduce the durability of the pavement. They also mention that there is a need to determine the effect of different materials on the thermal and structural properties of the pavement.

Hasebel et al. [4] reported a study on the use of energy from heated pavements to produce electricity and at the same time lower pavement temperatures during summer time. Measurements and modelling were used to evaluate the effect of the flow rate and temperature of the heat exchanger. It was concluded that the significant effect of the temperature of the heat exchanger fluid and the resistance of the thermoelectric modules on the peak power output.

The thermal energy potential of an asphalt collector is lower than that of a normal solar hot water system as well as the quality of the energy. However, asphalt collector may provide enormous renewable energy for the heating and cooling of adjacent buildings, eliminate the need for snow removal, offer greater safety for vehicles, and produce superior maintenance of pavement during extreme low and high temperatures [5].

Mallick et al. [6] performed a finite element model for investigation of temperature distributions in small samples and testing with small and large scale asphalt pavement samples. The results of small scale testing showed that the use of aggregates with high conductivity can significantly enhance the efficiency of heat capture. The efficiency can also be improved by using a reflectivity reducing and absorptivity increasing top layer over the pavement. Tests carried out with large scale slabs showed that a larger surface area results in a higher amount of heat capture, and that the depth of heat exchanger is critical.

Numerous modeling was initiated on heating and temperature distributions along the depth of asphalt pavements, especially when different asphalt binders, various aggregates, external environment, and other factors were considered. For experimental or computational investigation of asphalt solar collectors, the efficiency of an asphalt collector is always the first problem encountered.

[1] Professor, Key Laboratory of Silicate Materials Science and Engineering, (Wuhan University of Technology), Ministry of Education, Wuhan 430070, China.

[2] PhD Candidate, Key Laboratory of Silicate Materials Science and Engineering, (Wuhan University of Technology), Ministry of Education, Wuhan 430070, China.

[+] Corresponding Author: E-mail wusp@whut.edu.cn

Note: Submitted August 31, 2008; Revised January 4, 2009; Accepted March 31, 2009.

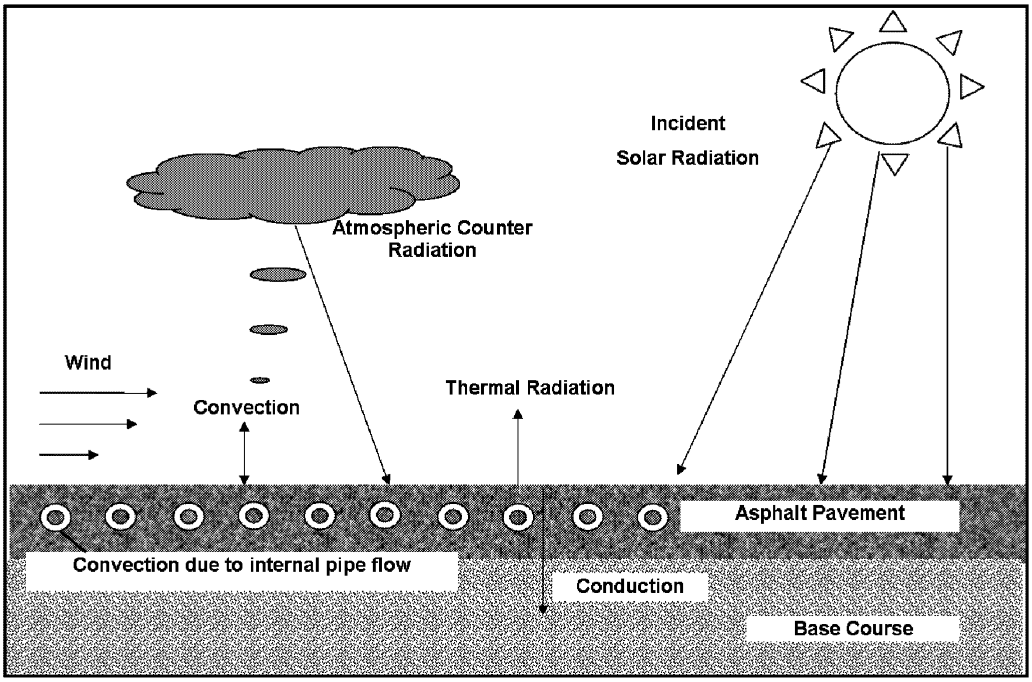


Fig. 1. The Mechanisms in Capturing Solar Energy from Pavement.

in Fig. 1. Heating of a pavement is an energy balance between the irradiation from the sun and atmospheric that is absorbed by the pavement, the convective heat transfer between the pavement and the ambient, the emission from the pavement and the conduction heat transfer between the surface and the interior. Internal convection from flow of heat transfer fluid through the pipes brings the solar energy out.

