HARVESTING ENERGY FROM ASPHALT PAVEMENTS AND REDUCING THE HEAT ISLAND EFFECT – WHITE PAPER-1

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This white paper presents the concept of using a piping network below the surface of asphalt pavements to flow an appropriate fluid, to reduce the temperature of the asphalt pavement, reduce Urban Heat Island Effect, and use the heated fluid for different end applications such as heating, power generation or refrigeration. The reduced temperature will extend the life of the pavement, while the reduced temperature of the near surface air will lead to savings in energy consumption of adjacent buildings and improvement in air quality (such as by reducing ozone concentration).

The concept is illustrated in **Figure 1**.

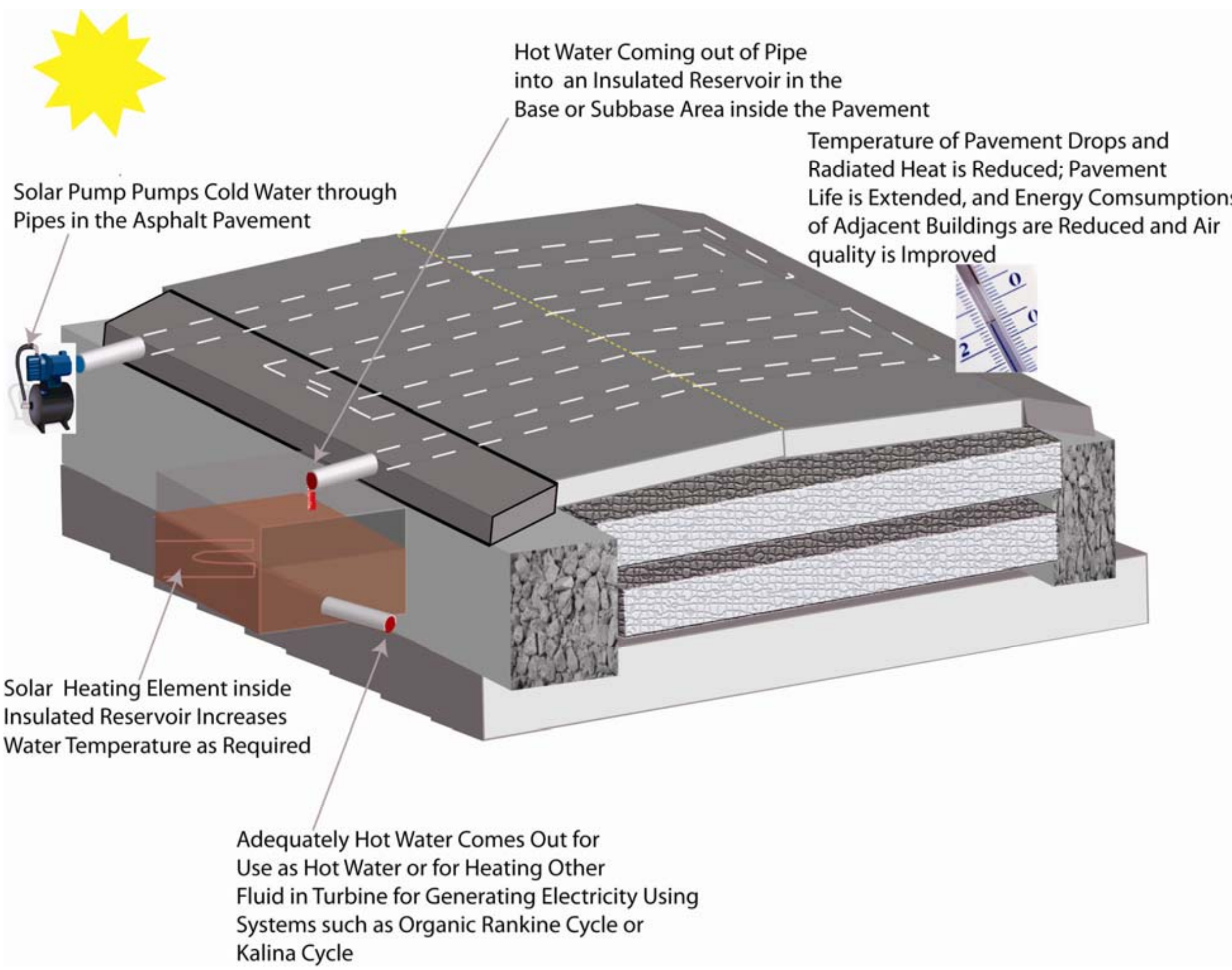


Figure 1. Concept of Harvesting energy from Pavements and Reducing Pavement Temperature

The **objective** of this paper is to present the facts and figures on the concept of using fluid in pipes to harvest energy from asphalt pavements and reduce the temperature of the pavement, to reduce the amount of heat that is radiated back from the pavement surface to the atmosphere (urban heat island effect), and reduce the high temperature related permanent deformation potential of the pavement.

The content of this paper is based on research that has been conducted so far by the authors of this paper at Worcester Polytechnic Institute (WPI).

Your comments and suggestions/inputs are most welcome.

Basic Considerations

Solar energy, in the form of radiation (also referred to as insolation), falls on the earth's surface (after parts of it being scattered in the atmosphere). The amount of radiation hitting a specific location on the earth's surface depends on a number of factors, namely,

- The month of the year
- Solar Altitude angle, α (angle between a line collinear with the sun's rays and the horizontal plane; note, solar zenith angle, $z = 90^o - \alpha$)
- Extraterrestrial solar radiation I
- Clearness number, C_n (difference between local and average sea level condition)

Detailed formula and explanation of the various terms are presented below.

$I_h = C_n I e^{-k/\sin\alpha} (C + \sin \alpha)$ (1)

$I = I_0 (D_0/D)^2$

I_0 = solar constant = 1,377 W/m^2

$(D_0/D)^2 = 1.00011 + 0.034221\cos(x) + 0.00128\sin(x) + 0.000719\cos(2x) + 0.000077\sin(2x)$

(2)

Where,

D_0 = yearly mean earth-sun distance = $1.496 * 10^{11}$ m

D = distance between the sun and the earth

$X = 360(n-1)/365^o$

n = Day number (starting from January 1 as 1)

Approximate relation:

$I = I_0[1 + 0.034\cos(360n/365.25)^o]$

Several different models are available for determination of radiation throughout the day and throughout the year (for example, Bird, R. E., and R. L. Hulstrom, *Simplified Clear Sky Model for Direct and Diffuse Insolation on Horizontal Surfaces*, Technical Report No. SERI/TR-642-761, Golden, CO: Solar Energy Research Institute, 1981, Macro-enabled spreadsheet available from http://rredc.nrel.gov/solar/models/clearsky/)

Asphalt pavements, such as those found in many parking lots, get heated up by the sun. The reason is while light colored surfaces reflect sun light, asphalt mixes do not reflect that much, but absorbs the solar radiation more. While shady trees prevent the solar radiation from reaching the pavement, and grass and plants utilize solar radiation for evapotranspiration, bare asphalt pavement surfaces absorb heat and then radiate the heat back to the atmosphere. This leads to an increased temperature of the air around asphalt pavement surfaces (such as parking lots) – contributing to what is known as the urban heat island effect.

Rise in air temperature leads to an increase in energy and water consumption, and indirectly contributes to the formation of smog and ozone production, which leads to significant health concern. With the potential for the doubling of the human population in the next 5 decades, and the resultant increase in the percentage of the population living in urban areas unmodified urban heat island effects have the potential to significantly impact sustainability. The extent of the problem is significant since more and more pavements are being constructed and it has been stated that the added volumes of pavements make up 29-45 percent of the urban area. A large portion of this is due to parking; in the Houston metropolitan area, the parking facilities account for approximately 60 percent of the transportation land use. The predominant surface type in pavements is asphalt.

Because of the presence of the asphalt binder, asphalt pavement material (or mixture, mix) behaves as a viscoelastic material. It exhibits higher stiffness at lower temperatures and relatively lower stiffness at higher temperatures (see **Figure 2** as an example). Consequently, the potential of shear stress related deformation (rutting) increases at higher temperatures. Rutting is one of the most important distresses in asphalt pavements.

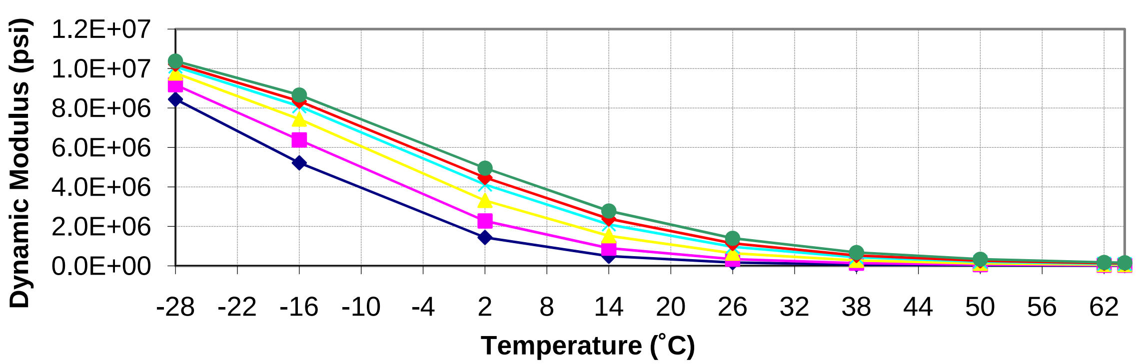


Figure 2. Effect of temperature on dynamic modulus of asphalt mix

For the asphalt mix part, the plastic strain is basically modeled as follows:

$$\frac{\varepsilon_p}{\varepsilon_r} = aT^bN^c$$

Where: ε_p=accumulated plastic strain at N repetitions of the load; ε_r= resilient strain of the asphalt mix, which is a function of the mix properties, temperature and time of loading, N =

number of load repetitions, T = pavement temperature and a, b and c are non-linear regression coefficients.

What are the factors involved in heating up of asphalt pavements?

There are four predominant mechanisms: solar radiation in and emitted radiation out of the pavement, conductive transfer of heat through the pavement, and convective transfer of heat above the pavement through wind.

Consider the following schematic (**Figure 3**).

