# Capturing Solar Energy from Asphalt Pavements

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**ABSTRACT**
The concept of extracting heat energy from asphalt pavements has been investigated in this study. The scope of work consisted of finite element modeling and testing with small and large scale asphalt pavement samples. Water flowing through copper tubes inserted within asphalt pavements samples were used as heat exchangers in the experiments. The rise in temperature of water as a result of flow through the asphalt pavement was used as the indicator of efficiency of heat capture. The results of small scale testing show 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 show that a larger surface area results in a higher amount of heat capture, and that the depth of heat exchanger is critical. An effective heat exchanger design will be the key in extracting maximum heat from the pavement.

## 1. BACKGROUND

The sun provides a cheap and abundant source of clean and renewable energy. Solar cells have been used to capture this energy and generate electricity. A more useful form of "cell" could be asphalt pavements, which get heated up by solar radiation. The "road" energy solar cell concept takes advantage of a massive acreage of installed parking lots, tarmacs and roadways. The heat retained in the asphalt mixture can continue to produce energy after nightfall—when traditional solar cells do not function. The idea of capturing energy from pavement not only turns areas such as parking lots into an energy source, but also could cool the asphalt pavements, thus reducing the urban heat island effect.

The significance of this concept lies in the fact that the massive installed base of parking lots and roadways creates a low cost solar collector an order of magnitude more productive than traditional solar cells. The significantly high surface area can offset the expected lower efficiency (compared to traditional solar cells) by several orders of magnitude, and hence result in significantly lower cost per unit of power produced.

The system uses an existing lot, so does not require purchase or lease of new real estate (as would be needed for a solar "farm" installation). The system has no visible signature — that is, the parking lot looks the same. This compares well against rooftop silicon panels that are often bulky and unattractive. The fact that roads and parking lots are resurfaced on a 10-12 year cycle could be a good selling point for the road energy system - any time the pavement is replaced, the energy system can be installed.

The captured energy from heated asphalt pavements can be used for relatively simple applications, such as heating of water, to sophisticated applications, such as generating electricity through thermoelectric generators.

## 2. OBJECTIVE

The objectives of the study reported in this paper were to determine which, if any, of the following, either by itself, or in combination, would enhance the amount and rate of flow of heat energy from heated asphalt pavements: 1. Appropriate primary construction materials, 2. Appropriate Additives, 3. Use of layers on top of the pavement

## 3. THEORETICAL CONSIDERATION

As shown in Figure 1, heating of a pavement is an energy balance between the irradiation

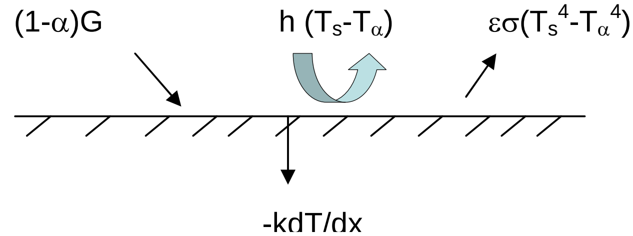



**Figure 1:** Thermal problem associated with pavement heating (G = irradiation, h = heat transfer coefficient, k = thermal conductivity, T = temperature, $\alpha =$ reflected component, $\varepsilon =$ emissivity of the surface

from the sun 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. In order to use the heat from the pavement, it is important to be able to model the temperature distribution within the pavement with increasing depth, by accounting for all the important boundary variables.

## 4. LITERATURE REVIEW

Numerous studies have been conducted on heating and temperature distribution along the depth of asphalt pavements. Of particular interest are the studies that have investigated the effect of different asphalt materials and mix properties on the thermal properties of asphalt pavement layers. Some studies have also been carried out regarding the actual use of heat from pavements.

Southgate (***1***) first presented a method for predicting temperatures in asphalt pavement layers, as a function of depth, time of the day, and the 5-day mean air temperature. Hermansson (**2**) presented a procedure based on finite difference procedure to determine pavement temperatures at different depths using formulas that consider convection short and longwave radiation. Park, Dong-Yeob, et al. (***3***) collected a large amount of temperate data and deflection profiles from various sites in Michigan to investigate how temperature affects the in-place strength of asphalt mixes. The results were validated by using data from other sites. Yavuzturk et al (***4***) presented the results of a study on the use of finite difference method to predict pavement temperature. Temperature predictions using the proposed model were most sensitive to (in decreasing order) variations in absorptivity, volumetric specific heat capacity, emissivity, and thermal conductivity of the mix.