This paper proposes a test method to predict the thermal response of asphalt pavements. In this study, Conductive Asphalt Concrete (CAC) is prepared and its performance is evaluated in laboratory. The work involves experimental simulating the process of solar energy conversion and estimating the efficiency of asphalt collector. Ultimately, the results aim at verifying the thermal energy potential of CAC and provide a basis to confirm critical parameters in extracting thermal energy.

Experimental

Materials and Gradation

Graphite is the primary conductive filler for asphalt mixtures. Microcrystal graphite powders were selected as thermal conductive fillers due to their low cost and abundance, excellent thermal properties, and compatibility with asphalt. Graphite powders have a particle size of 150*μm*, carbon content of 98.9%, and thermal conductivity of 68 to 72*W/m·K*.

A heavy traffic paving asphalt AH-90 was obtained from Panjin Northern Asphalt Ltd., Co. in Liaoning Province, P.R. China, with penetration of 90*dmm* at 25°C, ductility of more than 120*cm* at 15°C, and softening point of 46.5°C.

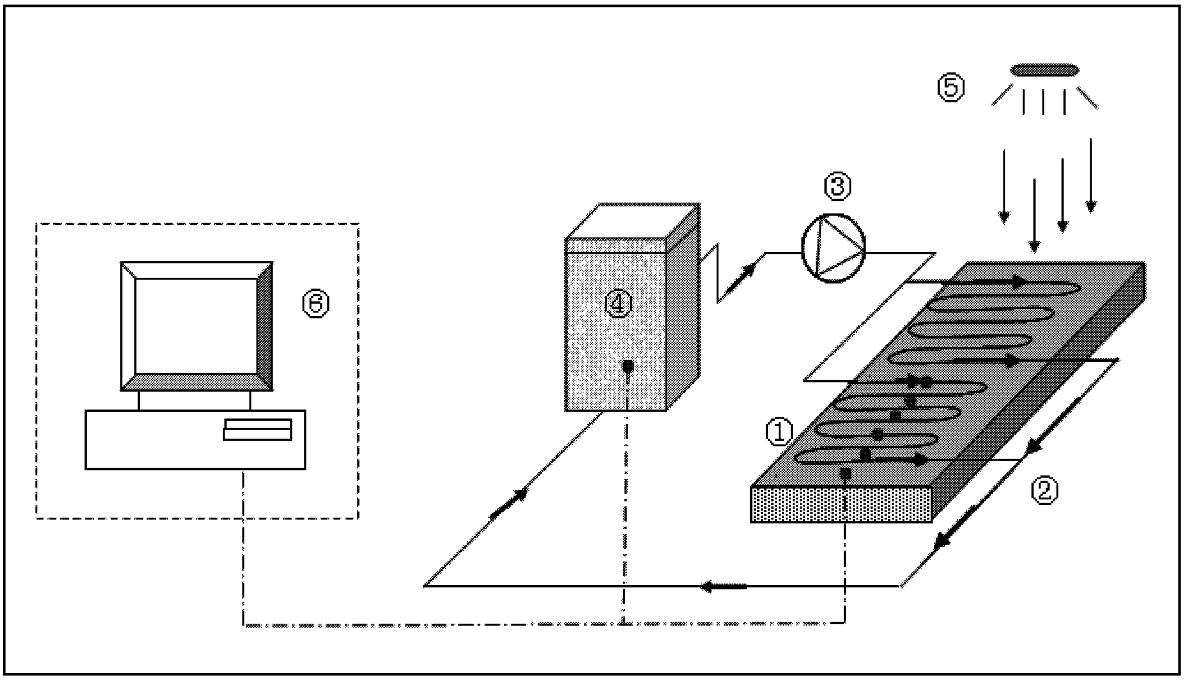
The pavement discussed in this paper is 300×300×150*mm* (length × width × depth) in dimension. The entire slab is made up of three structure layers; each layer is constructed by Hot-Mix Asphalt (HMA) concrete with thickness approximately 50*mm*. Two types of materials were used for preparing asphalt middle courses for the two slabs. The first middle course was prepared with a neat asphalt mixture as control group, whereas the second was prepared with the CAC. The CAC was obtained with a 12.5*mm* Superpave gradation. Basalt coarse aggregate and fine aggregate (Bulk specific gravity of 2.92 and 3.13, respectively) were used in the asphalt concrete. Limestone was used as mineral filler. Table 1 presents the selected mix gradation. Graphite content of 18% by volume of asphalt binder was used for thermal CAC. Graphite can replace some limestone powders due to its smaller size than mineral fillers. The preparation procedure of conductive asphalt mixtures is shown in the Reference [7]. Subsequently, a normal asphalt concrete have the same gradation of CAC except graphite content is 0%, as the surface course of the slabs and the middle course in control groups. The layers have been prepared for three times by using roller compactor. After measurement, the thermal conductivity of the CAC is 2.23*W/m·K* that increases from 1.73*W/m·K* as obtained from neat asphalt concrete [8]. Base course(conductivity 1.67*W/m·K*) in all of slabs were made with a 19*mm* Superpave gradation and the same material was used for 12.5*mm* Superpave gradation. The base mix gradation is also shown in Table 1. This type of asphalt mixture has 13 to 17% of voids content in mineral aggregates, which provides sufficient space for conductive fillers. In this study, the mixture proportion was 6.5 to 7.5% for asphalt, 85.6% for basalt aggregates, and 7.4% for fillers consisting of limestone powder and conductive powder. All the materials of the mixtures met the corresponding design code. The air voids and other volumetric properties of the test specimens were agreed with the design requisition.