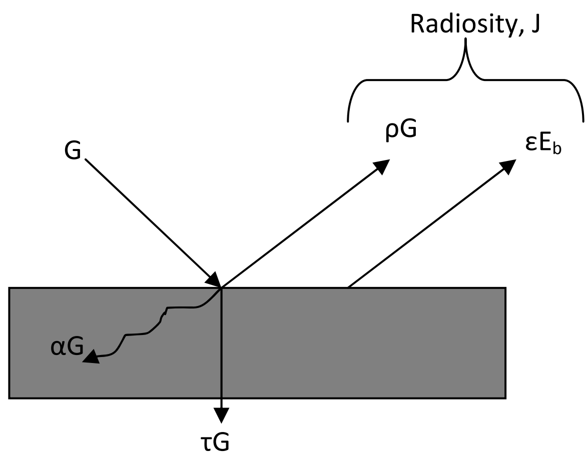


Figure 3. Energy Balance on the Surface of a Grey Body (after Introduction to Thermal Sciences, Schmidt et al, **3**)

G = solar radiation; J= Radiosity (total energy leaves from object); E_b= Energy from a Black body (perfect absorber); α= absorptivity; ρ= reflectivity; τ= transmissivity; ε= emissivity.

Albedo or reflectivity is defined as the ratio of the reflected radiation to the incident radiation; for asphalt pavements it is close to 0.09 or 0.1. Measured (with pyranometer) values at WPI (outside) show G, incident radiation as 1,050 W/m^2 and reflected radiation as 95 W/m^2, yielding an albedo or reflectivity value of 0.09.

The emissivity if a body is defined as the ratio of the energy emitted by a real body to the energy emitted by a black body. For asphalt pavements, it is considered as 0.9 **(4).**

The emissivity and the absorptivity (which is the ratio of absorbed radiation to incident radiation) are equal for a gray body (a body whose monochromatic emissivity and absorptivity are independent of wavelength and direction).

For engineering calculations, the radiation characteristics of the surface of a real body can be approximated by those of a gray body (3), and hence for a real body the emissivity can be considered to be equal to the absorptivity.

Now, for an incident radiation, G, the sum of absorptivity (α), reflectivity (ρ) and transmissivity (τ) for a surface equals one. If there is no transmissivity (transmissivity, τ = 0), then the sum of absorptivity and reflectivity equals one.

Hence, reflectivity (or albedo) = 1- absorptivity (which can be approximated to be equal to emissivity). So, if the emissivity of asphalt surface is considered as 0.9, the albedo will be approximately (1-0.9) = 0.1
Conversely, if the albedo of a pavement surface is changed to 0.4 (by covering the surface with a light colored paint, for example), then the emissivity = 1-0.4 =0.6

If the asphalt pavement was a good conductor of heat, the heat would have been transmitted in a relatively short period of time through the underlying layers. However, it is not.

How much heat is radiated back from the pavement to the air?

The amount of heat that is radiated from the surface of the pavement is governed by the difference of the temperature between the pavement surface and the air, according to the following equation:

$$q_r = \varepsilon\sigma(T_s^4 - T_{air}^4)$$

Where q_r = emitted radiation, ε is the emissivity of the material, σ = Stefan-Boltzmann constant = 5.68×10^{-8} W/($m^2 \cdot K^4$), T_s is surface temperature in Kelvin, T_{air} is air temperature Kelvin.

Proposed Concept

The proposed concept is that by flowing an appropriate fluid through a network of pipes in the pavement, the temperature of the asphalt pavement surface can be reduced, while the heated fluid may be used for different end applications such as heating, power generation or refrigeration. The reduced temperature will lead to a relatively higher stiffness of the asphalt pavement, specifically in hot climatic conditions, and will reduce or prevent deformation, and hence extend the life of the pavements.

How much energy can be harvested from pavements?

How much useful energy can be harvested from an asphalt pavement? The answer depends on:

A. How much energy falls on the pavement (that is amount of solar radiation)?
B. What is the total area of the pavement that is being considered?
C. How efficient is the pavement-heat exchanger system in transmitting the heat from the pavement to the fluid inside the system of pipes
D. How efficient is the turbine in converting heat energy to electrical energy?

Let's discuss each of the above topics.

A. The amount of solar radiation that reaches the pavement surface depends on:
1. The geographical location of the pavement
2. The specific day of the year
3. The presence or absence of cloud cover

The solar radiation is often expressed in $kWh/m^2/day$, for example 5 $kWh/m^2/day$. If this number is divided by 24, one gets the radiation in W/m^2 (for example 5,000 $Wh/m^2/day$ divided by 24 gives 208 W/m^2).

B. The total area of the pavement refers to the total area from which the heat energy is being collected. This gives the total energy that is available to us. For example, for a radiation of 5 $kWh/m^2/day$, and a parking lot of 45 m by 45 m (which is approximately 150 ft by 150 ft), the total energy available to us is (5)*(45*45) = 10,125 kWh/day.

C. The efficiency of the pavement-heat exchanger system in transmitting the heat from the pavement to the fluid inside the system of pipes depends on a number of factors, including:
   1. Type of pavement surface
   2. Type of pavement materials above, around and below the heat exchanger system
   3. The materials, layout and dimensions of the heat exchanger components
   4. The working fluid inside the pipes of the heat exchanger system
   5. The initial temperature and the flow rate of the fluid

1. The pavement surface actually collects the incident solar radiation. If it is a highly reflective surface (high albedo) then very little heat will be absorbed and be available for harvesting. If on the other hand, the absorptivity is increased (say by painting the surface black), then we will have more heat energy to harvest.

2. The function of the pavement materials depend on their location with respect to the heat exchanger system. For the materials in the layers above and around the heat exchanger system, the ideal function should be to transmit the heat (or conduct the heat, more approximately) in the most efficient manner. The function of the materials in the layer beneath the heat exchange system should be to insulate the system from the bottom layers, such that very little heat can be transmitted through the bottom layers.

3. The material of the heat exchanger system (which consists of pipes) should have a high conductivity and the layout should be such as to allow the exposure of the pipes to the pavement for sufficient length to allow the fluid to reach the maximum temperature achievable in the system. Additionally, the diameter/area of the pipes should be such as to allow the pumping of fluid at optimum flow rates.

4. The working fluid inside the pipe should be such that it can be pumped easily and can absorb the energy quickly. In applications where vaporization of the fluid is required, the fluid should ideally have a low boiling point.

5. The initial temperature of the fluid (that is the temperature of the fluid as it enters the heat exchanger system) should be low enough, in comparison to the temperature of the pavement, such that the there is significant difference between the two, and hence a significant rate of flow of heat into the fluid.

   Considering all of these, if the efficiency of the pavement heat exchanger system is considered to be 15%, then the heat energy that can be harvested is (continuing with the example in step B):

   10,125*0.15 = 1,518 Kwh/day

D. Efficiency of the turbine in converting heat energy to electrical energy
   The energy that is captured from the pavement is in the form of heat energy. It may or may not be used as heat energy – for example, it could be transferred into electrical energy. The efficiency of the specific equipment that is used for converting this heat energy to the electrical energy, is important. Because, taking into consideration that efficiency, the heat energy form the pavement should be such as to result in meaningful electrical energy output.
   So, if the efficiency of the turbine is considered to be 20%, then the electrical energy that can be harvested from the pavement is:

   1,518*0.2 = 303 kWh/day

However, there is a caveat. In order for the turbine to work at 20% efficiency, there should be a minimum temperature difference between the high and low temperatures of the working fluid, or, for a given low temperature, there is a minimum high temperature that the fluid must reach.

Now considering the pavement temperatures, it is obvious that the maximum temperature the fluid will reach is the temperature of the pavement at the depth of the pipe location.

How hot does it get inside the pavements?

The temperature at any depth of the pavement depends on the pavement materials and the surface temperature, which depends on a number of factors including the location, surface, the the wind speed and the cloud cover.
Based on available models, pavements temperatures at different depths can be predicted throughout the year.

The predictions can be accomplished through the following steps:

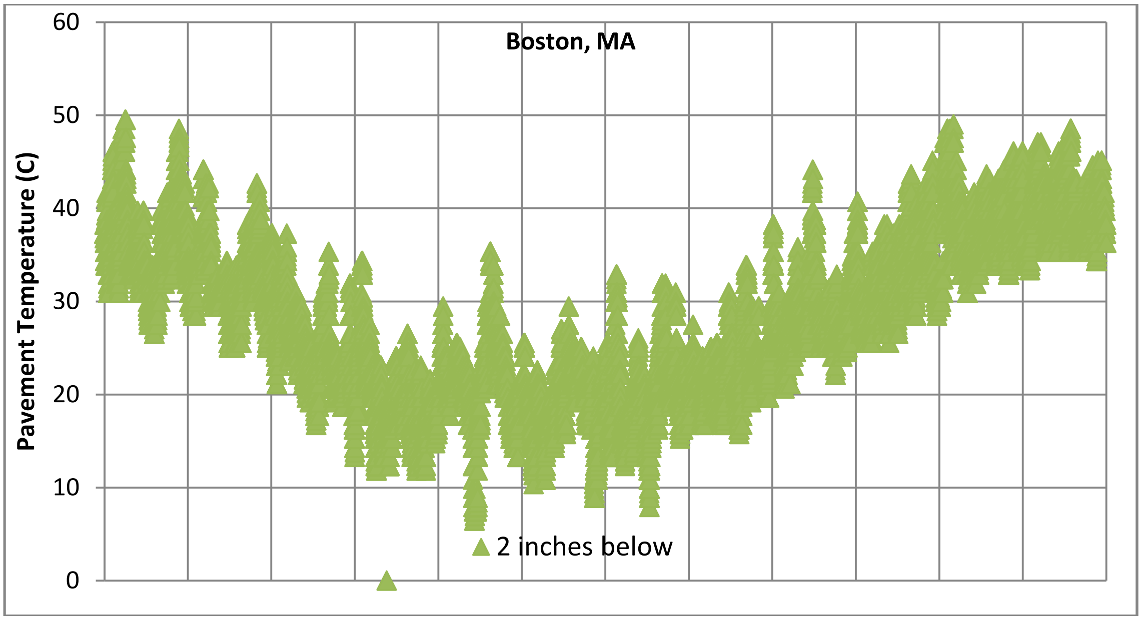
1. Collect air temperature data from NOAA website **(5)** **(http://cdo.ncdc.noaa.gov/pls/plclimprod/poemain.accessrouter?datasetabbv=DS3505)**
2. Predict surface temperature using statistical model
3. Predict temperatures at different depths, using statistical model

Note that in reality, the *surface* temperature is less than predicted, because of convective heat transfer due to the presence of wind. Generally, the maximum heat is at a depth of approximately 1 inch below the surface.

Examples of regression equations developed to predict the temperatures at any depth of the pavement are as follows:

Temperature at the surface	$T_{surf} = T_{air} - 0.00618\, lat^2 + 0.2289\, lat + 24.4$ Where, T is expressed in ^oC and the latitude is in degrees.	Solaimanian and Kennedy, 1993 (**3**), Huber, 1994 (**3a**), Solaimanian and Bolzan, 1993 (**3b**)
Temperature at different depths	$T(d) = T(surf)\,(1 - 0.063\, d + 0.007\, d^2 - 0.0004\, d^3)$, Where, T(d) and T(surf) are in ^oF and the depth, d, is in inches.	