Currently, the most widely cited temperature prediction equations for asphalt pavements are those based on the work by Solaimanian and Kennedy (***5***) and from SHRP and LTPP studies (***6***, ***7***). Solaimanian and Kennedy developed a method that was used mainly for the Strategic Highway Research Program binder and mixture specifications to calculate the maximum pavement temperature profile. The method was based on energy balance and temperature equilibrium at the pavement surface – they measured the data of hourly solar radiation, wind velocity, and emissivity from various test locations. The proposed equation was able to predict the maximum pavement temperature at specific location within 3 °C error, which was within the reasonable limit - considering various environmental factors and measurement uncertainty. The most recent validation of these equations has been from the NCAT test track (***8***). Diefenderfer et. al. (***9***) developed an equation on the basis of work conducted on the Virginia Smart Road project. Data from two randomly selected LTTP-SMP sites was used to validate the equations above. Using the data, new models were formulated which incorporated the day of year and latitude. In their 2002 TRB paper (***10***), Mrawira and Luca describe an approach in which thermal diffusivity and corresponding thermophysical properties are measured. These properties were found to be affected by density, saturation and temperature. Using the estimated thermal conductivities, the authors predicted the transient temperature conditions in an asphalt pavement under changing environmental conditions. They used energy balance equation and Fourier heat transfer equation. They show from their results that the asphalt pavement goes through daily temperature cycles, and the relative amplitude of such cycles decrease with an increase in depth. Subsequently, in their 2004 TRB paper (***11***) Luca and Mrawira describe a laboratory device to observe temperature changes inside a 150 mm diameter asphalt mix sample when subjected to heat from a halogen lamp. The authors conclude that thermal radiation is the most critical factor affecting the rate of change in temperature, which was higher at depths closer to the surface. In their 2005 paper (***12***), Luca and Mrawira point out the importance of getting reliable thermophysical data for the proper implementation of transient temperature models, and that the existing ASTM C177-85 is not suitable for testing HMA.

In some recent work conducted by Chen et al (***13***), temperature distribution along the depth of different types of pavement samples have been investigated in the laboratory. The study showed that temperature profiles along the depth of pavements with different structures/subsurface layers are different, predictive equations for both maximum subsurface and base temperature for pavements with different base layers have significantly different coefficients and that backcalculated thermal conductivity and heat capacity values for similar materials but placed with different densities and gradations and with different base layers are different.

As summarized by Bijsterveld et al (***14***) there are three potential ways of utilizing the heat from pavements. The heat can either be used to provide heating energy to buildings, or used to melt snow on the pavement during winter and keep its temperature at a higher than natural level, or can be extracted away from the pavement during the summer time to reduce the potential of permanent deformation (or rutting). In their paper, Bijsterveld et al describes a finite element modeling study to investigate the effects of providing a heat exchanger system inside the pavement on the temperature distribution, as well as stress, strains inside the pavement. They conclude 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 mention that there is a need to determine the effect of different materials on the thermal and structural properties of the pavement. Hasebe et al (***15***) has reported a study on the use of energy from heated pavements to produce electricity, and use the heat flux away from the pavement to lower high pavement temperatures during summer. Their study involved conducting experiments and modeling to evaluate the effect of the flow rate and temperature of the heat exchanger. They confirmed the significant effect of the temperature of the heat exchanger fluid and the resistance of the thermoelectric modules on the peak power output.

In their recent paper Gui et al (***16***) have presented a mathematical model to calculate the pavement near-surface temperatures using hourly measured solar radiation, air temperature, dew-point temperature, and wind velocity data. Their objective was to determine optimum combination of material properties and/or paving practices to lower air temperature rise caused by paving materials in urban areas. They point out that reflectivity and emissivity have the highest positive effects on pavement maximum and minimum temperatures, respectively, while increasing the thermal conductivity, diffusivity, and volumetric heat capacity is effective in lowering maximum temperatures.

From the literature review, the following general conclusions can be made: 1. A significant amount of work has been conducted to develop models to predict temperatures at different depths of asphalt pavements; 2. A number of significant factors affecting heat flow in asphalt pavements have been identified; 3. Successful laboratory and field experimental setups have been developed; 4. The feasibility of using heat from solar heated asphalt pavements has been investigated.

The current study was initiated on the basis of the above conclusions for optimizing a pavement system for capturing solar energy.

## 5. SCOPE OF WORK

The heat transfer from a pavement heated by solar energy can be enhanced by using a high conductivity material as well as by using an insulating layer on the top that would reduce reflectivity and emissivity. The amount of energy generated can also be increased significantly by increasing the surface area exposed to the sun. To ensure that the pavement is constructed using conventional equipment and techniques, and it is sufficiently durable, the materials that can be used are mineral aggregates, asphalt binder and additives, and the insulating layer on the top has to be either in the form of a powder or a liquid. Accordingly, the effect of higher conductivity material, layers on the surface, and surface area were evaluated in this study. The scope of work included finite element modeling, experiments with small 150 mm diameter, 114 mm thick pavement samples (henceforth referred to as small scale tests) (Hot Mix Asphalt, HMA samples, compacted using Superpave gyratory compactor in the laboratory, and a dense graded HMA mix gradation and asphalt content; all HMA used in this study had PG 64-28 grade asphalt binder), and finally with two 1.8 m long, 0.9 m wide and 125 mm thick slabs.