Experimental Set-Up

A general view of the experimental set-up is shown in Fig. 2. It mainly

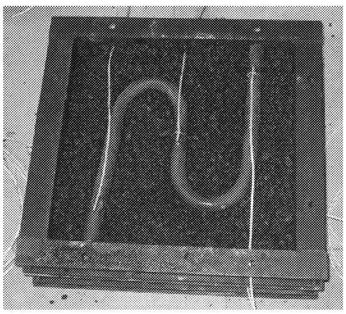
Table 1. Selected Mix Gradation.

Type	Sieves [*mm*]	25	19	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
12.5*mm*	Passing [%]	100	100	98.5	77.2	50.0	28.9	21.9	16.8	12.6	8.5	5.1
19*mm*	Passing [%]	100	97.5	69.4	59.8	39.1	29.1	19.5	13.2	8.5	5.5	3.9

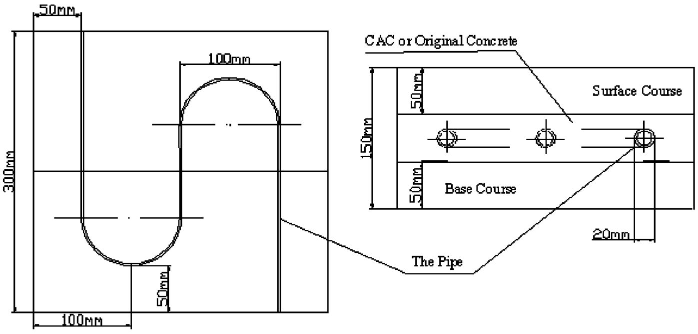


1. Asphalt Pavement, 2. Pipes and Circuit, 3. Circulation Pump, 4. Vacuum Flask, 5. Halogen Lamp, and 6. Data Acquisition Unit.

Fig. 2. Diagram of the Experimental Set-Up.



(a)



(b)

Fig. 3. The Configuration of Tubes in Tested Slab (a) Photo of Tested Sample with Tube and (b) The Schematic of Tested Slab.

consists of an asphalt pavement, U-shaped pipes, halogen lamps, a circulation pump, a vacuum flask, data acquisition unit, and a PC for data analysis. The sources of heat are emitted from halogen lamps. This setup was first proposed by Mrawira and Luca [9] and has since then been used by Nazarian and Alvarado [10]. The radiation energy over the HMA sample was 1200W/m^2, determined by the relative position of the heat source.