According to these regression equations, pavement temperature at different depths throughout one year were calculated for the cities of Houston, TX, Jacksonville, FL, Reno, NV, Atlanta, GA, Boston, MA. Albuquerque, NM, Nashville, TN and Los Angeles, CA. As examples, temperatures at a depth of 2 inches for the different cities are shown in **Figure 4**.



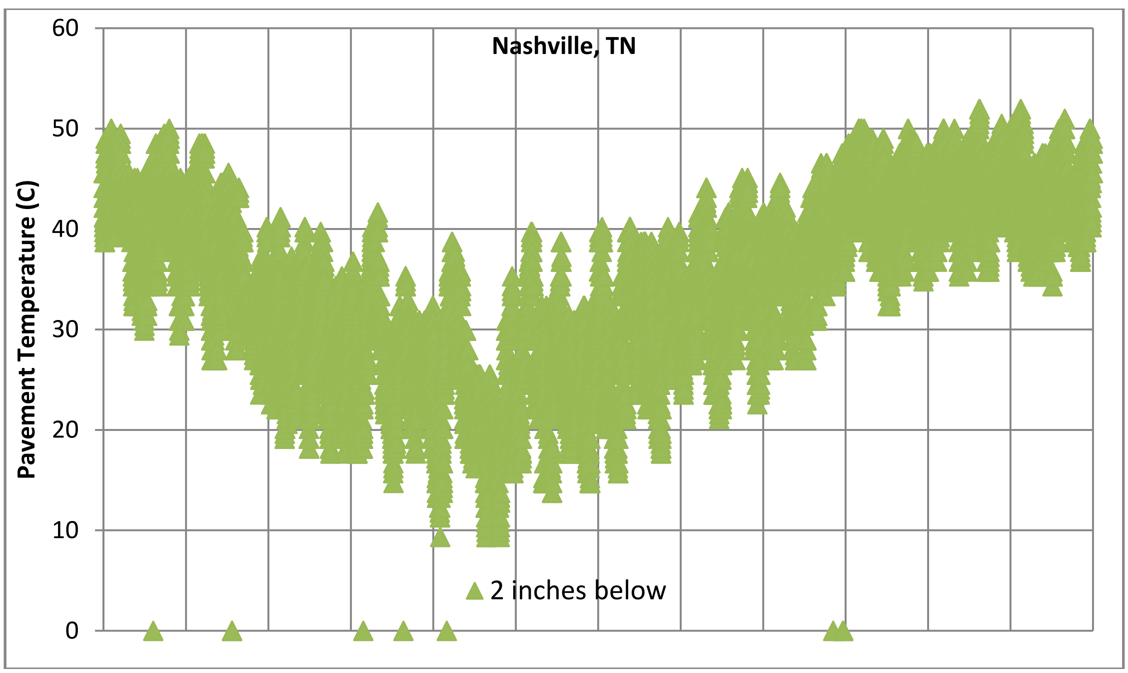
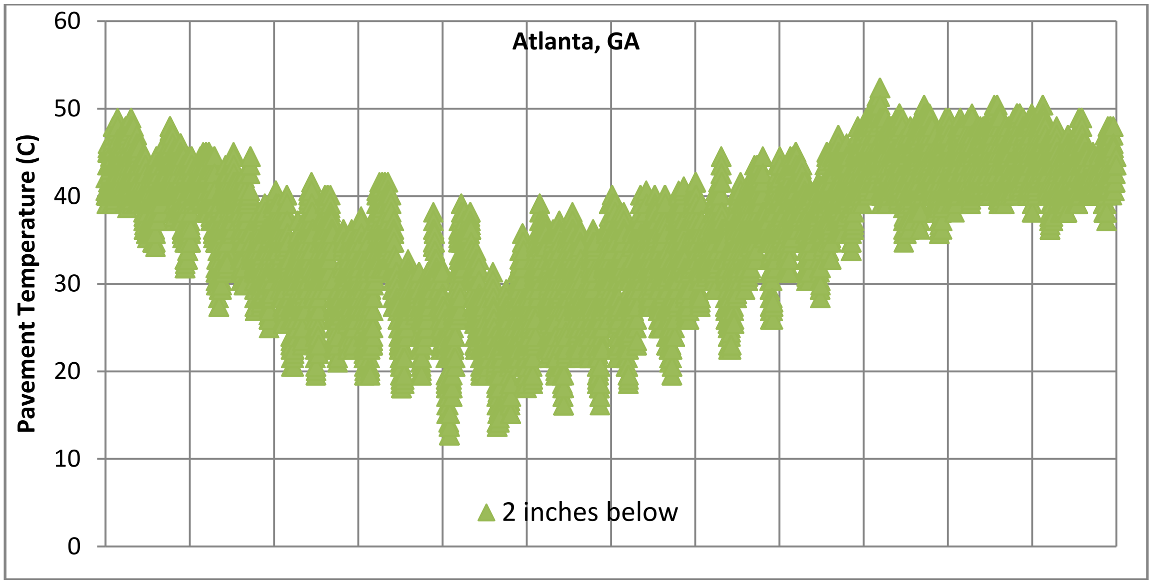


Figure 4. Estimated hourly temperature, on the basis of air temperatures, at a depth of 2 inch for the period of September 1, 2007 to August 31, 2008



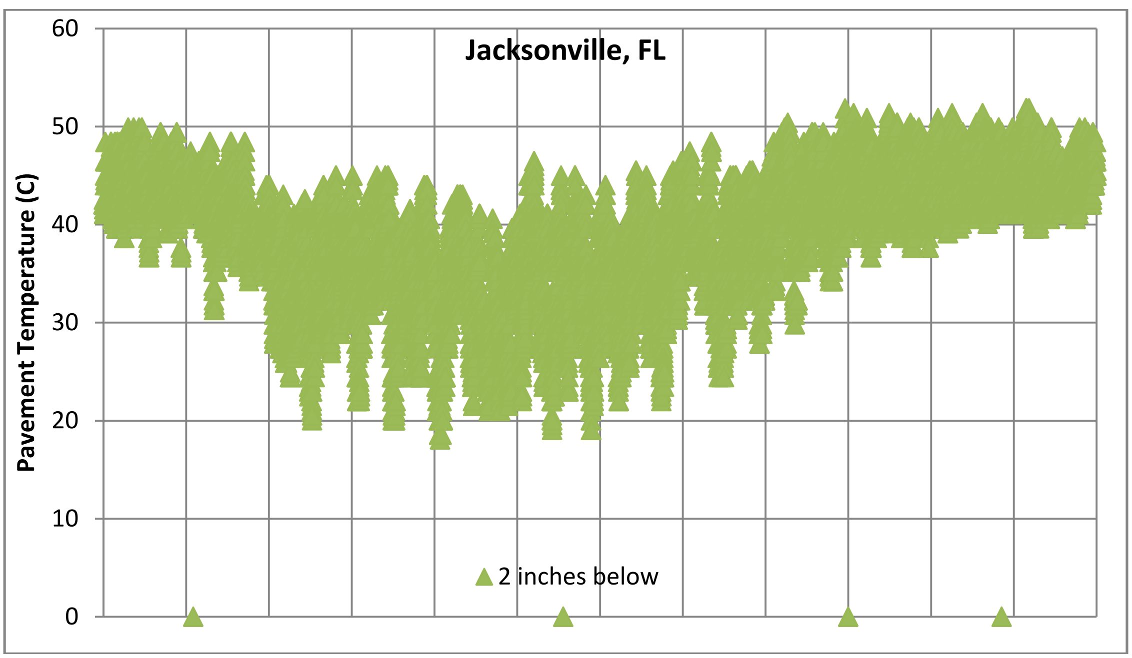


Figure 4. Estimated hourly temperature, on the basis of air temperatures, at a depth of 2 inch for the period of September 1, 2007 to August 31, 2008 (continued)