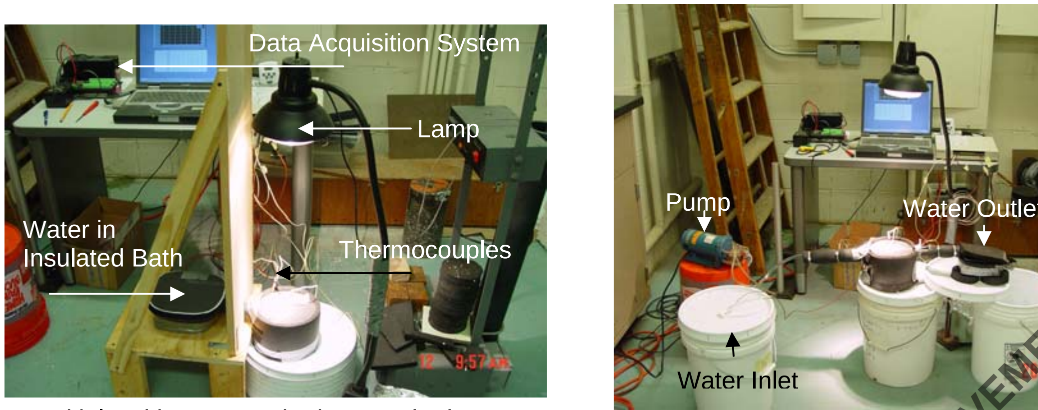
## 6. TESTING AND MODELING

This study started with the preliminary experiments for investigation of temperature distributions in 150 mm diameter pavement samples, which were subjected to heat from a halogen lamp (***13***). Note that this setup was first proposed by Luca and Mrawira (***11***) and has since then been used by Nazarian and Alvarado (***17***). For the current study, this set up was modified – a copper pipe was inserted inside the sample, the other end of the copper pipe was placed in a small bath of water. Initially, the copper tube was used as the "heat exchanger" between the heated HMA sample and the water in the bath, but subsequently, water was pumped through the copper tube, and used as the heat exchanger. Thermocouples fixed to the sample at different heights, and the bath/inlet and outlets were connected to a data acquisition system, which allowed continuous recording of temperature. The initial and final test setups (referred to as small scale tests) are shown in Figure 2.

The relative position of the heating lamp over the HMA sample was selected to provide 1,000 W/m$^2$ of radiation (average summer time radiation in Worcester, MA area). The objective was to investigate change of temperature in the water caused by conduction of heat from a heated HMA sample for a time span of 6 hours, and as well to evaluate the effect of thermal conductivity. Along with these preliminary tests, simulations with finite element modeling (of the setup) were conducted with COMSOL (***18***) software. A typical model and results are shown in Figure 3. Small scale tests were carried out with a number of laboratory compacted HMA samples. The different aggregates used for these samples were quartzite and limestone, as well as locally available aggregates (in mixes).

In the second phase, tests were carried out with large scale slabs. Two slabs were prepared – each with approximately 125 mm thick HMA layer, with a frame of copper tube (Figure 3) embedded inside. The copper tubes were provided for pumping water (heat exchanger) through the slab. Thermocouples were inserted along the depth and at various points in the slabs, including points in line with the copper tube locations, and inlet and outlet points of the water flowing through the copper tubes. Two types of materials were used for preparing mixes for the two slabs. The entire 125 mm thickness of the first slab was prepared with a mix obtained from a local HMA plant (using aggregates identified as greywacke, with quartz and feldspar), whereas the second slab was prepared with the local mix for the bottom 64 mm, and quartzite aggregate mix (prepared in the laboratory) in the middle and the top layers. Mixes with both aggregates were made with the same gradation and asphalt content. Copper tube frames with multiple tubes along the width and one tube along the length were placed approximately 38 mm below the surface in both slabs, during placement and compaction inside wood carts. The schematics of the two slabs, with copper tube frame as well as thermocouple locations are shown in Figure 4. Note that for all of the testing and analysis, the difference in temperature between initial and final water temperature or between incoming and outgoing water (Delta T) was used as an indicator of the "efficiency", E, of the system, which can be represented as:

