A Multiphysics Approach to Optimize Systems for Harvesting Heat Energy and Reduce the Urban Heat Island Effect of Asphalt Pavements

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ABSTRACT: Asphalt pavements absorb a large amount of solar radiation because of their thermal properties. The concept of reducing the urban heat island effect of pavement by harvesting its heat energy has been presented. This energy can be supplied for providing heated water for household or commercial use, and other applications such as in absorptive chillers. The concept has been proven to be feasible through finite element analysis and small and large scale testing. However, several practical considerations need to be made before the concept can be applied to practice. These considerations involve those related to the traffic and thermal stresses, and their combined effects on the pavement and pipe structures. The many important factors include piping material, depth of location, and the type of flowing fluid, its incoming temperature and rate of flow, and environmental conditions such as solar radiation and air temperature. An integrated approach is needed to consider all of the important factors and mechanisms, and design an efficient system that would be economical and practical for construction. This paper presents the results of a study on the use of Multiphysics problem solution for modeling and simulation with a wide range of different variables, including those obtained from experiments. The approach utilizes coupling of heat transfer and structural mechanics equations for determination of the effect of different factors on the pavement-pipe system. The results could be utilized for the design of a system that can function efficiently throughout different seasons, in different parts of the world.

KEY WORDS: Heat extraction, pavement, heat island, economic analysis, structural analysis

1 INTRODUCTION

Asphalt pavements absorb a large amount of solar radiation because of their thermal properties – low conductivity (1-1.8 W/m*K) and relatively high heat capacity (1,200-1,800 J/kgK) (Chen et al. 2008). The concept of reducing the urban heat island effect of pavement by harvesting its heat energy has been presented (Mallick et al, 2008, Mallick et al, 2009-1, Mallick et al, 2009-2, Chen et al, 2009). This energy can be supplied for providing heated water for household or commercial use, and other applications such as in absorptive chillers. The concept has been proven to be feasible through finite element analysis and small and large scale testing (Mallick et al, 2008). However, several practical considerations need to be made before the concept can be applied to practice. These considerations involve those related to the temperature profiles in the pavement, amount of available heat energy, traffic and thermal stresses, and their combined effects on the pavement and pipe structures. The many important factors include piping material, depth of location, and the type of flowing fluid, its incoming temperature and rate of flow, and environmental conditions such as solar radiation and air temperature. An integrated approach is needed to consider all of the important factors and mechanisms, and design an efficient system that would be economical and practical for construction.

2 OBJECTIVE

The objectives of the study are to present a step-by-step method for evaluation of the potential of harvesting heat energy from asphalt pavements for a specific location, aided by the analysis of environmental and financial data, and the use of Multiphysics finite element software.

3 APPROACH

In its most simple form, the proposed concept of extracting heat energy from a pavement can be illustrated with Figure 1. (Mallick et al, 2009). The system involves installing a network of pipes under the pavement, flowing a fluid (such as water, if there is no chance of freezing, or glycol where there is), and extracting the heat via the hot fluid that comes out of the pavement.

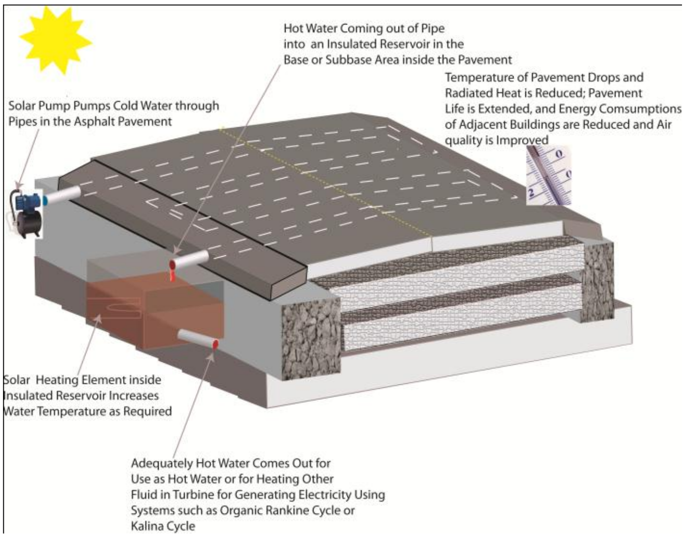


Figure 1: Proposed solution concept

This paper presents a step by step approach directed at answering the following questions. For a specific location, what is the temperature of the pavement throughout the year? How much energy can be extracted? Is the extraction economically feasible? From structural considerations, at what depth should the pipe be located and what piping material should be used?