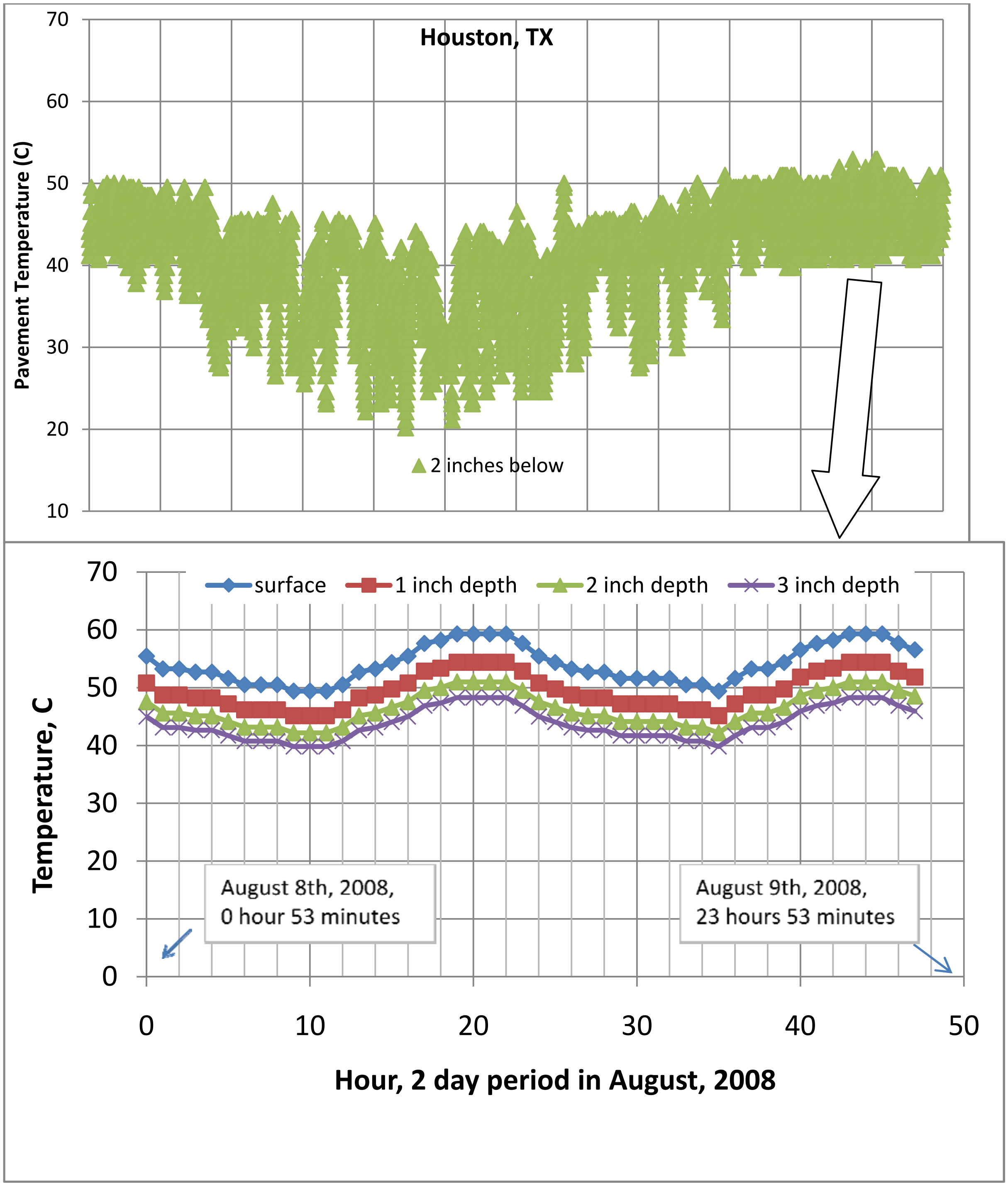
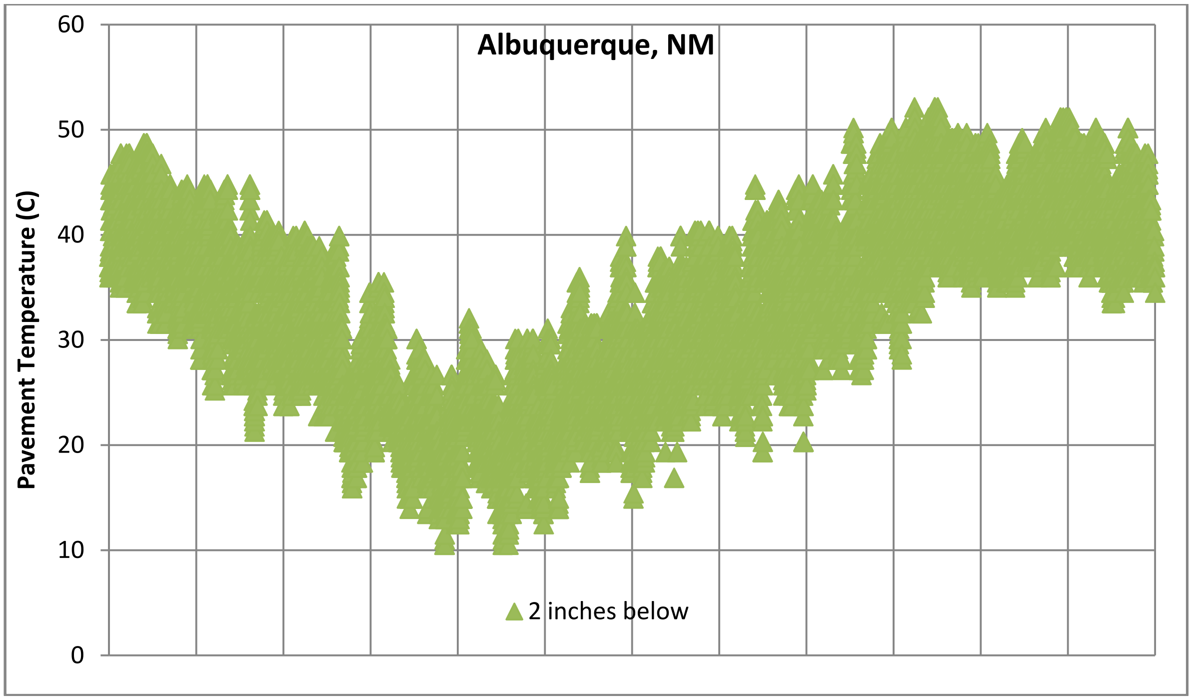


Figure 4. Estimated hourly temperature, on the basis of air temperatures, at a depth of 2 inch for the period of September 1, 2007 to August 31, 2008 (continued)



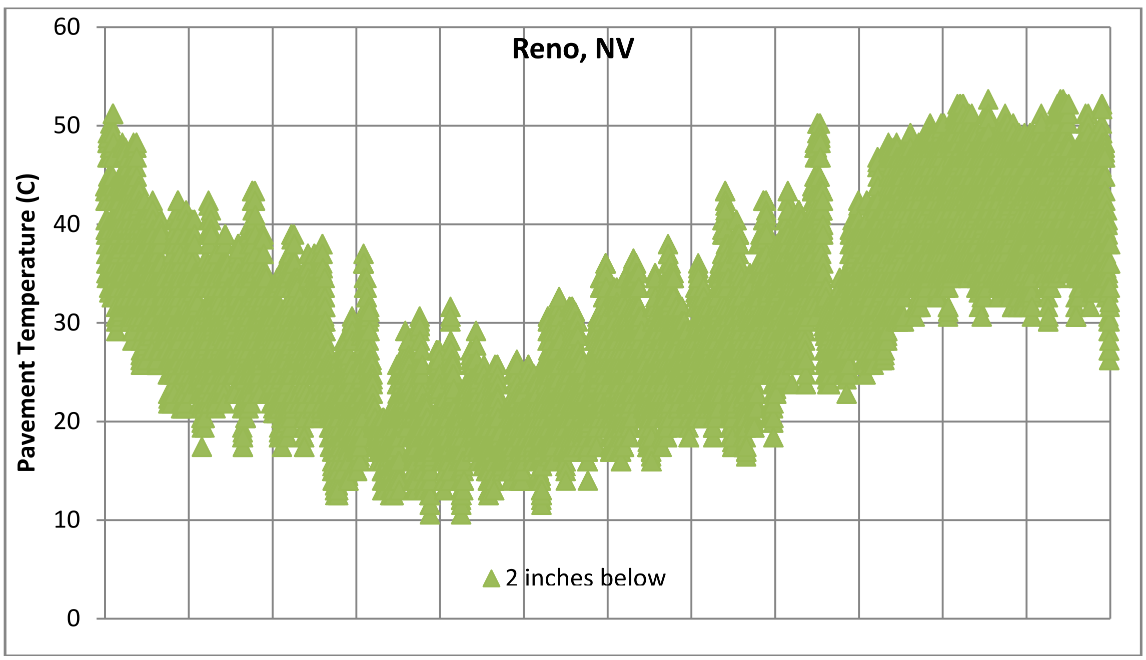


Figure 4. Estimated hourly temperature, on the basis of air temperatures, at a depth of 2 inch for the period of September 1, 2007 to August 31, 2008 (continued)

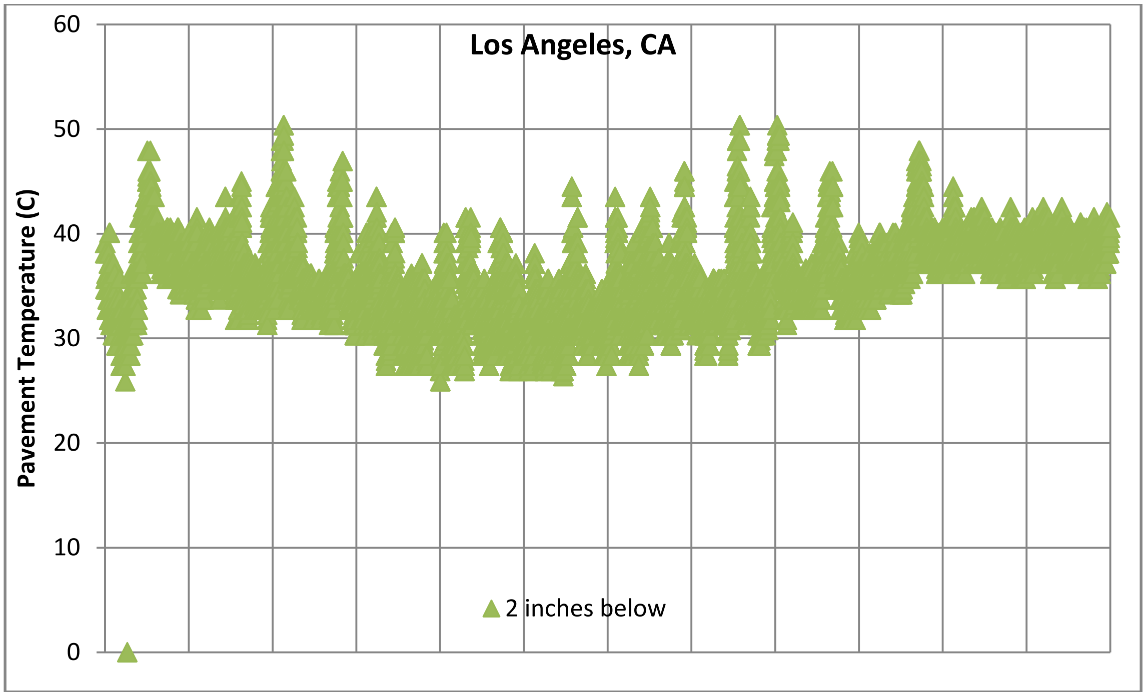


Figure 4. Estimated hourly temperature, on the basis of air temperatures, at a depth of 2 inch for the period of September 1, 2007 to August 31, 2008 (continued)

Are these temperatures high enough for successful use of electricity generating turbines?

The answer depends on the location of the pavement, and the depth of the pipes. However note that it is always possible (relatively cheaply) to use a secondary non-energy consuming technology, such as a solar concentrator or a solar heating element to increase the temperature from the maximum temperature in the pavement to the minimum temperature required for the end use.

The range of temperatures required for systems utilizing such concepts as the Organic Rankine Cycle (ORC) or even better, the Kalina Cycle (**6, animation in 7**) is relatively low and, harvested heat from pavements could be used.

Note that the hot water could always be used as "hot water", and the temperature reduction caused by the harvesting of energy from the pavement will lead to a reduced energy consumption of adjacent buildings.

Can something be done to the asphalt pavement to increase the amount of heat that can be harvested from pavements?

Two steps can be taken to improve the amount of heat that can be harvested from asphalt pavements.