A U-shaped pipe was inserted in the middle course, which was compared to other two non-pipe slabs, helps to measure the pavement temperature distribution. The pipe is embedded in a serpentine configuration as shown in Fig. 3. The pipe spacing is 10*mm* and is buried 75*mm* in depth. Nominal pipe diameters are 20*mm* and the inside diameters are 15*mm*. In order to prevent pipes from removing, both ends of the pipes are fixed to the specialized mould on the process of the compaction. The copper tubes were used to pump water through the slab and functioned as the heat exchanger. A metering pump impels water through the pipes, whose flow rate range is 0 to 60*L/hr* in 0.6*MPa*, ±1.5% in accuracy and ±0.3% in fidelity. The inlets and outlets of the copper pipe were placed in a small vacuum flask of water by hose pipes. A vacuum flask, through interposing an evacuated region to provide thermal insulation between the contents and the environment, is a vessel or insulated shipping container which keeps its contents hotter or cooler than their environment without modifying the pressure. Besides, a 15*mm* thick foamed polystyrene plate (Thermal Conductivity 0.038$W/m{\cdot}K$) is fixed around and on bottom of the asphalt slabs and

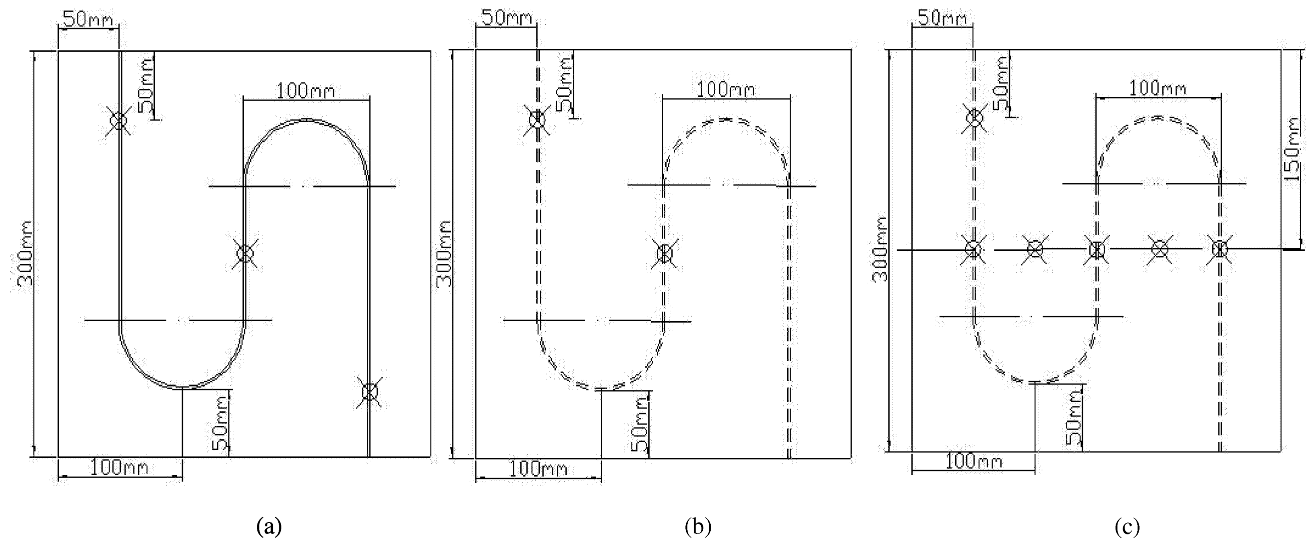


Fig. 4. Measuring Point Distribution at Different Depths in (a) 5, 25, 50, 75, 100, and 125*mm*, (b) 25*mm*, and (c) 75*mm*.

hose pipes which exposed to the ambient to reduce heat loss.

Accounting for the important application conditions and evaluate the effects of the heat exchanger and CAC, it is necessary to measure the temperature distribution within the pavement's different location with increasing depth. Temperature sensors were inserted along the depth and at various points (including points in line with the tube and the passageway) in slabs. A type of high precision thermal resistor (Pt100) with a measuring range of -50 to 250°C and ±0.15°C in full-range is selected. Sensor locations are shown in Fig. 4. Every sensor was connected to a Keithley2700 data acquisition system with two pieces of Keithley7702 Differential Multiplexer Module, which have 40 channels of 4-pole multiplexer switching for 4-wire PT100 and allow continuous recording of temperature and scan every channel range in 0.1*ms*. The display precision and measuring accuracy of acquisition system can reach 0.001°C.