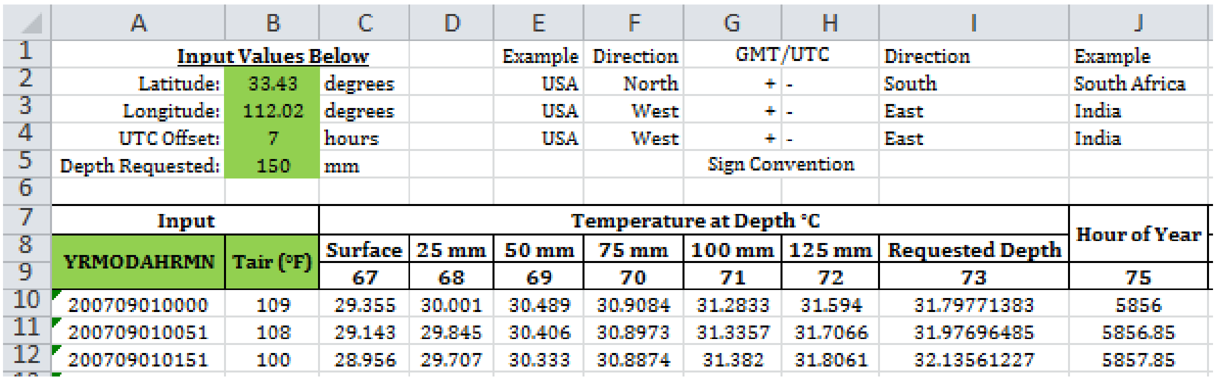
4 IS IT ECONOMICALLY FEASIBLE?

Areas incurring significant exposure to solar radiation as well as having consistently high ambient temperatures serve as ideal locations for the implementation of a thermal energy harvesting system. High incident solar radiation provides a continuous source of energy which is converted into thermal energy as it is absorbed by the pavement. Flowing water through a pipe network in the pavement provides an alternative energy path. The thermal energy stored in the pavement passes to the flowing water through convection, increasing the temperature of the water and reducing the temperature of the pavement. For a system to be feasible locations of high ambient temperature and significant solar radiation must be chosen.

Phoenix, Arizona, Houston, Texas, and Miami, Florida were chosen for the analysis of a pipe network installed to extract the heat energy stored within asphalt pavements. All three cities are located in the southern half of the United States where they will experience the highest amount of solar radiation possible in the United States due to their greater proximity to the equator. Throughout most of the year they also experience moderate to high ambient air temperatures. An additional location in the northeastern part of the United States, Boston, Massachusetts, was analyzed to provide validation to the results obtained for these three locations.

Three spreadsheets were created to evaluate the feasibility of the heat extraction network. The first determines the temperature profile in the pavement according to equations developed by Viljoen (Denneman, 2007). It requires the input of air temperature readings for the period of at least one year obtained from NOAA as well as a location's longitude, latitude, and offset from Universal Time. The second uses the temperature profile to calculate the available energy and determine the size of the network. The third uses the network parameters to calculate the cost of the system and reports the payback period for that configuration. For this analysis, the requested depth was chosen to be 150 millimeters.

Figure 2 presents example spreadsheet output data for one location, Phoenix, Arizona. This worksheet contains all of the initial air temperature readings, located in column 'B' of the worksheet and the time code (YRMODAHRMN) corresponding to the reading. Columns 'C' through 'I' contain pavement temperatures which the spreadsheet has calculated for the listed depth in including the requested depth. For ease of plotting the temperature profile, the hour of the year corresponding to that reading is located in column 'J'.