1. The surface of the pavement can be painted with a reflectivity decreasing/absorptivity increasing paint, such as black sealer. This will increase the amount of energy that is trapped inside the pavement. Laboratory results show that the use of black acrylic paint can increase the difference between incoming and outgoing water (through asphalt pavement) by almost 50% (**Figure 5**).
2. The thermal conductivity of the pavement mix can be improved by using aggregates with higher thermal conductivity, such as quartzite (containing high percentage, >90%, of quartz). Laboratory test results show that the difference between incoming and outgoing water (through asphalt pavement) was increased by 100% by replacing limestone aggregates with quartzite aggregate (**Figure 6**)

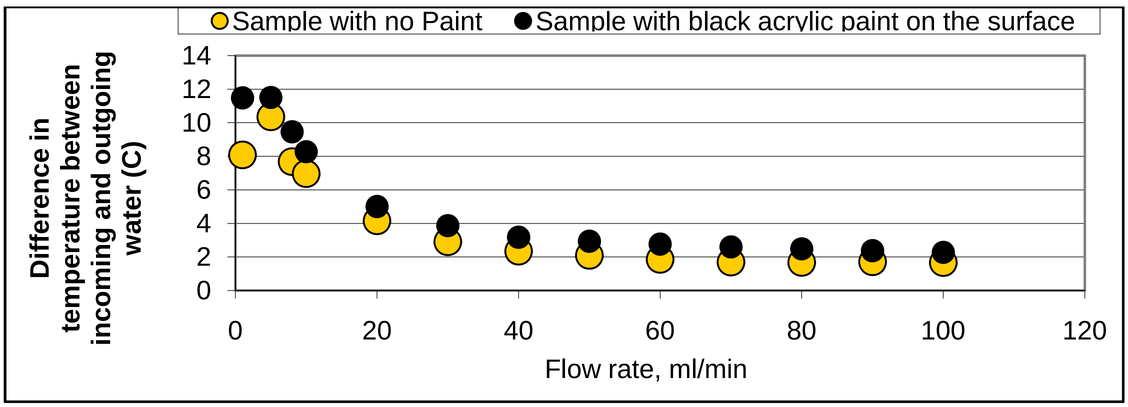


Figure 5. Effect of paint on the temperature of water

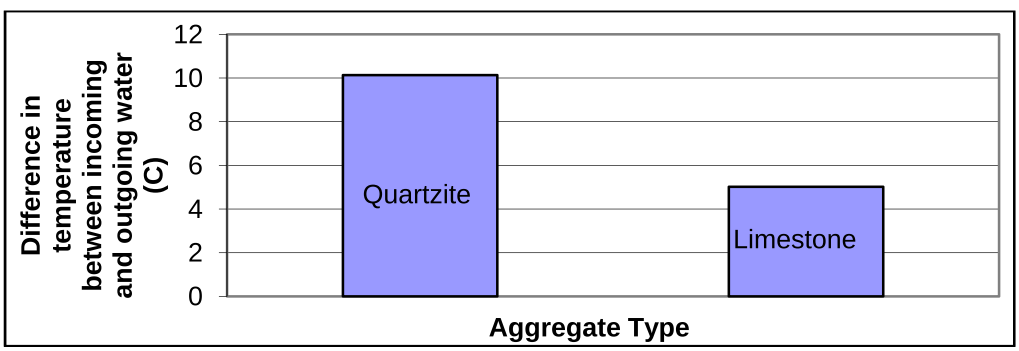


Figure 6. Effect of aggregate type on temperature of water

Is there a minimum pipe length required for the water to reach the pavement temperature?

A minimum length of the pipe is required for the water to reach the pavement temperature at the depth of the pipe. This value depends on the rate of flow. Values, as obtained from analytical calculations are shown below in **Table 1**, for a pavement temperature of 50^{o}C. Plots of water temperature versus pipe lengths for a flow rate of 0.033m/s (1, 4, 16, and 36L/min) are shown in **Figure 7**.

Table 1. Required pipe length at wall temperature= 50 °C

	Water Flow Rate (mL/min)														
Pipe Diameter (m)	20	40	60	80	100	200	400	600	800	1000	2000	4000	6000	8000	10000
0.05 (2inch)	1.5	3	4.5	6	7.5	15	30	45	60	75	150	300	450	600	750
	Pipe length (m)														

*highlight is where turbulent flow occurs

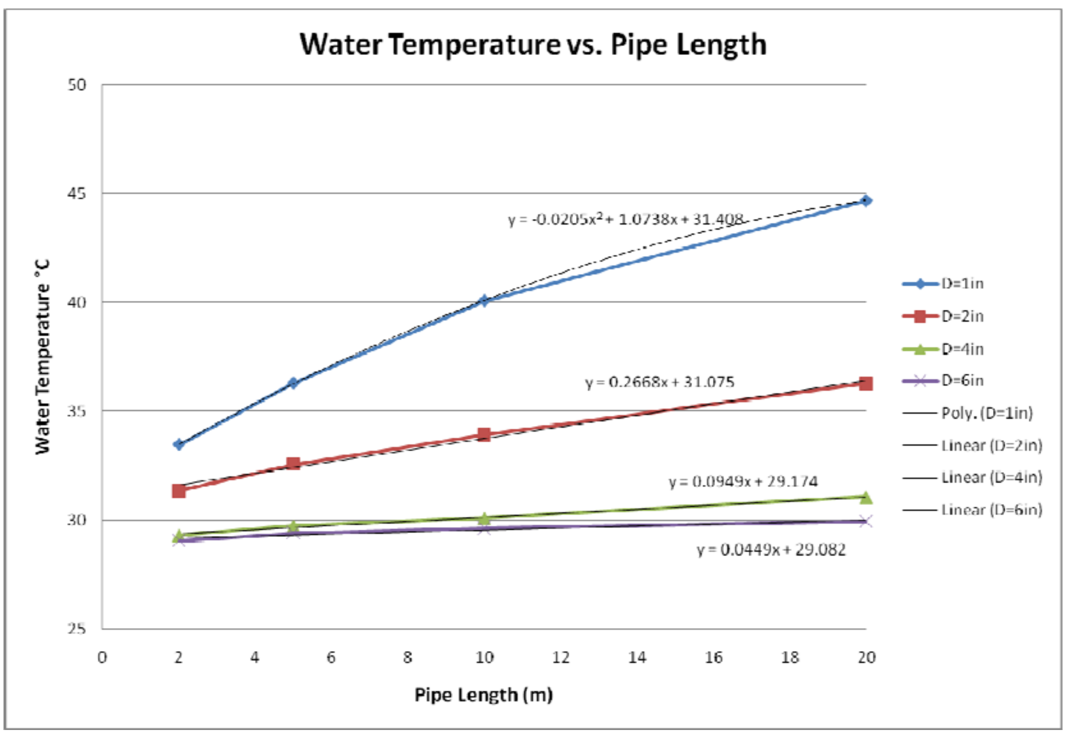


Figure 7. Plots of water temperature versus pipe length

The water/fluid carrying pipes must be placed at a minimum spacing such that there is no low temperature or "cool" spot formation between the pipes (**Figure 8**).

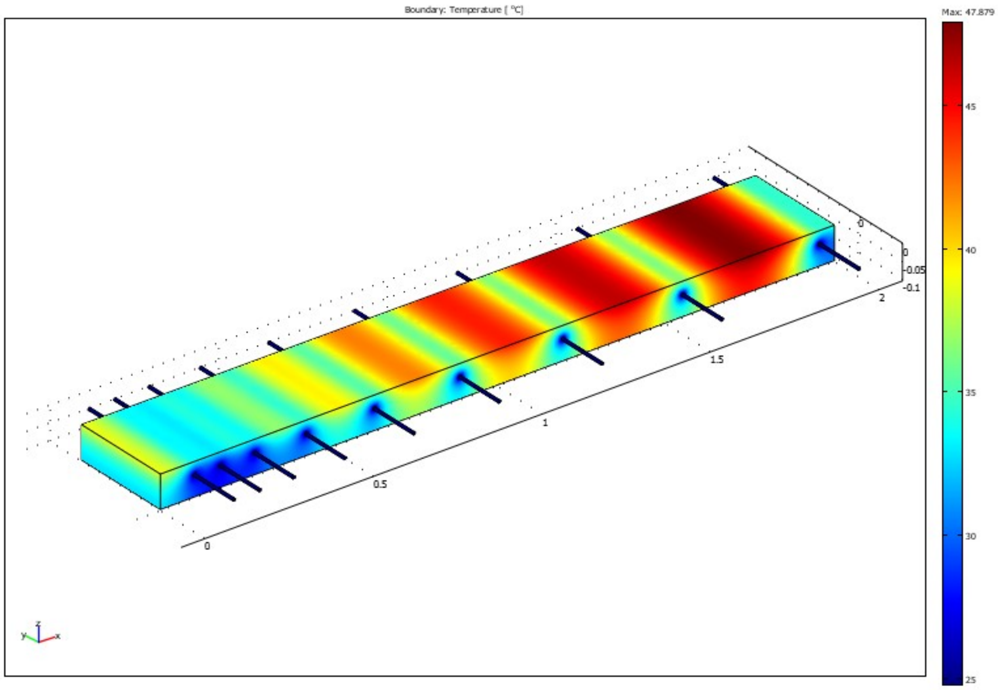


Figure 8. Cool spot due to close spacing of pipes

Based on finite element modeling, the following Figure (**Figure 9**) was developed. Note that for a specific flow rate, there is a minimum spacing, depending on the diameter of the pipe.

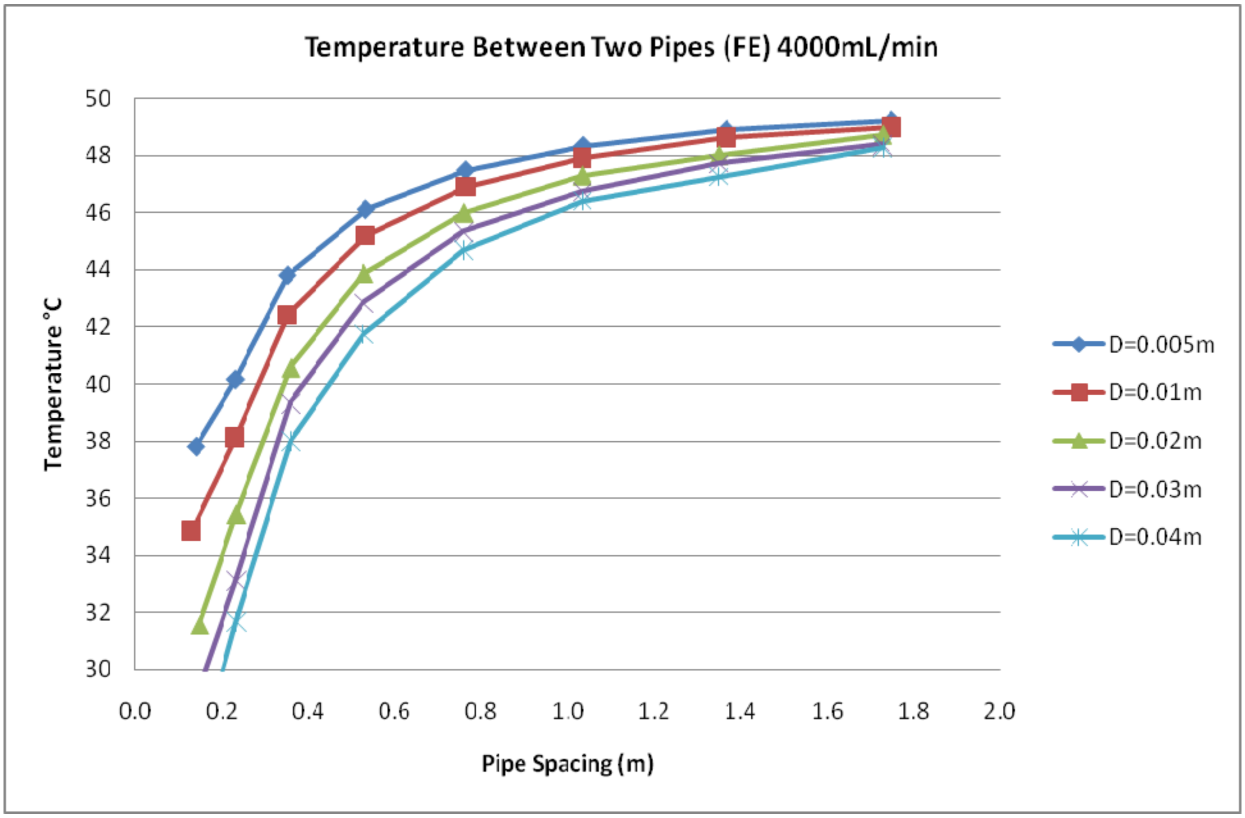


Figure 9. Plots of pipe spacing versus water temperature

By how much can the radiated heat be cut back with this concept?