In all of the testing and analysis, the difference in temperature between incoming and outgoing water (Delta *T*) worked as an indicator of the "efficiency", i.e. *E*, of the system, which can be calculated by:

$$E = \frac{MC(T_0 - T_i)}{R} \tag{1}$$

E is the efficiency of extracting heat energy from asphalt pavements, M the mass of water (*kg*), C the specific heat of water (*J/kg*·°C), T_0 the outlet water temperature of water in vacuum flask (°C), T_i the inlet water temperature of water in vacuum flask (°C), and R the radiation energy over the HMA sample.

All of the tests were conducted in the laboratory where there is no wind, relative humidity between 60 to 80% and isoperibol between 20°C±1°C regulated by air-conditioners. Before testing, the slabs have been preserved in a constant temperature for 24*hrs*, and every measuring point temperature in slabs remains uniform at 20.0°C±0.5°C.

Experimental Results and Discussion

Effects of CAC on the temperature distributions

The lamps provide constant radiation of 1200W/m^2 over the sample till the temperature of samples keeps stationary. Two types of sample without copper pipes were heated for 10hrs. Fig. 5 shows the vertical distribution of non-pipe slab temperature at different time. The results indicate that the temperature of samples decreases with heating from top to down. Every layer of conduction process in the neat slab was uniform due to the linear decreasing tendency. However, the decrease was non-linear in the CAC slab profile. The slope of temperature profile between 50 and 100*mm* increases a bit compared with that of the surface and base course of the asphalt concrete slab, which shows the rate of heat dissipation of the middle course of CAC is higher than that of the neat slab. Likewise, the maximum temperature decreases with the increase of depths from 25 to 50*mm* due to high thermal conductive of graphite in CAC. The temperature varies from 32.30 to 25.61°C when the depths vary from 50 to 75*mm* in CAC slab, but the temperature range is between 31.44 and 28.04°C in neat slab. In other words, the CAC can quickly transfer the heat energy absorbed by surface course to base course. All these can be validated by the temperature difference between neat and CAC slabs at a depth of 125*mm*. The temperature of CAC at depth of 125*mm* remains higher than that of neat slab all along after they were heated for one hour.

Fig. 6 presents the effects of graphite on the temperature distributions at different depth over a period of 8.5hrs. The results show that the temperature of the samples increases with time. At depth of 100*mm* for both slab types, the temperature profile shows little difference. It can be obtained from Figs. 5 and 6 that the surface temperature decreases proportionally to the quantity of graphite. Identically, it reflects that the addition of graphite can accelerate the heat-transmission from top to down, which enhances the energy efficiency of asphalt solar collector. Moreeover, the effect of graphite on the temperature variations tends to be clear at depth of 75*mm*. Asphalt mixtures with graphite presents lower temperature rising rate and the temperature is consistently lower than

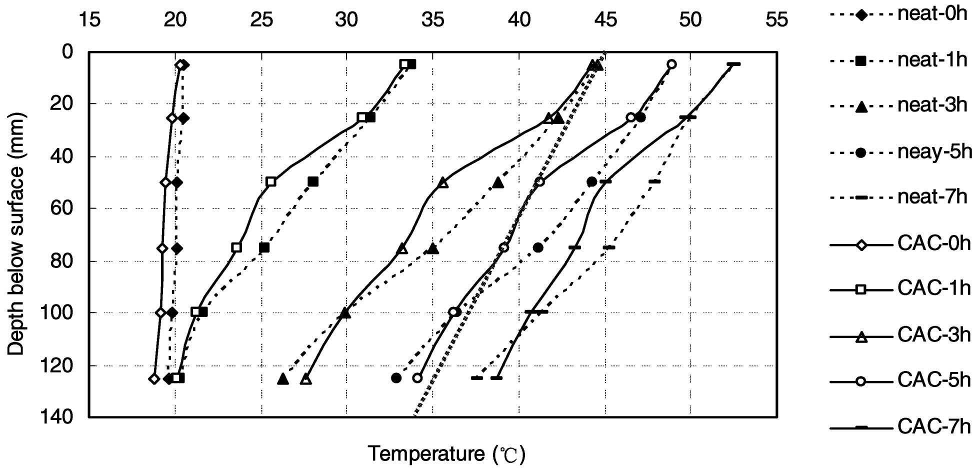


Fig. 5. The Non-Pipes Slab Vertical Temperature Distributions at Different Time.