	A	B	C	D	E	F	G	H	I	J
1	Input Values Below				Example	Direction	GMT/UTC		Direction	Example
2	Latitude:	33.43	degrees		USA	North	+	-	South	South Africa
3	Longitude:	112.02	degrees		USA	West	+	-	East	India
4	UTC Offset:	7	hours		USA	West	+	-	East	India
5	Depth Requested:	150	mm				Sign Convention			
6										
7	Input		Temperature at Depth °C							Hour of Year
8	YRMODAHRMN	Tair (°F)	Surface	25 mm	50 mm	75 mm	100 mm	125 mm	Requested Depth	
9			67	68	69	70	71	72	73	75
10	200709010000	109	29.355	30.001	30.489	30.9084	31.2833	31.594	31.79771383	5856
11	200709010051	108	29.143	29.845	30.406	30.8973	31.3357	31.7066	31.97696485	5856.85
12	200709010151	100	28.956	29.707	30.333	30.8874	31.382	31.8061	32.13561227	5857.85

Figure 2: Example of output data (Phoenix, AZ)

Figure 3 is the result of plotting the entire time-temperature profile of the pavement surface for the period of one year. Phoenix is characterized by extremely high pavement temperatures exceeding 70° C as well as a large difference in the maximum and minimum pavement temperature for a short period of time, declining to more moderate temperatures with a minimal difference between the maximum and minimum pavement temperatures.

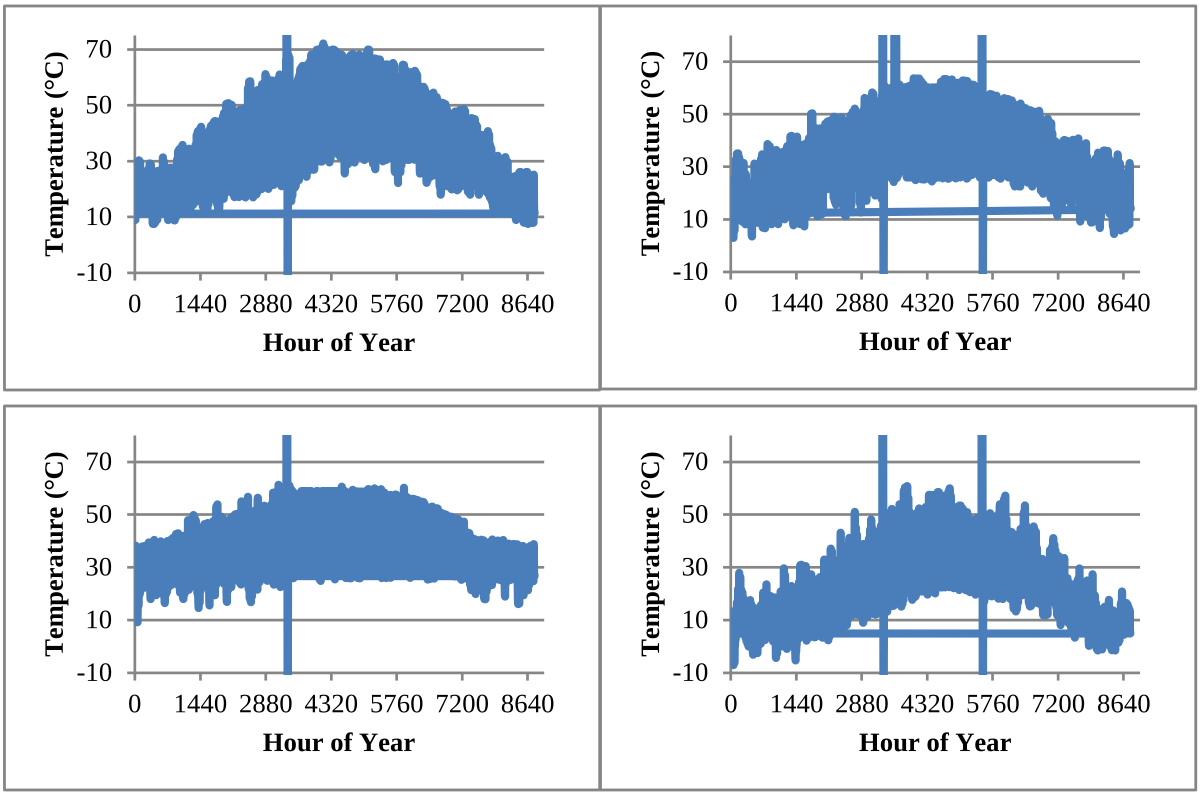


Figure 3: Continuous surface temperature profile: (upper left) Phoenix, AZ (upper right) Houston, TX (lower left) Miami, FL (lower right) Boston, MA