Laboratory test results show that the surface temperature of the pavement can be reduced by as much as 13°C (**Figure 10**), and the radiated heat from the pavement can be reduced by as much as 56% under peak radiation conditions.

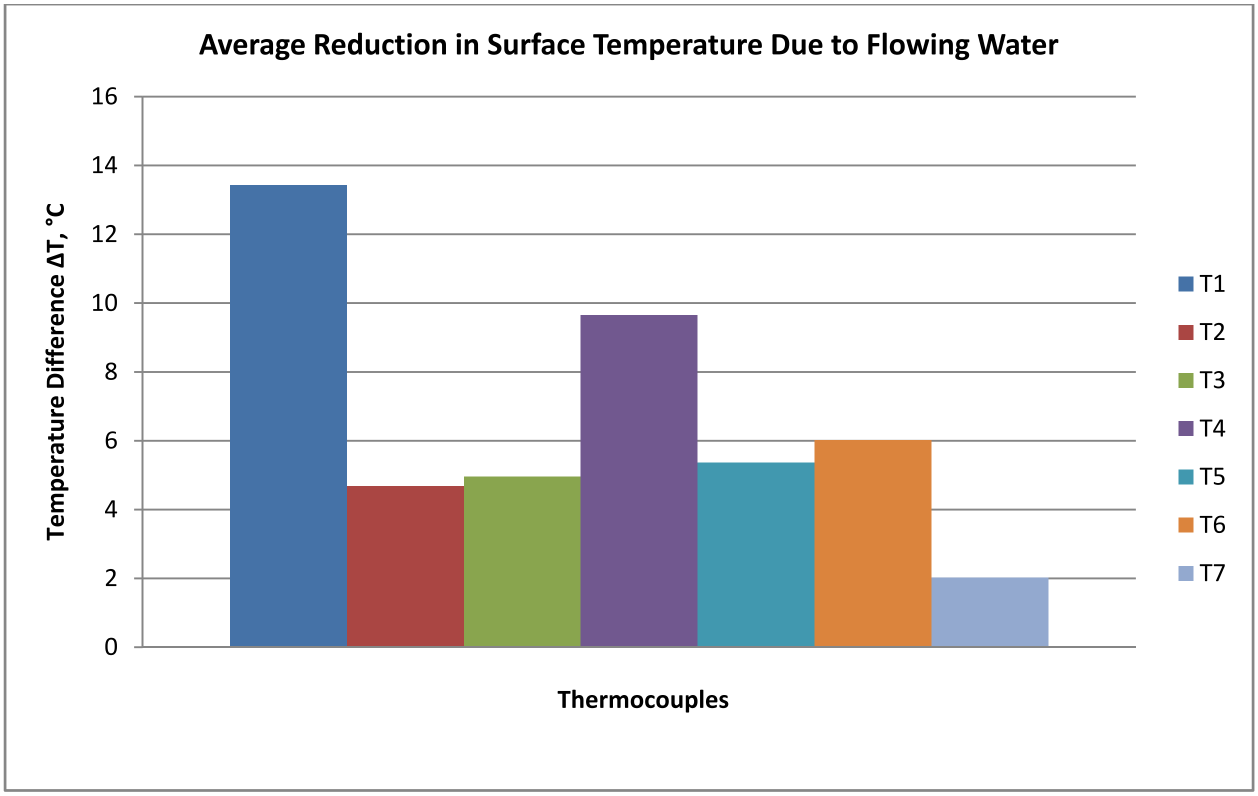


Figure 10. Reduction of surface temperature of asphalt mix sample

Finite element simulation was conducted to determine the amount of heat that will be radiated back from an asphalt pavement surface under different conditions. For example, how much heat would be radiated back from an usual pavement surface, from a pavement surface which has been painted white, and from the surface of a pavement that has water carrying pipes. Furthermore, how is the radiated heat affected by the different controllable parameters – pipe spacing, pipe diameter, asphalt mix conductivity and depth of location of pipes.

The typical 3D model was simulated for 24 hour heating and cooling cycle, in which the asphalt pavement was subjected to solar radiation from time= 0 to 14 hours, and water was pumped in from time= 4 hours to 24 hours. The heat transfer coefficient on the surface of asphalt pavement was calculated based on different wind speed by using Vehrencamp and Dempsey (8)

$$h_c = 698.24\left[0.00144T_m^{0.3}U^{0.7} + 0.00097(T_s - T_{air})^{0.3}\right]$$

Where h_c is the radiation loss to the air in W/m^2, which depends on the surface temperature T_s, T_{air} is the air temperature, T_m is average temperature of T_s and T_{air}, and U is wind velocity.
The surface of asphalt pavement was subjected to 800W/m^2 solar radiation, pipe location= 0.0381m, pipe spacing= 0.1524m, wind speed=2.24m/s, initial water temperature= 25°C, asphalt thermal conductivity= 1.5 W/m^2·K, and emissivity= 0.9. The radiative heat flux was obtained by integration of surface boundary layer.
Finite element simulation was conducted using 3D (transient, **Figure 11**) models.

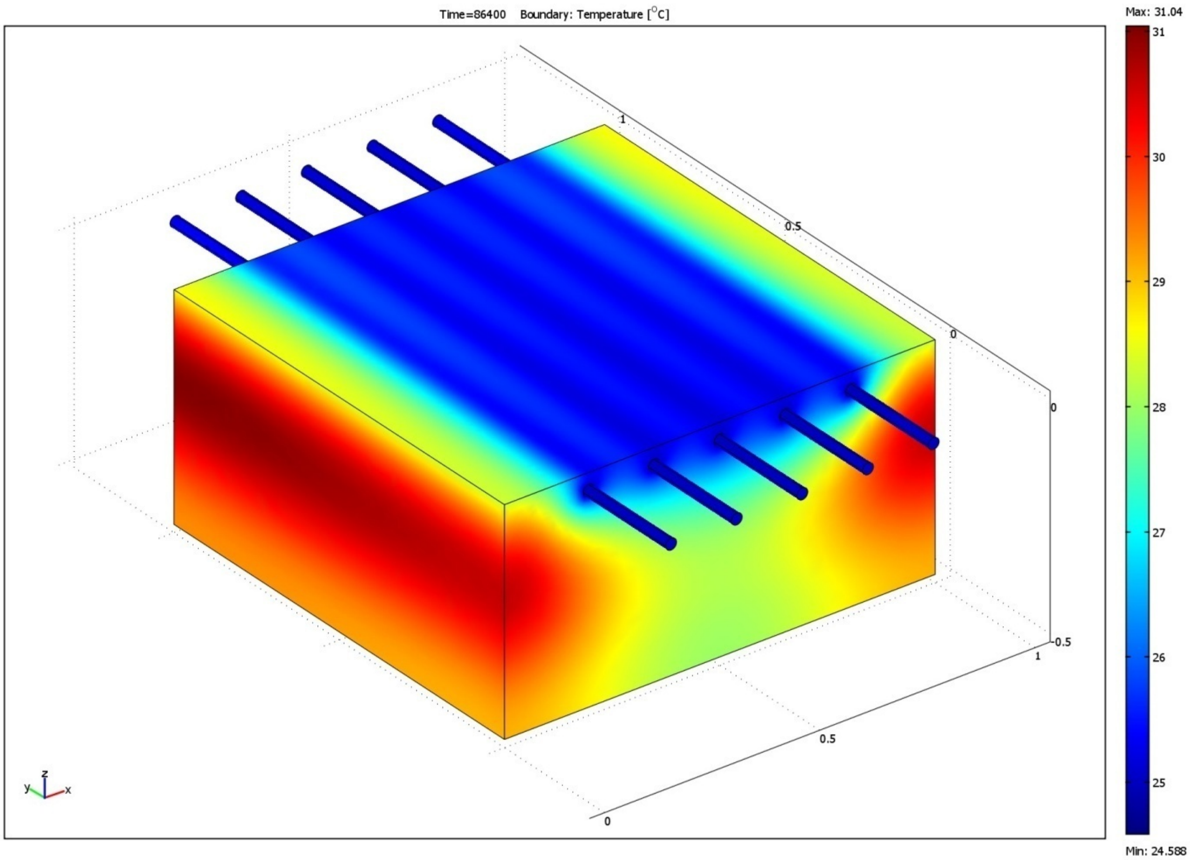


Figure 11. 3-D simulation

The parameters of simulation were

Asphalt Pavement Dimensions (3D)

Length= 1m (3.3ft)

Width= 1m (3.3ft)

Depth= 1m (3.3ft)

Modeling Parameters

Solar Radiation= 200, 500, 800, 1000 W/m^2

Pipe Location = 0.0381, 0.0762, 0.1143, 0.1524 m (1.5, 3, 4.5, 6 inch)

Pipe Diameter = 0.0254, 0.0508, 0.1016, 0.1524 m (1, 2, 4, 6 inch)

Pipe Spacing = 0.1524, 0.3048, 0.4572, 0.6096m (0.5, 1, 1.5, 2ft)

Wind Speed= 0.894, 2.24, 6.71, 13.41 m/s (2, 5, 15, 30 mph)

Water Temperature= 10, 25, 40, 50 °C

Asphalt Thermal Conductivity= 1.2, 1.5, 1.8, 2.0 W/$m^{2\cdot}$

Emissivity= 0.9, 0.8, 0.7, 0.5

Figure 12 shows the effect of different parameters on the reduction of emitted heat.