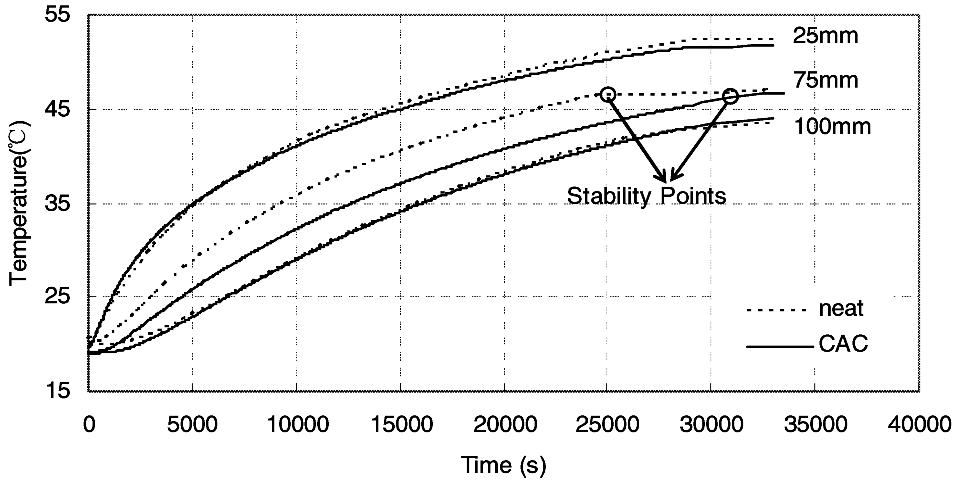


Fig. 6. Temperature Distributions of Different Depths over 8hrs.

the control group. The maximum temperatures difference at depth of 75*mm* increases by 3.54°C when the slab is heated over 12,700*s*.

In the same environment, the time at which steady state is reached at different depth variations. The sensors at depth of 25 and 100*mm* nearly reach steady state simultaneously at the last moment. The respective temperatures of CAC slab and neat slab at the depth of 75*mm* are different from each other and usually the difference is about one hour period.

Effects of Hydronic Piping on Slabs

Based on the results obtained so far, another two different types of HMA sample were procured for subsequent laboratory test, which have the same materials, gradation, and manufacture method with the one used before. Here, the manufacture method mainly refers to embedding of the copper pipe. The copper pipe has been used to load hydronic water through the slabs. The basic objective was the same as that of the previous test to determine the effects of CAC on the pavement, Firstly; the slabs were kept under the lamps for six hours without any water-flow. Next, a hose was connected; the water is supplied to pump through the copper tubes in both slabs at the same rate (flow rate 600*ml/min*, temperature 20.0°C±0.1°C) and similar irradiation.

Fig. 7 illustrates the temperature variation due to the hydronic water. Looking at the profiles, we can easily find that there are temperature decreases at different depth of the slabs. The steady state of all points of sensor in profiles was reached quickly in half an hour. At the depth of 25*mm*, rates of temperature change are having similar trend between two slab types while the temperature in CAC is lower than the other by 1.5hrs. Identically, the rates of temperature change at depth of 50 and 100*mm* show similar trend but the temperature difference is relatively big between two slab types. The temperature of slabs at depth of 50*mm* is 32.86°C in neat slab and 29.19°C in CAC slab, which decreases by 3.67°C. However, at depth of 100*mm* in CAC slab, the temperature changes by 5.14°C, which means the rate of temperature change at depth of 100*mm* in CAC slab is higher than that in neat slab. It also demonstrates CAC can accelerate the heat energy transfer from surface to bottom and the circulating water can prevent the heat energy to transfer from top to down and can decrease the slab temperature

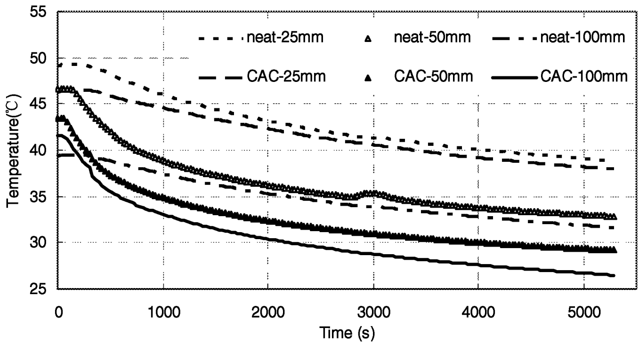


Fig. 7. Temperature Decreases Due to the Hydronic Water.