Houston, which does not achieve temperatures as extreme as Phoenix, exhibits a much greater difference between the maximum and minimum temperatures throughout more of the year. In Miami, the sharp peak in the summer is even less pronounced in favor of a more moderate temperature range about a higher temperature throughout the year. While each location exhibits a different profile, each is a suitable location for the installation of a pipe network for the identified reason. Boston, Massachusetts, however, is not as suitable a location. While it exhibits a peak similar to that of Phoenix and Houston it does so for an even shorter period of time. The temperature then quickly declines, remaining below 20 °C, the minimum presumed operating temperature of the heat extraction system, for a significant period of time. The lower temperature profile of Boston, Massachusetts validates the sensitivity of the temperature-profile calculation spreadsheet to different climatic conditions. The subtle differences in the profiles of the southern locations also support this sensitivity by providing temperature profiles that are identical to the climatic conditions present at each location.

Figure 4 shows the temperature profile in Phoenix, AZ for the hottest day of the year as well as the two surrounding days for the depths of 0, 25, 50, 75, 100, 125 and 150 mm (0, 1, 2, 3, 4, 5, and 6 inches) below the surface. This plot, a subsection of the plot presented in Figure 3, illustrates the temperature behavior of the asphalt at depth in relation to the surface temperature as dictated by the equations developed by Viljoen. According to Denneman, validation of the temperature model came from comparison of approximately 600 experimentally determined temperature profiles (Denneman, 2007). Similar temperature profiles at depth can be developed for the other locations which could aid in the development of the asphalt pavement in which the pipe network will be located such as in the selection of an appropriate asphalt binder.

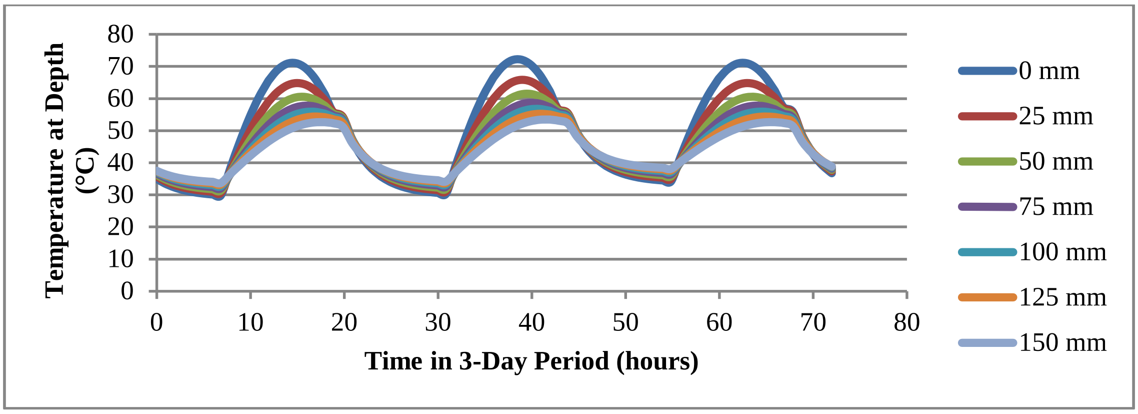


Figure 4: Hottest 3-day temperature profile (Phoenix, AZ)

A continuous temperature profile for the entire year provides a quantitative measure of the amount of thermal energy available for capture. A second spreadsheet was developed to take the results of the temperature profile calculation spreadsheet and calculate the total energy available at a requested depth in the slab. Water was assumed to be passing through a pipe at this depth and heated to the temperature of the slab at that depth. The amount of energy gained by the water is equivalent to that harvested from the pavement. Energy values are summed for the entire year to produce a total yearly energy yield. The cost of electricity provides a means for converting this energy yield into yearly savings. Based on the temperature profiles at depth developed for the four locations similar to Figures 3 and 4, Figure 5 indicates the amount of harvestable energy present in the asphalt at a 50 mm depth of pipe and for a water flow rate of 13 L/min.