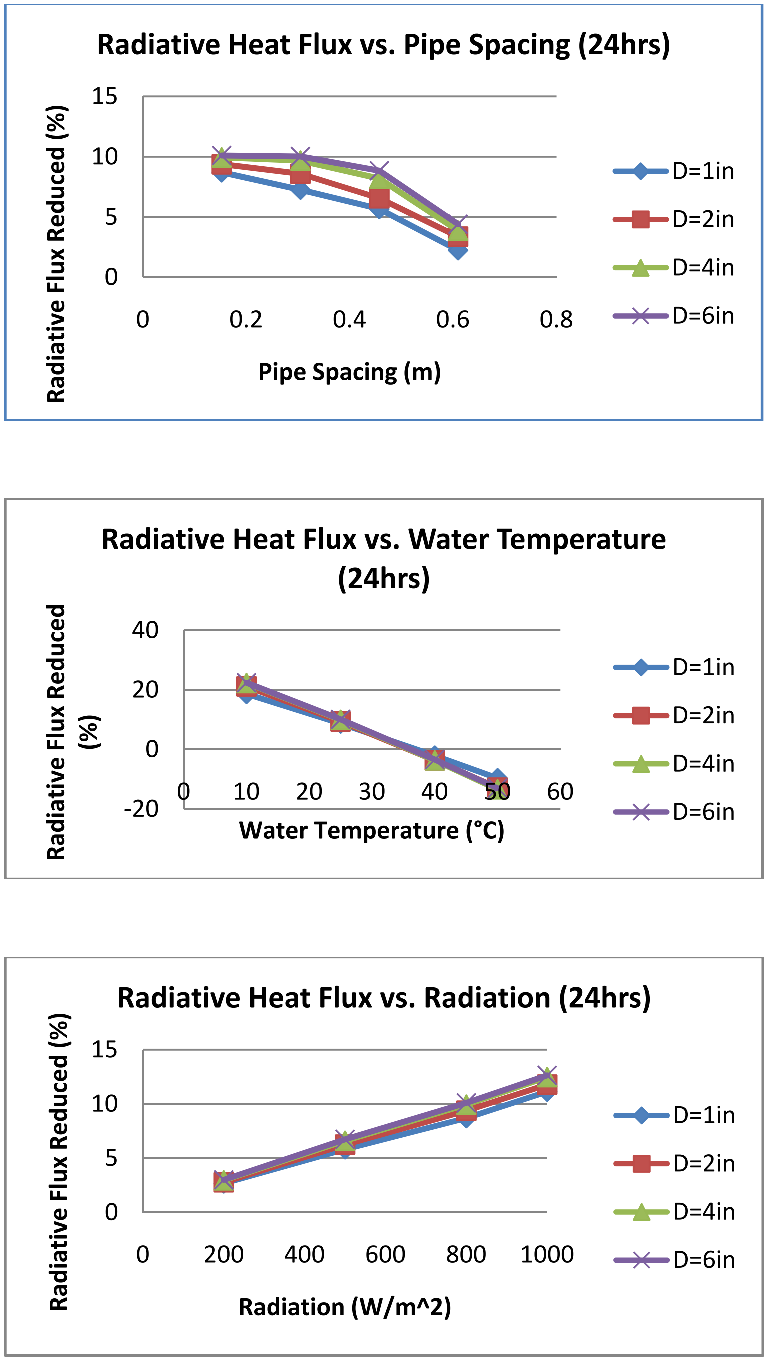


Figure 12. Effect of different parameters on the reduction of radiative flux

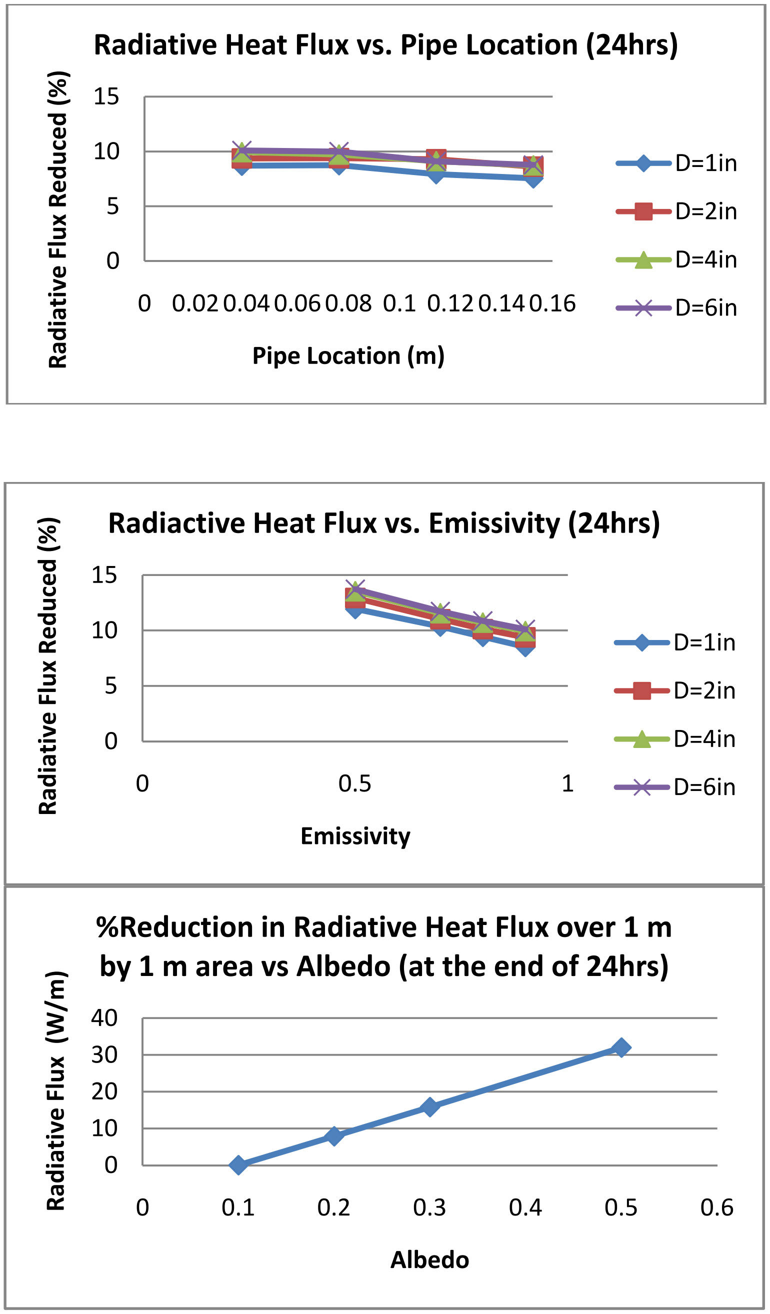


Figure 12. Effect of different parameters on the reduction of radiative flux (continued)

By how much is the near surface air temperature reduced due to a lowering of the surface temperature and the radiative heat from the pavement?

A finite element model was created and utilized to simulate the surface and air temperature for different fluid flow conditions. A serpentine pipe was modeled using different segments of a straight pipe, and using different inlet water temperature (**Figure 13**). The radiation of heat from the surface of the pavement to the near surface air layer was modeled. Examples of reduction in near surface air temperature are shown in **Figure 14**. Note, a 10^{o}C reduction in near surface air temperature for the case shown.

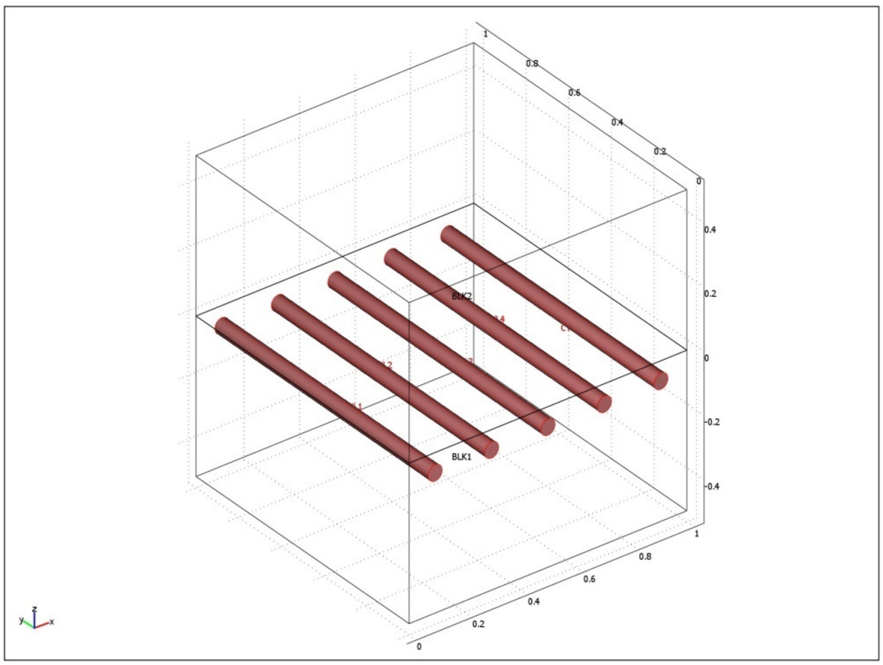


Figure 13. FE Model of serpentine pipe in pavement

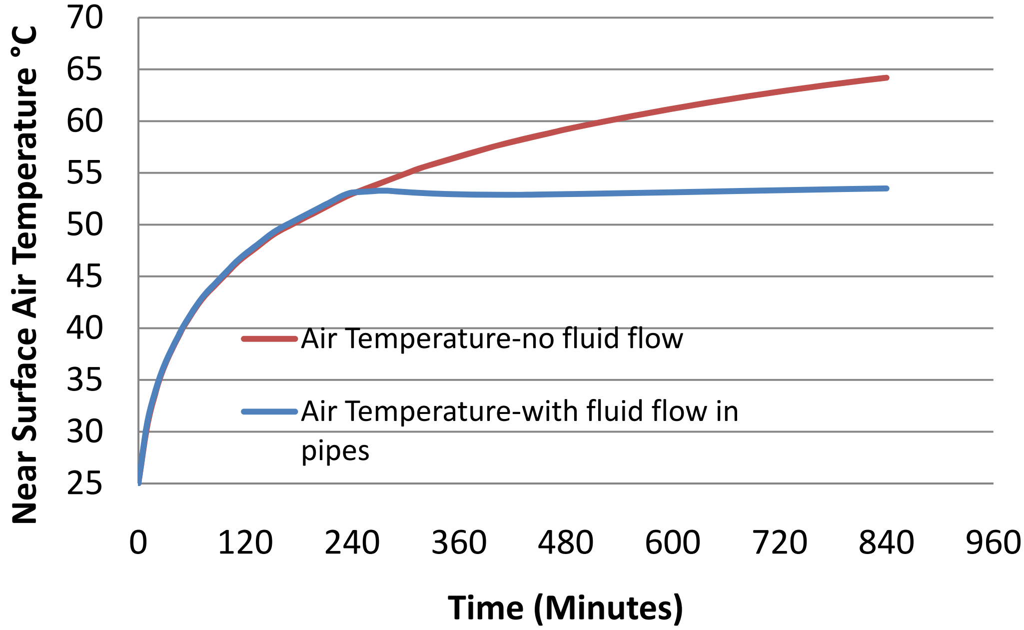


Figure 14. Near Surface air temperature for pavements with and without proposed system

