The Potential of Heat Collection from Solar Radiation in Asphalt Solar Collectors in Malaysia

Salmia Beddu1*, Siti Hidayah Abdul Talib1, Zarina Itam1
1Department of Civil Engineering, Universiti Tenaga Nasional, Malaysia
E-mail: Salmia@uniten.edu.my

Abstract. The implementation of asphalt solar collectors as a means of an energy source is being widely studied in recent years. Asphalt pavements are exposed to daily solar radiation, and are capable of reaching up to 70°C in temperature. The potential of harvesting energy from solar pavements as an alternative energy source in replace of non-renewable energy sources prone to depletion such as fuel is promising. In Malaysia, the sun intensity is quite high and for this reason, absorbing the heat from sun radiation, and then utilizing it in many other applications such as generating electricity could definitely be impressive. Previous researches on the different methods of studying the effect of heat absorption caused by solar radiation prove to be quite old and ineffective. More recent findings, on the other hand, prove to be more informative. This paper focuses on determining the potential of heat collection from solar radiation in asphalt solar collectors using steel piping. The asphalt solar collector model constructed for this research was prepared in the civil engineering laboratory. The hot mixed asphalt (HMA) contains 10% bitumen mixed with 90% aggregates of the total size of asphalt. Three stainless steel pipes were embedded into the interior region of the model according to the design criteria, and then put to test. Results show that harvesting energy from asphalt solar collectors proves highly potential in Malaysia due its the hot climate.

1. Introduction
Most countries currently rely on non-renewable energy sources such as coal, oil, and natural gases as an energy source. These non-renewable sources will eventually deplete and become too expensive or too environmentally damaging to retrieve. In contrast, renewable energy resources such as wind and solar energy has the tendency to become a regenerative energy with no consequence of environmental damage. Most renewable energy comes either directly or indirectly from the sun. The sun provides a cheap and abundant source of clean and renewable energy.

In the 1980’s, Malaysia started implementing asphalt pavements which consists of bituminous surfacing, granular road base, drainage sub-base, and the formation subgrade replacing bituminous macadam surfacing, and design in accordance to the Arahan Teknik (Jalan) 5/85 which was adapted from American Association Of State Highway Officials (AASHTO) Road Test, subjected to specific modifications based on local experiences [1, 2]. Asphalt pavements has the capability of absorbing higher heat flux, with the capacity to produce an average of 400 to 600MJ/m² solar radiation per month due Malaysia’s geographical profile which is at the equatorial region, thus increasing the pavement temperature [4, 5].

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd
Hasebel et al. performed a study on the use of energy from heated pavements to produce electricity, and at the same time lower pavement temperatures during summer [9]. Measurements and modeling were used to evaluate the effect of the flow rate and temperature of the heat exchanger. It was found that the temperature of the heat exchanger fluid and the resistance of the thermoelectric modules showed a significant effect on the peak power output. Rajib et al. investigated the temperature distributions in small samples by means of finite element modeling. Tests on small and large-scale asphalt pavement samples were also performed. Many researchers have studied the thermal response in asphalt pavement especially in modern countries where sustainable development is deemed crucial. Similar to other developing countries, Malaysia is keen to promote solar energy as the alternative source to be used in the future [4]. However, since studies related to solar energy is yet to be a common research in Malaysia; therefore a wide range of data collection is needed for further development, integration, and innovation.

2. Problem statement
Asphalt pavement has gained more attention in the recent years as a potential source of renewal energy. Its surface temperature can reach up to 70°C in summer, inducing a rise in temperature of adjacent air at the surface, which is generally known as the heat island effect. This leads to an increase of power consumption due to excess use of air conditioning, which may lead to a decrease of air quality in cities. In particular, thermal oxidation rate doubles with each 10K increment in temperature. Moreover, pavements under such high temperatures are prone to suffer from rutting. Therefore, immediate actions should be taken as Malaysia is encountering a remarkable increase in energy demand and economic growth. Renewable energy is one of the best solutions to supply energy since it can be generated constantly and replenished naturally.

Asphalt solar collectors consist of pipes embedded in the pavement with an internally circulating fluid. Since solar radiation increases the thermal gradient between the pavement and the fluid circulating through pipes from its initial condition, heat transfer occurs from the pavement to the fluid. This process will continue until thermal equilibrium is reached, where both the pavement and fluid will have the same temperatures, leading to a decrease in pavement temperature and an increase in fluid temperature. This drop in asphalt temperature contributes to mitigate the heat island effect and reduce the risk of permanent deformations to the pavement. Asphalt solar collectors are usually coupled with low temperature geothermal heat pumps, resulting in reasonable efficiency and operating costs. What makes asphalt solar collectors intriguing is the potential of harnessing energy from the temperature rise from the circulating fluid in the pipes. This study aims to develop a prototype for a solar harvesting system which will prove the potential of harvesting energy from solar energy in Malaysia. Therefore, the efficiency of asphalt pavement as an energy harvester will be discovered.

Malaysia is one of the Asian countries with a warm, tropical climate. Its temperature ranges from 21°C to 35°C. The annual average daily solar irradiations for Malaysia range from 4.21 to 5.56kWh/m². The highest solar radiation was estimated at 6.8kWh/m² in August and November while the lowest was 0.61kWh/m² in December. Hence, the potential of Malaysia to use solar as a renewable energy resource is high. Al-Abdul et.al. [2] showed that a wide range of temperature variation results in drastic variation of asphalt concrete modulus. As temperature increases from 30°C to 60°C, the resilient modulus reduces from 5500MPa to 800MPa. Thus, to study the in-situ characteristics of various pavement designs, it is imperative to know the temperature distribution within the pavement cross-section. Recently, researchers carried out experimental slabs to investigate heat transfer characteristics of the Slab Solar Collection (SSC), heat collecting efficiency, and the influence of pipe spacing and flow rate on the SSC process [7]. It has been proven that the average heat collecting capacity is about 150 to 250W/m² in summer conditions. Bijsterveld et. al. conducted finite element simulations to investigate the effects of heat exchanger system embedded in asphalt pavement on the temperature distributions and stress/strains inside the pavement [1]. It was found that placing the heat
Exchanger tubes at shallow depths can extract more energy but result in higher stresses in the pavement, thus reduced durability of the pavement. For this reason, the effect of different materials on the thermal and structural properties of the pavement must be studied.