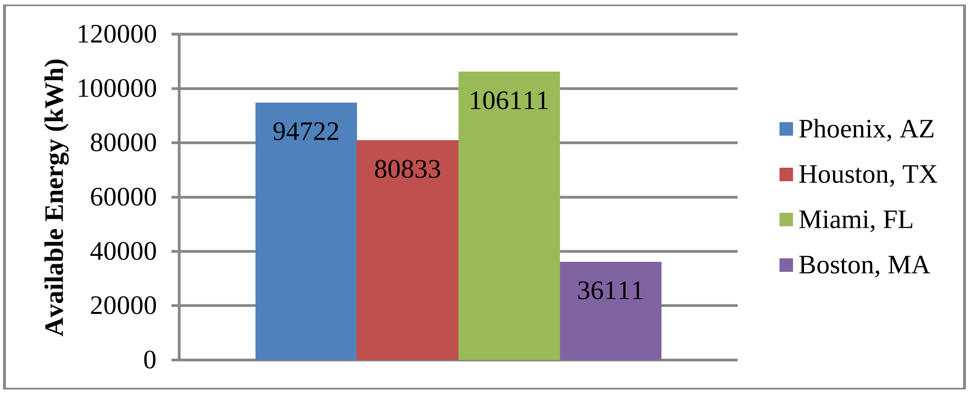


Figure 5: Available energy for harvesting for four case studies (50 mm pipe depth, 13 L/min flow rate)

A third spreadsheet was responsible for determining the size of the pipe network and the payback period for the installed system. Required inputs for this spreadsheet are the inner and outer diameters of the pipe to be used, flow rate of water, and inlet water temperature. For this analysis, a 19 mm (¾ inch) diameter type K copper pipe was used with a chosen inlet water temperature of 20 °C. The spreadsheet identifies the maximum temperature in the profile at a specified depth and produces a chart of outlet water temperatures versus the length of the pipe network. This chart is a measure of the contact surface area between the pipe and the pavement required to achieve the maximum temperature identified for the depth. A pipe network length is chosen so that the outlet temperature of the network is within one Celsius degree of the maximum temperature identified at that depth.

The capital cost of the network can be determined by simply multiplying the length of the network by the cost of the material per unit length and adding it to the cost of all the required equipment as well as additional installation costs. Maintenance costs exist in addition to the cost of pumping the water through the network. The cost of pumping as well as the total yearly savings are based on the cost of electricity at the time. Considering the capital cost, yearly cost, and yearly savings, a cash flow diagram can be produced which also represents the payback period for the installation pipe network at a given location. For a given flow rate of 13 liters per minute, a pipe network length of 675 meters was required for each location. A cash flow diagram comparing the three locations and Boston, Massachusetts is presented in Figure 6. In the determination of payback periods it was assumed that the installation location was to be paved already and thus the cost of paving was not factored into the payback period. The estimated payback periods using this configuration supports the feasibility of a pipe network in the three southern locations.

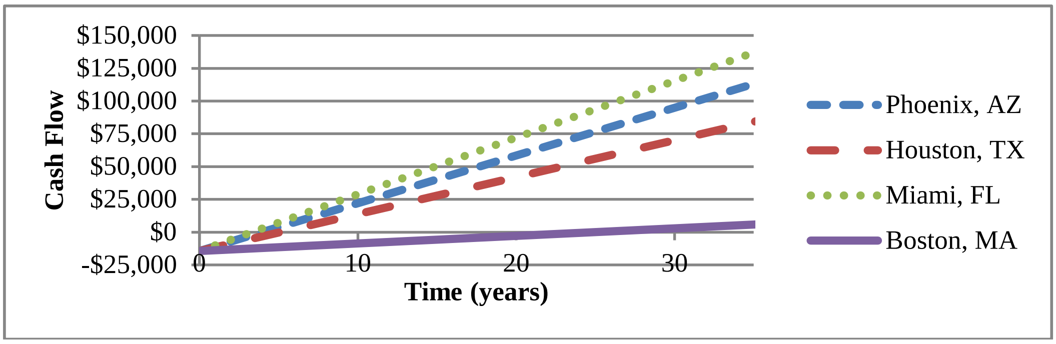


Figure 6: Cash flow comparison; payback periods for Phoenix, Houston, Miami and Boston are 3.9, 5.1, 3.3 and 24.9 years, respectively