$$E = \frac{MC(T_{out} - T_{in})}{GA}$$




Initial - with copper tube in water bath

Final – water pumped through copper tube

**Figure 2:** Small scale test set-up

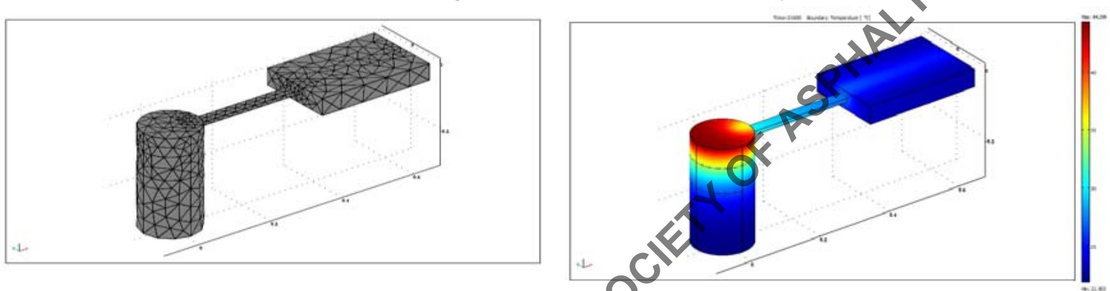


**Figure 3**: FEM Model of test setup and results from simulations

Where, E = efficiency
M = mass of water, g
C = specific heat of water, J/kg
$T_{out}$ = temperature of outgoing water, or final temperature of water in a bath, °C
$T_{in}$ = temperature of incoming water, or initial temperature of water in a bath, °C
G = radiation, W/m$^2$
A = area of heat conduction = (pi*pipe diameter * length of pipe inside HMA), m$^2$

**Small scale versus large scale testing**

The factors that were evaluated either with small scale testing or with slab testing or both are:

1. Aggregate with high conductivity; 2. High conductivity material; 3. Absorptivity enhancing paint ;
4. Partial replacement of granite aggregate with quartzite

All of the small scale testing was conducted inside the laboratory without any wind and at constant radiation of 1,000 W/m$^2$, whereas the slab tests were done outside in the presence of natural sunlight and wind. The small scale samples were compacted using 75 gyrations of a Superpave gyratory compactor, and the slab mixes were compacted with a 36.29 kg, 0.5 m wide roller (Figure 4d). The temperature distribution along the depth of a small sample and a slab of the same mix (quartzite aggregate) are shown in Figure 4.

**Comparison between quartzite HMA performance under controlled conditions and outdoor:**

Figure 5 shows the difference in the temperature profile attained after approximately six hours of heating between the small sample and the slab. An immediate look at the profiles