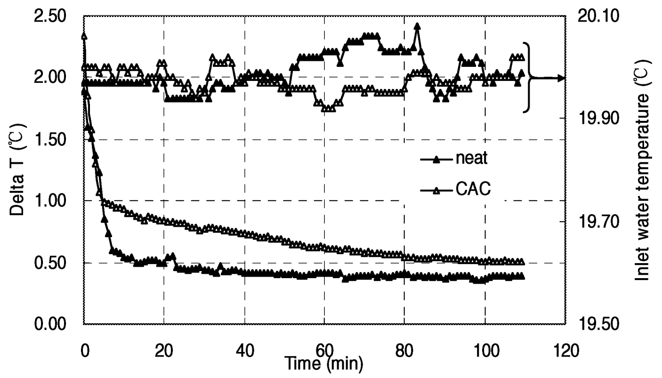


Fig. 8. The Difference between Inlet and Outlet Water Temperature.

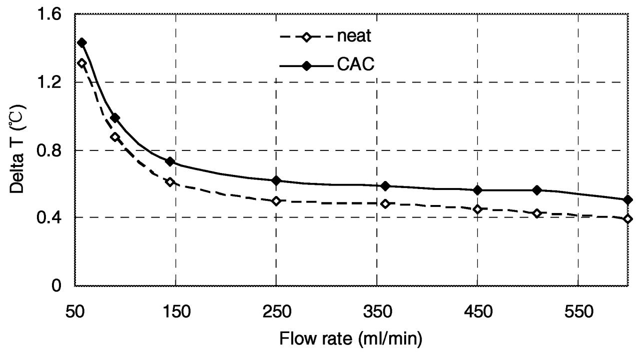


Fig. 9. The Delta *T* as Function of the Flow Rate.

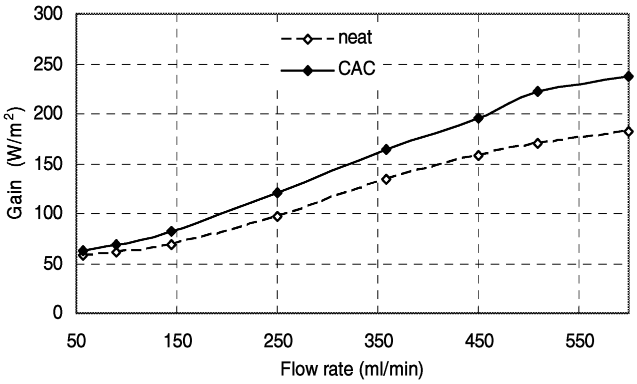


Fig. 10. The Gain of Thermal Energy as Function of the Flow Rate.

clearly, thus reducing the possibility of permanent deformation in a certain degree.

The Efficiency of Hydronics on Asphalt Concrete

The above description based on CAC set-up and valid test in which lead to temperature change are also applied in the following test. Water flowing through copper tubes inserted in HMA samples was used as heat exchanger in the experiments. The rise in temperature of water as a result of flowing through the asphalt slabs was used as the indicator of efficiency of heat exchange. Fig. 8 presents the temperature difference between inlet and outlet water temperature (Delta *T*) measured in experiments. The results show that the sample with CAC course had a significantly higher temperature difference compared to the neat asphalt slab. The comparison reveals that the higher conductivity is clearly beneficial in heating water by extracting heat from deep inside the asphalt pavement. The circulating water (the inlet temperature invariable) was heated by approximately 0.51°C when the steady state was reached in the CAC sample, while by 0.39°C in the neat slab.