The user also has the ability to change the flow rate present in the system where higher flow rates also require a greater length of the pipe network to increase the amount of time the water is in contact with the pavement heat source. For the three selected pipe depths at each installation location, the flow was varied from 6 L/min to 18 L/min to develop a matrix of payback periods. The same piping material (copper) and size (19 mm (3/4 inch)) as well as initial water temperature (20 °C) was used throughout this analysis. The results of this analysis pointed to an optimal flow rate of 12-14 L/min with a pipe network length of 612.5 to 675 meters and a range of payback periods of 3.1 to 5.9 years. The variations in temperature profiles of the three locations were responsible for these subtle differences. The difference in payback periods between the optimal configuration and the results presented in Figure 5 using an identical flow rate of 13 L/min for all three locations are 0.0 years for Phoenix, 0.2 years for Houston, and 0.2 years for Miami. This sensitivity analysis established a design flow rate of 13 L/min that can be used in later finite element modeling of the pipe network.

5 WILL IT SURVIVE?

To address the issue of structural survivability a finite element model was developed using COMSOL Multiphysics software. The model dimensions include a pavement slab width and length of 0.9 m and depth of 0.3 m with a 19 mm diameter copper pipe located at a variable depth of 25 to 150 mm below the surface. The depth of the pipe is measured from the surface to the centerline of the pipe. A continuity boundary condition between the copper pipe and the surrounding pavement was used to represent a no-slip condition between the pipe and pavement. The two faces through which the pipe does not pass and base of the slab were structurally fixed allowing no displacement or rotation to represent a continuous pavement slab on a rigid foundation. Only the top course of the pavement was modeled. A circular area load with a radius of 150 mm and a magnitude of 621 kPa was placed at the center of the surface of the slab to represent a typical truck tire. A parametric sweep was completed varying the temperature of the model from 0 degrees Celsius to 70 degrees Celsius in increments of 10 Celsius degrees and obtaining a solution. This process was repeated until solutions were developed for a pipe at a depth of 25, 50, 75, 100, 125 and 150 mm (1, 2, 3, 4, 5, and 6 inches) from the surface. Identical mesh settings were used for each of the solutions to minimize its effect on the solution.

Figure 7(a) presents a slice through the center of the model perpendicular to the pipe showing the stress profile in the pipe and the surrounding pavement. Zooming in on the pipe was required to highlight the contrast in stresses in the pipe which places the boundaries of the pavement outside of the capture. The pavement appears to be the same color throughout representing a singular stress. The magnitudes of the differences in pipe stresses are much greater than those in the pavement and as such differences in stresses in the pavement receive less definition.

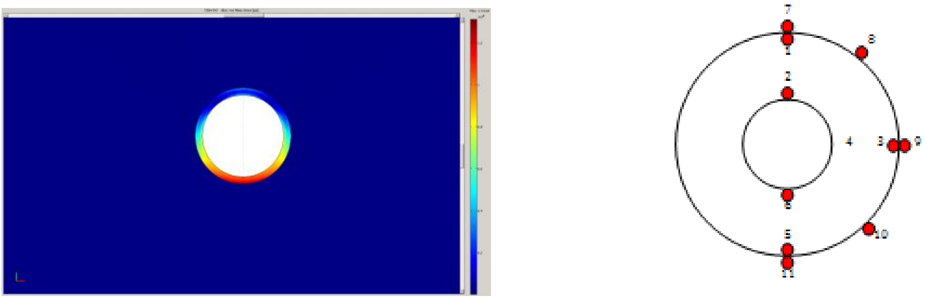


Figure 7: (a) Example COMSOL Von Mises stress plot (75mm pipe depth) and (b) critical stress investigation points