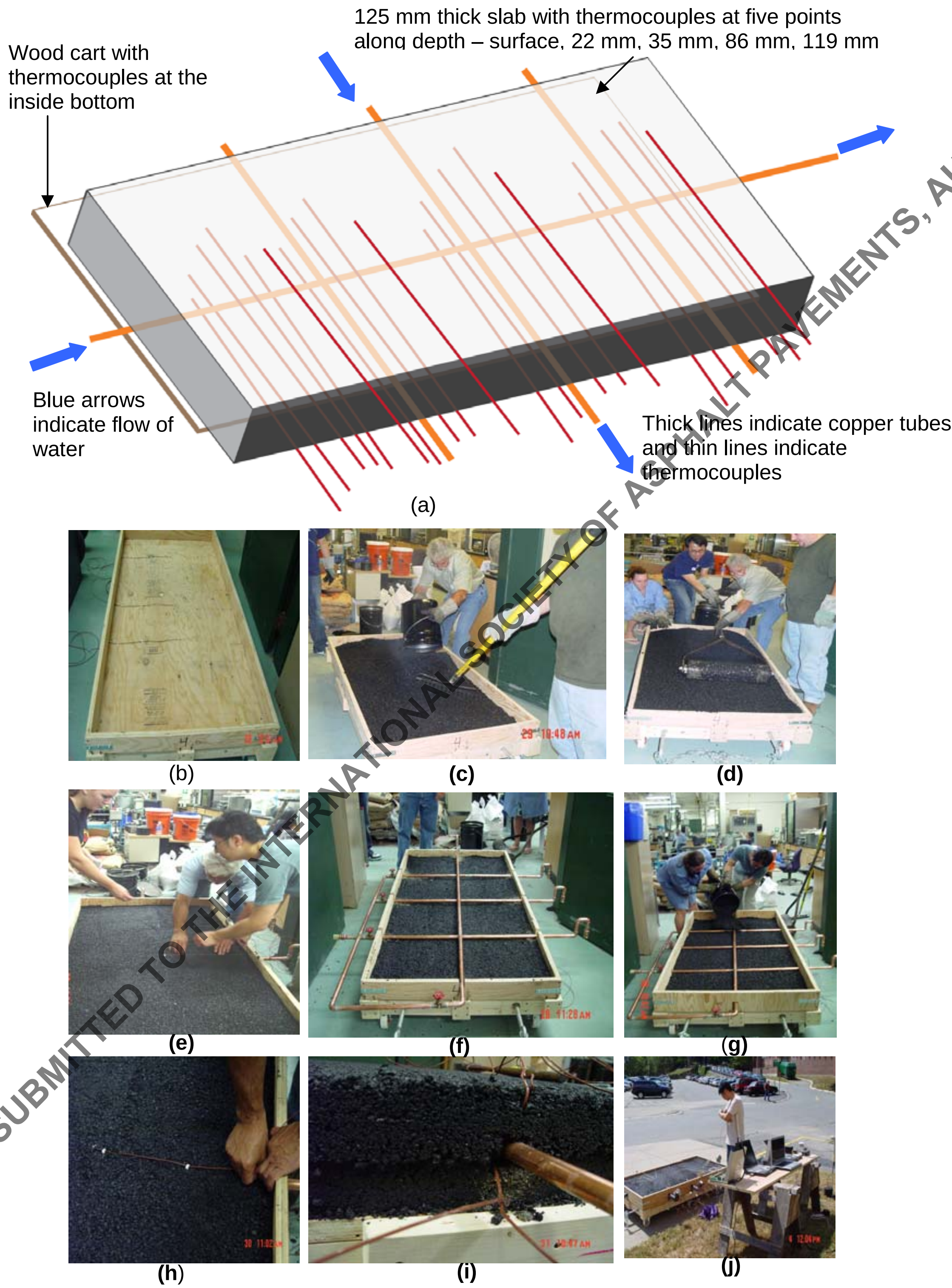



**Figure 4:** (a) Schematic of the slab; (b) Cart with thermocouple at the bottom; (c) Laydown of mix; (d) Compaction; (e) Fixing thermocouples; (f) Copper tube frame; (g) Covering up copper tube frame; (h) Close-up of fixing thermocouples; (i) Close-up of slab showing copper tube and thermocouples at different depths; (j) Completed slab ready for testing

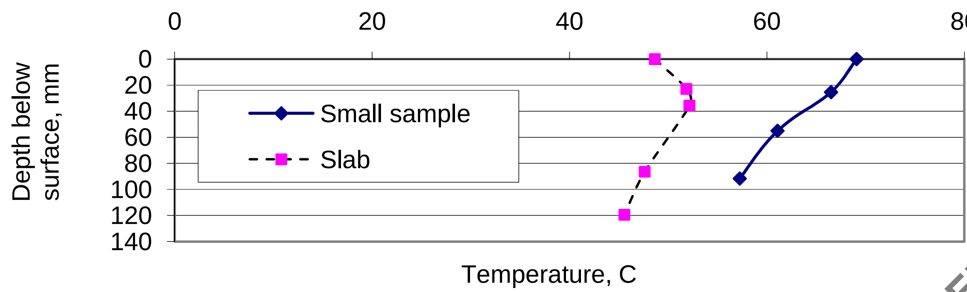



**Figure 5:** Comparison of two quartzite samples heated under laboratory and real solar radiation conditions. Thickness of the small sample = 100 mm, Thickness of slab= 119 mm; Sample heated with 1,000 W/m$^2$ radiation for 6 hours with no wind; slab heated for 5.7 hours with solar radiation of an average of 716 W/m$^2$ with 4.8 km/h wind

show that there is a temperature gradient in the slab that indicates that the convective heat transfer process on the slab surface offers little resistance to heat transfer (Biot number, ratio between the internal resistance to the transfer of heat and the resistance to the transfer of heat offered at the boundary >1), and convective coefficient is of the same order or higher compared to conduction. Therefore, it is important to characterize the temperature profile within the sample in order to ascertain optimal depths for placing heat exchanger. As seen in the small sample with a steady radiation heating, the temperature profile follows a slope of decreasing temperature from the surface. The slope decreases a bit towards the lower end of the sample indicating some non-linearity in the profile. The slab has a stronger convective boundary condition on the top because of wind and a lower (and variable) solar radiation. This leads to lower temperature profiles with the surface temperature, approximately 50°C. The effect of convection is illustrated in a non-linear profile with temperature maxima somewhere between 25-28 mm below the surface. Similar results have been reported in other studies of temperature profile characterization of pavements (**1-12**). After reaching the maxima, the slope of the temperature profile is similar to that of the small samples; differences in slope can be attributed to the difference in thickness between the small sample and the slab.

## 7. RESULTS

Since more than ninety five percent of HMA consists of mineral aggregates, the first set of simulations was carried out to evaluate the effect of thermal conductivity of the aggregates on the heating process. Assuming that the conductivities (K) of the mixtures are primarily influenced by the conductivity of the aggregates, K values of 5.38 and 2.15 W/m-K were used to represent quartzite (consisting of mainly quartz) and limestone aggregates (representing approximately two extremes of K for aggregates) mixes, respectively. The K values were obtained from Reference (***19)***. The results of the FE simulations confirmed the significant effect of thermal conductivity of the HMA on the change in temperature of the water bath – a delta T of 22.77 and 18.55 °C were noted for the quartzite and the limestone samples, respectively.