The higher increase in temperature of the circulating water means a larger amount of extracted heat energy. But the temperature varies according to the flow rate. Fig. 9 presents the temperature difference between inlet and outlet water temperature changes due to the flow rate. The relation between the gain of thermal energy and flow rate is shown in Fig. 10. The gain of thermal energy increases gradually as flow rate is increasing, with the water temperature simultaneously climbs. With same flow rate, a longer piping, supplying a larger area of heat transfer, is necessary to realize a temperature rise. Adequate flow rate can offer water with high temperature and gain more power if longer tubes are served. The results indicate that both slabs having heat exchangers with a large surface area exposed to sun and using thermal conductive fillers which help asphalt mixtures with better conductive can enhance the efficiency of extracting heat energy from pavements.

Conclusions

It is important to make good use of asphalt pavements and airport runways as environmentally friendly solar collectors for the heating and cooling of adjacent buildings as well as to keep the pavements ice-free directly. The process of extracting heat energy from the HMA slabs prepared in laboratory has been investigated in the present work. The following conclusions can be obtained:

1. With graphite as contents in middle layer, the temperature of asphalt slabs on the surface (5*mm*) decreases slightly while decrease significantly at depth of 50 to 75mm. The temperature change is more obvious inside the asphalt layer than that on the surface.
2. The circulating water clearly decreases high temperature of the pavement, thus controlling and reducing the possibility of permanent deformation during summer in a certain level. Using highly conductive concrete like CAC can enhance the heat transfer efficiency and lower high temperature of the pavement to a proper level.
3. The gain of thermal energy increases gradually as flow rate is

in a rise; with the water temperature simultaneously climbs. The gain of thermal energy is increased due to the adding of CAC slab. Adequate flow rate can offer water with high temperature and gain more power if longer tubes are served.

4. An effective heat exchanger and materials design will be the key in extracting maximum heat from the asphalt pavement. The future work of this study will be focused on improving the heat transfer from the pavement through various appropriate types of material and confirming how to select the parameters of materials in extracting thermal energy from solar irradiation.

Acknowledgements

This work is part of a research Project 50878171 supported by National Natural Science Foundation of China. The authors gratefully acknowledge its financial support.

References

1. Bijsterveld, W.T., van Houben, S.A., and Molenaar, A.A.A., (2001). Using Pavement as Solar Collector: Effect on Pavement Temperature and Structural Response, *Transportation Research Record*, No. 1778, pp. 140-148.
2. Diefenderfer, B.K., (2006). Model to Predict Pavement Temperature Profile: Development and Validation, *Journal of Transportation Engineering*, 132(2), pp. 162-167.
3. Hermansson A., (2000). Simulation Model for Calculating Pavement Temperatures Including Maximum Temperature, *Transportation Research Record,* No. 1699, pp. 134-141.
4. Hasebel M., Kamikawa, Y., and Meiarashi, S., (2006). Thermoelectric Generators Using Solar Thermal Energy in Heated Road Pavement, *25th International Conference on Thermoelectric, IEEE,* Vienna, Austria, pp. 697-700.
5. Loomans, M., Oversloot, H., and de Bondt, A., (2003). Design Tool for the Thermal Energy Potential of Asphalt Pavements, *8td International IBPSA Conference*, Eindhoven, Netherlands, pp. 745-752.
6. Mallick, R.B., Chen, B.L., Bhowmick, S., and Hulen, M.S., (2008). Capturing Solar Energy from Asphalt Pavements, *International ISAP Symposium on Asphalt Pavements and Environment,* Zurich, Switzerland, pp. 161-172.
7. Wu, S.P., Mo, L.T., and Shui, Z.G., (2002). An Improvement in Electrical Properties of Asphalt Concrete, *Mater. Sci. Ed.*, *Journal of Wuhan University of Technology*, 17(4), pp. 69-72.
8. Wu, S.P., Li, B., Yue, X., Ling, P., and Mo, L.T., (2008). The Effect of Thermal Conductive Fillers on Thermal Properties of Asphalt Mixtures, *International ISAP Symposium on Asphalt Pavements and Environment*, Zurich, Switzerland, pp. 153-160.
9. Mrawira, D. and Luca, J., (2004). Solar-Convection Simulator for Laboratory Investigation of Transient Temperature Fluctuations in HMAC Pavements, *Transportation Research Record*, No. 1809, pp. 160-171.
10. Nazarian, S. and Alvarado, G., (2006). Impact of Temperature Gradient on Modulus of Asphaltic Concrete Layers, *Journal of Materials in Civil Engineering*, 18(4), pp. 492-499.