3. Experimental program
The model was fabricated from wood, and embedded with asphalt and stainless steel (see Figure 1). Details of the model are as the following:

- A 30×30×15 cm wooden box was designed for the solar asphalt pavement model.
- Bituminous mixture consists of a well-graded mixture of coarse aggregates, fine aggregates and mineral filler, bound together with petroleum bitumen using asphalt cement.
- Standard steel pipe was placed in the middle layer of the box with the length of 35 cm and 2.2 cm diameter. Six inlet and outlet valves sockets were added to the end of pipes in order to insert and discharge the liquid easier.

![Figure 1. Asphalt solar collector model.](image)

The model was then placed in a selected open space area, in this case, a parking lot, chosen due to its optimal environmental condition for solar radiation. Two cases has been specified:

1. **Case 1** – Testing was conducted with the frequency of 3 times a day for 5 consecutive days. The scheduled time for testing are:
   - 9 am to 10 am in the morning.
   - 1 pm to 2 pm in the afternoon.
   - 5 pm to 6 pm in the evening.
   Such times were chosen to know the actual temperature at the time of solar radiation exposure itself.

2. **Case 2** – Testing was conducted between 9 am to 3 pm, and 3 pm to 9 pm for 10 consecutive days. Temperature readings will be done after every 6 hours. This is in order to determine the temperature for transient thermal conditions.

Heat efficiency of the model is based on the fluid and air temperatures, and is calculated from the following formulation:

\[
\text{Heat efficiency} = \frac{\text{Fluid temperature}\left[^\circ\text{C}\right] - \text{Air temperature}\left[^\circ\text{C}\right]}{\text{Fluid temperature}\left[^\circ\text{C}\right]} \times 100
\]  

(1)
4. Results and discussion

4.1. Case One

- Results show that the percentage of heat efficiency is higher the afternoon than other times. Due to the tropical weather conditions in Malaysia, constant air temperature has been observed. Therefore, we could realize that the heat efficiency for these 5 days are similar to each other.
- The lowest heat efficiency among these five days was on the second day and in morning at 3.70% due to low and constant temperature condition, causing steady state condition within the model.
- The highest heat efficiency was on the fifth day with 25.58%. In the afternoon, the sun radiation was high enough to heat the pavement and steel, causing the heat to be captured well.

4.2. Case Two

- Results show that the percentage of heat efficiency in the first period of time which is between 9 am to 3 pm is higher than 3 pm to 9 pm. This is mostly because of the air temperature which was higher during this period.
- The lowest heat efficiency was obtained on the third day with 12.12% during the 3 to 9 pm period.
- The highest heat efficiency among the 5 days was on the fourth day with 57.69% during the 9 am to 3 pm time frame. The percentage of heat efficiency is really high and shows that the system is really effective in terms of harvesting heat and energy. The temperature that recorded is 33 °C and the fluid temperature reached to 78ºC after six hours.

5. Conclusion

Based on the results obtained, the following conclusions can be made:

- Heat transfer efficiency was affected mostly by weather temperature and fluid temperature.
- The maximum heat efficiency obtained for Case 1 was on the fifth day with 25.58% efficiency in the afternoon, and for Case 2 on the fourth day between 9am to 3pm with 57.69% efficiency. These results show high efficiency of the model used for this project.

Acknowledgment

The authors would like to acknowledge the personnel of the Faculty of Civil Engineering & Earth Resources, University Malaysia Pahang for their assistance in the experimental testing. This research is financially supported by the Internal Grant RDU 130383.

References

[1] Berdahl P, Akbari H, Levinson R, Miller WA. Weathering on Roofing Materials – An Overview. Constr. Build. Mater. 2006;22(4), pp. 423–33.
[2] Al-Abdul Wahhab, H. and Balghunaim, F. (1994). Asphalt pavement temperature related to Arab Saudi environment. J. Mater. Civ. Eng., 6(1), pp. 1–14.
[3] B. K. Diefenderfer, I. L. Al-Qadi and S. D. Diefenderfer. Model to Predict Pavement Temperature Profile: Development and Validation. Journal of Transportation Engineering, Vol. 132, No. 2, 2006, pp. 162-167.
[4] Hermansson, A. (2000). Simulation Model for Calculating Pavement Temperatures, including Maximum Temperature. Transportation Research Record 1699, Transportation Research Board, Washington, D.C., pp. 134–141.
[5] Shaopeng W., Mingyu Chen., Jizhe Z. Laboratory Investigation into Thermal Response of Asphalt Pavements as Solar Collector by Application of Small-scale Slabs. Applied Thermal Engineering vol. 31 issue 10 July, 2011. pp. 1582-1587.
[6] X.B. Liu, S.J. Rees, J.D. Spitle. Modeling Snow Melting on Heated Pavement Surfaces: Model Development. Applied Thermal Engineering 27 (2007), pp. 1115-1124.
[7] Q. Gao, M. Li, M. Yu, J.D. Spitle and Y.Y. Yan. Review of Development from GSHP to UTES in China and other Countries. Renewable and Sustainable Energy Reviews 13.