Based on these results, two different types of aggregates, quartzite and limestone, were actually procured for subsequent laboratory testing. The quartzite aggregate, consisting of approximately 95% quartz and with traces of hematite (giving it a pink color) was obtained from New Ulm quarry, MN. This aggregate is currently used mainly for poultry and traction grit as well as for railroad ballast and surface seal mix aggregates. The limestone aggregate, typically used in HMA mixtures, was obtained from Calera, AL.

Two HMA samples were prepared, one each with quartzite and limestone aggregates. Rise of temperature in water was noted from tests conducted with the small scale experimental setup described above. The results (Figure 6) showed that the sample with quartzite aggregate had a significantly higher temperature difference (between original water temperature and final water temperature) compared to the limestone aggregate mix. The comparison reveals that the higher heat capacity of quartzite (1.5 times higher) and conductivity (2.5 times higher) are clearly beneficial in heating water by extracting heat from depth inside the pavement (via copper tube inserted at a depth of 25 mm). The water was heated by approximately 10°C for the quartzite sample over 6 hours as opposed to 5°C for the limestone sample. This shows preliminary evidence that altering the pavement material will allow us to extract higher amount of heat energy from the pavement for similar radiation conditions.

From this point onwards, all small scale laboratory tests were conducted with HMA samples with quartzite aggregates, and water was flowed through the copper tube to capture the heat energy. Since a higher conductivity would help in obtaining a higher rate of energy transfer, a metal with high conductivity, copper (K = 401 W/m-K) – was used by replacing about 22% of the quartzite aggregate. The copper powder was mixed with the aggregates prior to mixing with the asphalt binder. The sample was tested at different flow rates of water. A comparison of delta T for samples with and without copper is shown in Figure 7. No significant increase in delta T was observed for the copper-HMA sample. In fact, the delta T was reduced with the introduction of copper. This could be due to the fact that the copper was covered with asphalt during mixing and also was partially oxidized during the heating of the aggregates prior to mixing.

The sample with copper was then covered with a layer of acrylic paint to observe any effect on delta T. As Figure 8 shows, a significant increase in delta T was observed. This test with acrylic paint proves that there can be a significant rise in temperature due to a lowering of the reflective radiation losses and/or increase in the absorptivity on the surface. For certain flow rates the temperature rise is 40% more for the acrylic painted sample compared to the unpainted sample.

Based on the results obtained so far, it was argued that a partial replacement of locally available aggregates with quartzite aggregates would significantly increase delta T. Two samples were prepared and tested to investigate this – one with 100 % locally available reclaimed asphalt pavement (RAP) materials (with aggregate from bedrock characterized as biotite-quartz-plagioclase granofels)) and the other with 75% RAP and 25 % quartzite aggregate. As Figure 9 shows the addition of quartzite has a significant positive effect on delta T.

While both aggregates of higher conductivity and absorptivity enhancing paint layer can improve the efficiency of heat capture, as mentioned earlier, the most important advantage of this system is the large surface area of available paved surfaces, and the ability to utilize it. Theoretically, one can argue that a pipe system carrying water through a large surface area would be more efficient in terms of heat transfer. To evaluate this, in the next step, tests were carried out with slabs (described earlier). The basic objective was the same as that in the case of small scale tests – to determine delta T for locally available aggregates (greywacke, with quartz and feldspar) and a quartzite mix, and evaluate its change with a change in flow rate of water.

Temperature data was first collected for both slabs without flowing any water. The data received from the thermocouples inserted at various points were used to determine the temperature profile within the slabs. Next, a hose was connected from the same water supply