From the stress plot shown in Figure 7(a) and previous modeling, 11 points inside and surrounding the pipe as shown in Figure 7(b) were identified as possible locations for the occurrence of the maximum stress in either of the materials. Six of these points covered the inner and outer walls of the copper pipe at the top, side, and bottom of the copper pipe, while the remaining five were just outside the pipe wall starting from the top of the pipe to the bottom of the pipe at 45 degree increments. A matrix for each depth of pipe was created presenting the stress in the material at each point under investigation as a function of the global model temperature from 0 to 70 degrees Celsius. The maximum stress in the copper pipe was determined to occur along the outer wall at the bottom of the pipe (point 5) and at the right side of the pipe (point 9) at all depths. These maximums occurred are at opposite ends of the temperature range studied. At 0 degrees Celsius, the pavement witnesses its maximum Von Mises stress of 1,614 kPa as a result of having a modulus of elasticity greater than the copper at that temperature. Conversely, at the highest temperature studied of 70 degrees Celsius, the pavement lost the majority of its stiffness and the system depended on the copper pipe, which now has the greater modulus of elasticity, to carry the truck tire load. Here the pipe witnesses a maximum Von Mises stress of 90,721 kPa. Selecting only the maximum stresses determined for each material at a given depth of pipe, Figure 8 was developed.

The maximum stress in the copper pipe of 90,721 kPa occurred when the pipe is placed at middle-depth of 75 mm. This stress value was less than the tensile strength of the copper alloy in all of its different application types (345,000 kPa for pipe application) proving that pipe will survive at any depth greater than 25 mm from the surface. The Copper Development Association recommends that the copper pipe be placed at least 38 mm below the surface for applications in asphalt pavements (Copper Development Association, 2006). Unlike the copper pipe, the maximum stress in the pavement occurred at a depth of pipe of 25 mm below the surface at a value of 1,614 kPa which is less than most cited tensile strength of good quality HMA. A greater depth of pipe realizes further reduction in pipe and pavement stresses which may have implications towards fatigue life. This analysis supported the survivability of the pipe network under the influence of a typical truck tire load.

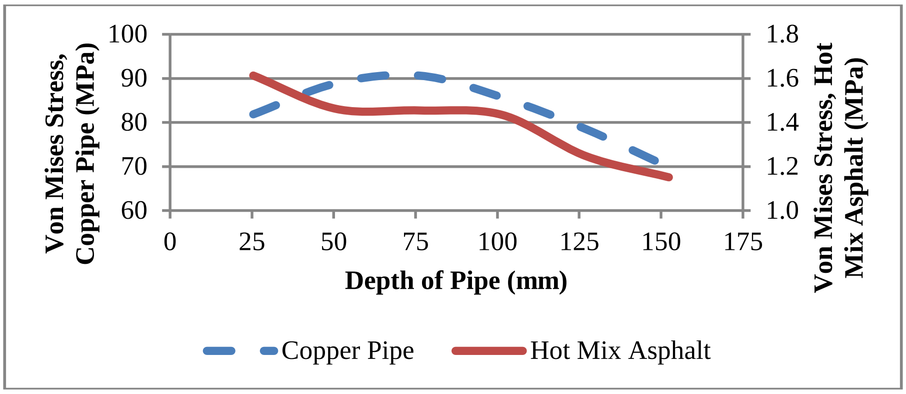


Figure 8: Copper pipe and pavement Von Mises (MPa) stress versus depth of pipe (mm)

Material properties such as the modulus of elasticity of a material play a major role in the behavior of a structural system. Hot mix asphalt as a thermoplastic material exhibits a wide range of behaviors depending on the temperature to which it is subjected. Huang et al. provide equations which were used in each analysis for both the modulus of elasticity, E (adjusted to provide output in MPa, original equation (in psi) in brackets), and Poisson's ratio as a function of temperature, θ (in degrees Celsius) as follows in Equations 1 and 2 (Huang et al. 2004):

$$E(\theta) = 0.006894 \times [9 \times 10^7 \cdot \theta^{-2.0889}] \tag{1}$$

$$\nu(\theta) = 0.0887 \cdot \theta^{0.3791} \tag{2}$$

Two other pipe materials, PVC and PEX (cross-linked polyethylene), were investigated to determine the effect of the different materials on the stresses present in both the pipe and the pavement as a function of temperature. Two additional models were created with a pipe at a depth of 100 mm (4 inches) containing the new materials in the place of copper.