Note: These temperatures are at the location above the center of a pipe, for a paving mix with thermal conductivity of 1.8 W/mK, with heat capacity of 1,050 J/kgK; with inlet water temperature of 25°C, water flow rate of 100 ml/minute and pipe diameter of 2 inch placed (top of pipe) 1.5 inch below the surface; solar radiation of 800 W/m^2, wind speed of 5 mph; solar radiation for 14 hours (0-840 minutes) with flow of water starting after 4 hours (at 240 minutes); the thickness of the near surface air layer: 0.5 m

What is the effect of reduction in air temperature over energy consumption and air quality? One can determine the effect of reduced near-surface air temperature (caused by a reduction of the pavement temperature) using the Urban Heat Island Mitigation Impact Screening Tool (MIST), available at http://www.heatislandmitigationtool.com/Inputs.aspx?t=1. The maximum allowable temperature reduction in the tool is 5°F. The temperature reductions using the fluid flow concept can be significantly larger than that (as evident from Figure 14). Even with a 5°F reduction, for example, in Houston, significant savings in energy consumption and reduction in 1-hour/8-hour ozone concentration can be achieved (**See Table 2**).

Table 2 Effect of reduction in 5°F air temperature on energy consumption and 1 hour/8 hour ozone concentration (from MIST)

Inputs

Location: Houston; Mean Temperature: 73.4°F; Cumulative Degree Days (CDD): 2,810
Heating Degree days (HDD): 1,552; Typical maximum 1 hour ozone (ppb): 182
Typical maximum 8 hours ozone (ppb): 138

Outputs:

Savings in energy consumption:
Post 1980 buildings
Electricity heated buildings: residential: 22%; office: 11%; Retail: 13%

Reduction in ozone concentration
For 1 hour ozone concentration: 3.4 – 5.6 ppb
For 8 hour ozone concentration: 2.5 – 4.2 ppb

This reduction in 5^{o}F can be caused by an increase in albedo of all paved surfaces 0.51. Note that in general asphalt pavements have 0.09 to 0.1 albedo, and the use of light colored aggregates or paints can typically increase the albedo from 0.1 to 0.35.

In a typical parking lot how much of the area is available for high temperature?
Probably close to 100% of the parking lot is available for work areas on weekends, and recreational or church areas on weekdays. Conversely, approximately 45% of the area is available in work areas on weekdays and church or recreational areas on weekends. For example, see **Figure 15** which shows that approximately 45% of the area in the parking lot on a weekday (for an university parking lot) is at relatively high temperature (red-yellow area in surface plot and light colored areas in contour plot).

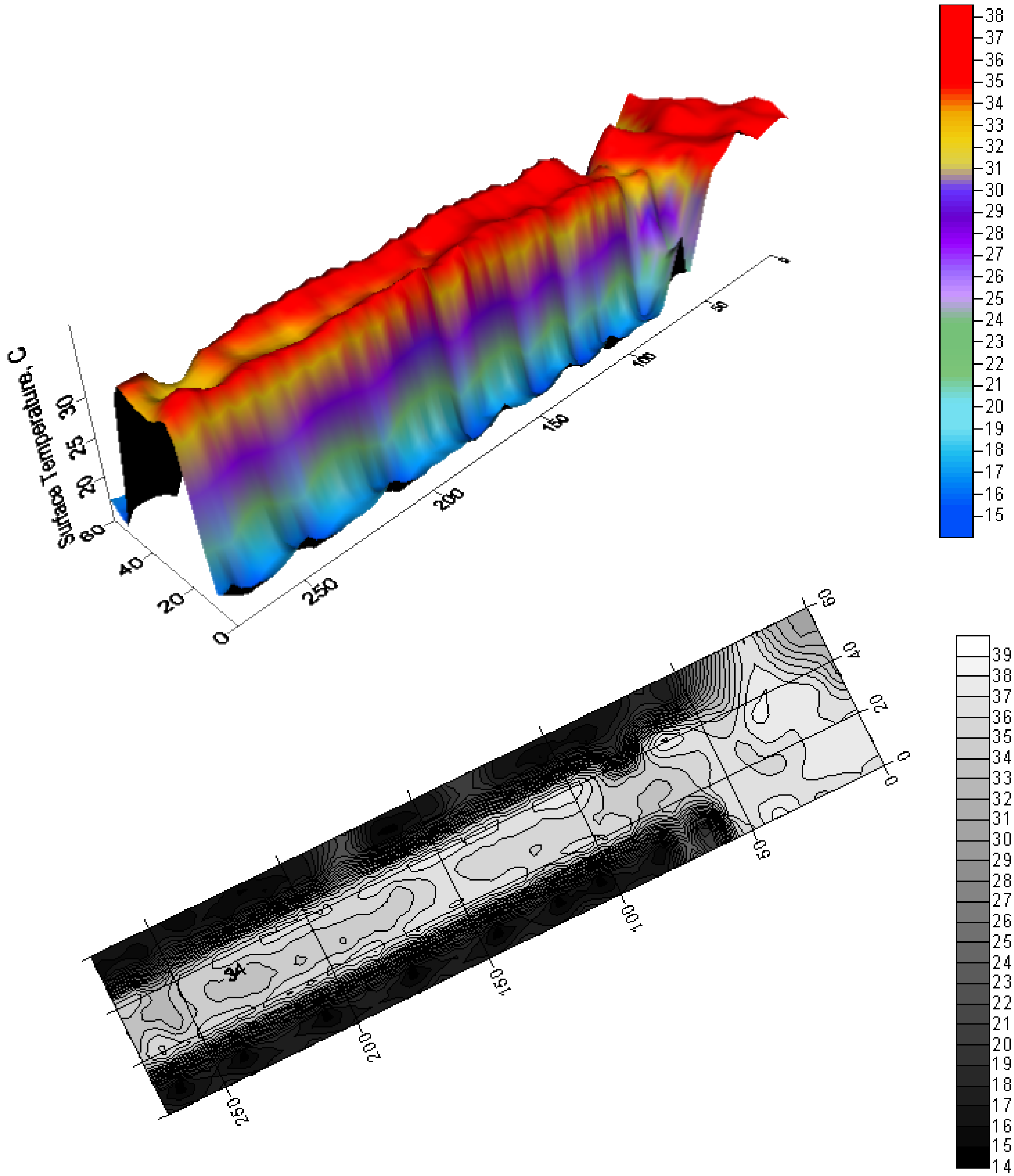


Figure 15 Temperatures in different areas of a parking lot with cars on a weekday

By how much can the life of a pavement be extended with this concept?

The NCHRP 1-37A Mechanistic Empirical Pavement Design (MEPDS, commonly referred to as the Design Guide 2002, or DG2002, 9) software is a Windows-based application for the simulation of pavement structures. It can be used to simulate pavement structures under different traffic and climatic conditions. The software has the ability to predict the amount of damage that a structure will display at the end of its simulated design life. In addition to using laboratory test results, predicting properties for pavement mixes can be done by using correlations. Values (either default or entered by the user) that represent structural, climatic, or traffic properties are used in calculating distresses.

The software can be used for predicting the rutting damage over different years, considering the usual pavement temperature, and then a range of temperatures that are lower than the usual temperature. To do this, the weather database in the MEPDS can be utilized. An example of calculation of years to failure (or service life) is shown below. For this example, four cities were selected to consider a range of maximum pavement temperatures, from 70 to 52^{o}C. These are, in decreasing temperatures, Houston, Raleigh-Durham, Chicago and Portland (ME). A pavement located in Houston was simulated, using the climatic information for the above four cities, to determine the rutting damage over the years, and the years to failure, for the range of temperatures (70 to 52^{o}C). The results are shown in **Figure 16**. It can be seen, that for the same traffic and the same materials, the life of the pavement can be extended by 5 years for a drop of temperature of 5^{o}C. The drop in temperature is more effective in extending the life of the pavement at higher temperatures.

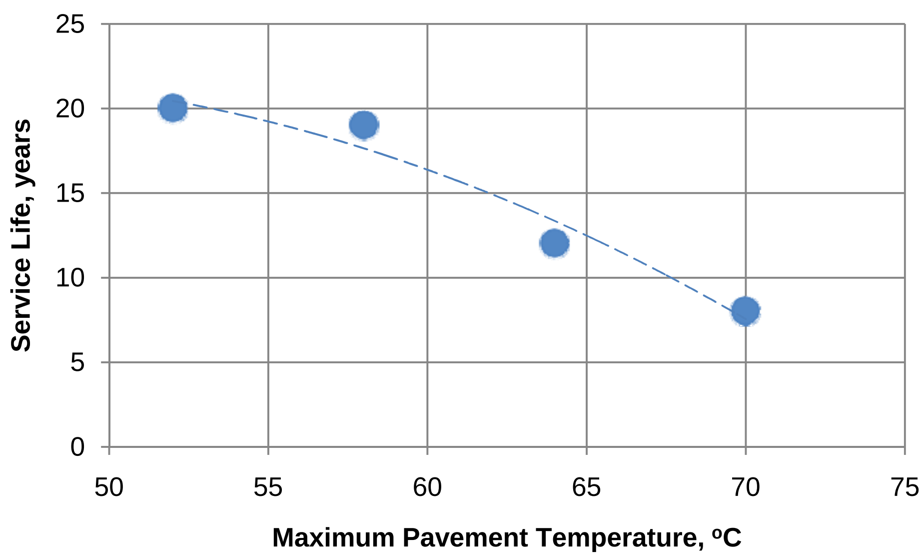


Figure 16. Effect of maximum pavement temperature on service life of asphalt pavement (considering high temperature related permanent deformation only)

What are the important cost considerations?

The important cost considerations are those that are needed for the installation of the system – labor and materials, for piping and pumping, as well as for the end application (for example, a turbine, if the generation of electricity is required), and maintenance of the system. The payback period can be estimated by calculating the savings in energy consumption, and/or selling of excess energy to a grid.

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