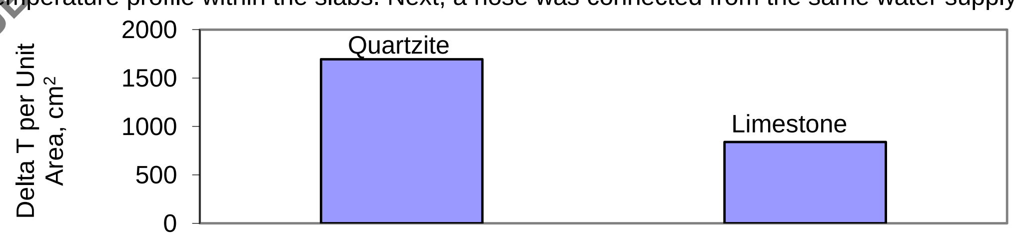



**Figure 6:** Effect of aggregate type

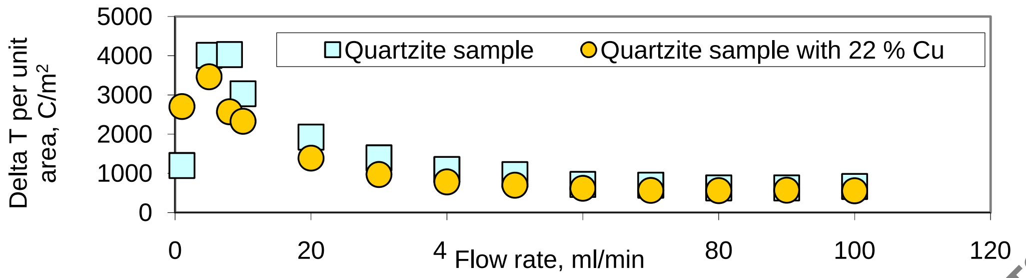



**Figure 7:** Effect of Copper

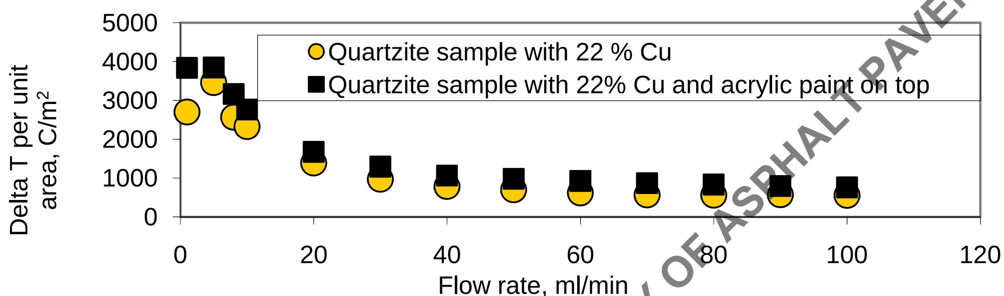



**Figure 8:** Effect of acrylic paint

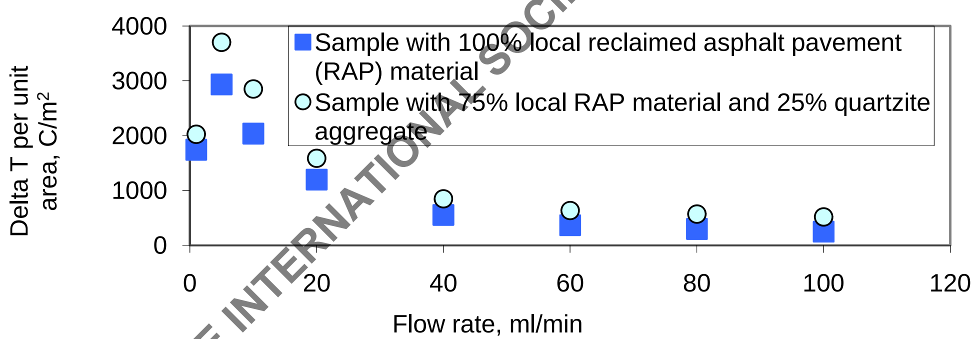



**Figure 9:** Effect of partial replacement of non-quartzite aggregate mix with quartzite mix

to pump water through the copper tubes in both slabs at the same rate. First, before flowing any water, the slabs were kept under the sun for approximately two hours, and temperatures at the various depths at the center of the slabs were recorded. Next, water was pumped at 1, 2, 3 and 4 l/min through both slabs at the same time, and temperature of the slab at the middle copper tube location as well as incoming and outgoing water were measured (Figure 10).

Figure 11 illustrates the temperature profiles over time at different depths over a period of 3 hours. As clearly indicated by the temperature profiles of thermocouples placed with increasing depth, temperature is a function of depth, with thermocouples placed closer to the surface recording higher temperature at any instant of time. This process is consistent through all the reading and progressive depths. However, an important observation from these sets of graphs is that the time at which steady state is reached at different depths vary. At 12.5 mm depth, steady state is reached quickly (the scatter in the data induced by solar radiation fluctuation and wind velocities make the exact prediction impossible). At 25 mm steady state is reached in 60-80 minutes. The lowest 2 thermocouples at 75 mm and 132 mm ft never reach steady state in the three hour span. The results indicate that the depth at which the pipe is placed is clearly important for problems like this as seen from the graphs. At a hypothetical depth of 25 mm a somewhat steady state temperature of approximately 43°C can be obtained for heating pipes whereas at 25 mm the temperature is 41°C and transient for a longer period [Note: this is based on the observations over the 3 hour period; however as indicated earlier, this problem will remain a transient problem over time and some temperature difference will be there with depth].