Figure 9 compares the behavior of the two new materials with that of copper, and Table 1 summarizes the maximum stresses. Copper witnessed the highest pipe stress as well as the lowest pavement stress due to its high modulus of elasticity (117,300 MPa). The extreme difference in the modulus of elasticity of the PVC (2,898 MPa) and PEX (630 MPa) from copper resulted in significantly lower stresses in the pipe; however, the difference in the maximum stresses in the pavement versus that produced with the copper was very small. Although the difference in maximum pavement stress increased slightly with temperature, it did not exceed the tensile strength of good quality HMA in any application. The range of stresses determined for the HMA of 1.2 to 1.6 MPa are consistent in magnitude with those presented by Bondt et al. (Bondt et al. 2006). Also, for all of the pipe materials, the maximum stresses did not exceed the yield strength of the pipe material. One last model utilizing the copper pipe was created to investigate the effect on pavement stresses from placing the edge of the wheel load directly over the pipe. This model yielded a maximum pavement stress of 1 MPA which was less than that determined for the central loading of the slab. This analysis demonstrates the ability to evaluate the survivability of alternative pipe materials under the same conditions, which provides additional design options.

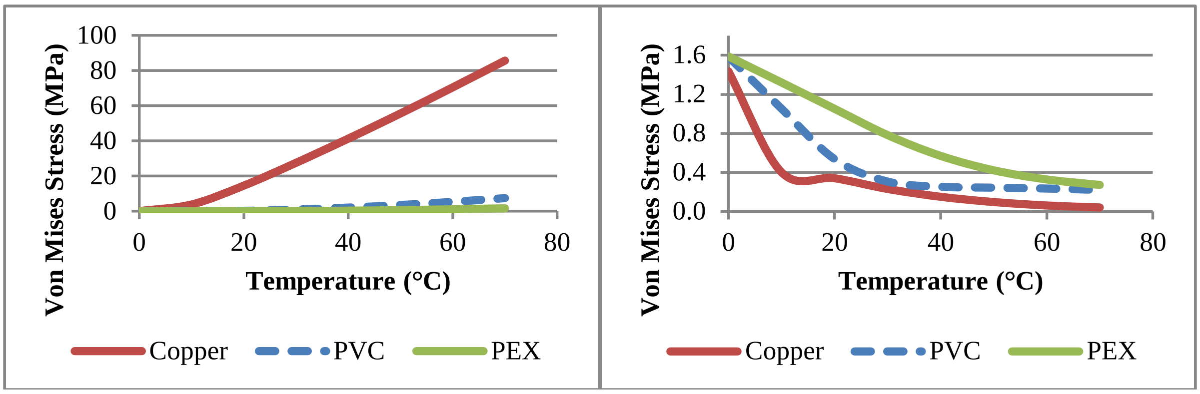


Figure 9: Maximum pipe (left) and pavement (right) stress profiles versus temperature for different pipe materials (100 mm pipe depth)

Table 1: Maximum determined stress summary for different pipe materials (100 mm depth)

Material	**Tensile Yield Strength (MPa)**	**Maximum Stress (MPa)**	
		Pipe	**Pavement (HMA)**
Copper	345	85	1.4
PVC	51	7.5	1.6
PEX	15	1.7	1.6
HMA	2	-	-

7 SUMMARY

Passing water through a pipe network installed in the pavement provides a method to extract the thermal energy and lower the temperature of the pavement thus reducing the urban heat island effect. A procedure was introduced to first address the economic feasibility of such a pipe network followed by the structural analysis of the pipe network through finite element modeling. Through the use of three spreadsheets, a pavement temperature profile is developed, the amount of harvestable energy is determined, and the size of the network is established. Based on these parameters a payback period is calculated to determine the economic feasibility at that location. Once economic feasibility has been proven, a finite element model can be developed to determine structural survivability. Solutions over the entire temperature range to which the pavement will be subjected must be completed to adequately analyze the performance of the pipe network. This process is repeated for each depth of pipe to be considered, resulting in a matrix of stress profiles. The points of maximum stress in each material are then compared to the yield stress for that material resulting in a pass or fail condition for that material. At this point a variety of materials can be explored until a desired material passes at which point the pipe network configuration has achieved structural survivability. The end result this method is a system that is both economically feasible and will structurally survive its intended application to extra thermal energy from asphalt pavements and reduce the urban heat island effect.

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