As shown in Figure 12, variation of temperature profile with spatial location (at any given depth) was minimal. This signifies that edge effects of the boundary were negligible and the heat transfer problem is largely one dimensional. Figure 13 shows that, with increasing flow rate the temperature rise of water flowing through a pipe is reduced. The temperature rise is generally more for the longer tube because of the higher area of heat transfer available due to the longer length. This translates into more power being extracted

**Figure 10:** Data Acquisition from both slabs with water flowing through copper tubes

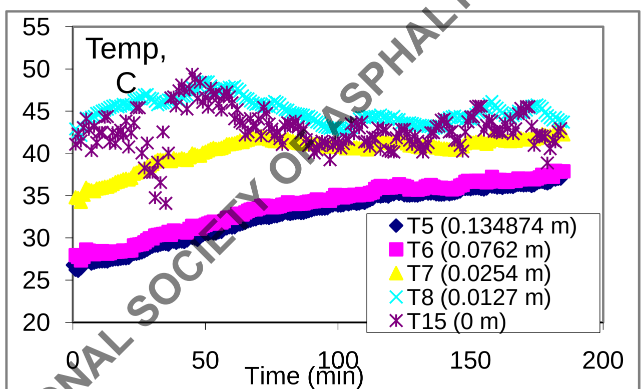



**Figure 11:** Plot of temperature vs. time at different depths (HMA)

by flowing the water through a longer tube. The results indicate the beneficial effect of having heat exchangers with a large surface area exposed to the pavement for extraction of heat. A comparison between Quartzite and non-quartzite-HMA blocks show that the power extracted from the quartzite pavement is higher for flow rate of 1 and 3 liters/min, whereas the non-quartzite HMA block shows more power output for the long tube at 4 liters/min.

## 8. CONCLUSIONS AND FUTURE WORK

The conclusions and recommendations from this study can be summarized as follows: 1. The use of a higher conductivity aggregate, such as quartzite, can enhance the heat transfer efficiency to a significantly higher degree. 2. To increase heat transfer, the use of a higher conductive aggregate is most likely a much better alternative to using commercial high conductivity additives (e.g. cooper powder) because of practical concerns 3. The use of a reflectivity decreasing/absorptivity increasing paint on the surface of the pavement can enhance the heat transfer efficiency, 4. The depth of heat exchanger is critical, and 5. An effective heat exchanger design will be the key in extracting maximum heat from the pavement. The future work of this study will be focused on improving the heat transfer from the pavement materials to the heat exchanger fluid through the use of appropriate materials, better contact, and optimum geometry of the heat exchanger system.

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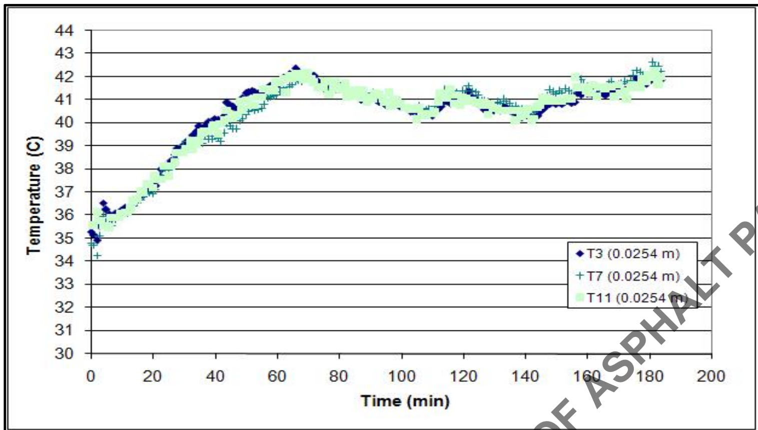


**Figure 12:** Temperature readings at a depth of 25 mm at different locations in the slab.

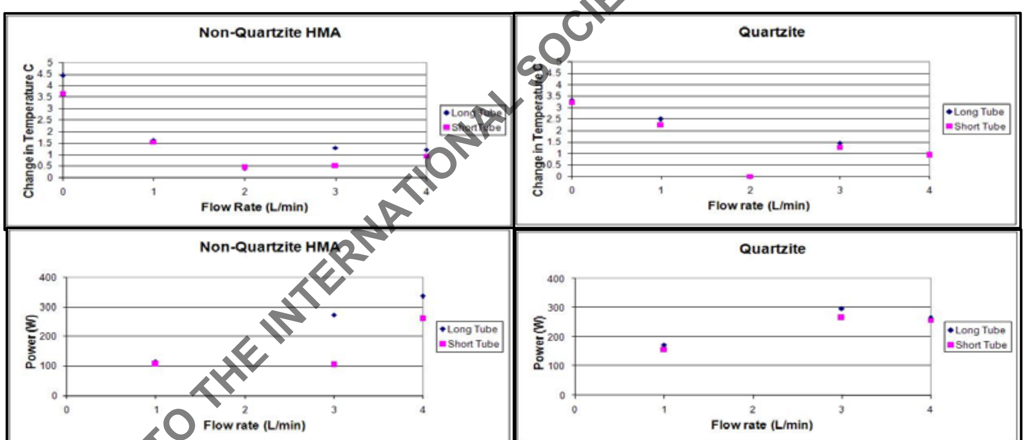


**Figure 13:** Plot of ΔT (between outlet and inlet water temperature) and power extracted at different flow rates from tubes that were 1.5 m (long tube) and 0.9 m (short tube) for Quartzite and non-quartzite-HMA slabs.

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