Hindawi Publishing Corporation
Journal of Energy
Volume 2014, Article ID 602087, 9 pages
http://dx.doi.org/10.1155/2014/602087

Research Article

Structural and Thermal Analysis of Asphalt Solar Collector Using Finite Element Method

Jinshah Basheer Sheeba[1] and Ajith Krishnan Rohini[2]

[1] *Department of Automobile Engineering, KMCT College of Engineering, Kallanthode, Kozhikode, Kerala 673601, India*
[2] *Department of Mechanical Engineering, Jyothi Engineering College, Cheruthuruthy, Thrissur, Kerala 679531, India*

Correspondence should be addressed to Ajith Krishnan Rohini; ajithjec@gmail.com

Received 23 August 2014; Accepted 28 October 2014; Published 15 December 2014

Academic Editor: Guobing Zhou

The collection of solar energy using asphalt pavements has got a wide importance in the present energy scenario. Asphalt pavements subjected to solar radiation can reach temperature up to 70°C because of their excellent heat absorbing property. Many working parameters, such as pipe diameter, pipe spacing, pipe depth, pipe arrangement, and flow rate, influence the performance of asphalt solar collector. Existing literature on thermal energy extraction from asphalt pavements is based on the small scale laboratory samples and numerical simulations. In order to design an efficient asphalt solar collector there should be a payoff between the thermal and structural stability of the pavement, so that maximum heat can be absorbed without structural damage due to external load condition. This paper presents a combined thermal and structural analysis of asphalt solar collector using finite element method. Analysis is carried out in different models so as to obtain optimum pipe spacing, pipe diameter, depth, and pipe arrangement under the specified condition.

1. Introduction

Sustainable supply of energy is the key factor that determines the development of an economy. The current growth rate of energy consumption will lead to complete scarcity of the major energy resource, fossil fuels, in the near future. The situation is most worrying because of the effect of major pollutants like CO_2 on the earth atmosphere. This situation forced the researchers to think of green technologies by which the global energy production can be increased. This points to the importance of distributed power generation. Distributed small scale production can increase the global energy production and at the same time it has an advantage of low transmission cost. Asphalt solar collector is not a new technology. This system is employed in many countries for the purpose of heating and cooling of road pavements in winter and summer, respectively. By proper design the technology can be utilised to power some of the applications at the site where it is utilized (distributed power generation).

Solar energy is the primary energy source for all other forms of energy which is green thermal source distributed around the globe. Road pavements can be considered as the largest solar thermal collector cum storage system on land. It receives solar radiation all the day and stores some of the energy from it. This energy is completely or partially dissipated to atmosphere by night time. Studies show that on an average summer day the temperature of an asphalt pavement can reach up to 60–70° because of its excellent heat absorbing property. The solar thermal energy collected by the asphalt pavement can be harvested by circulating fluid through it. A system that is designed for this purpose is called asphalt solar collector (ASC). Harvesting of thermal energy from asphalt pavement is a challenging technology for energy production in the future.

An ASC consists of tubes or pipes embedded in the pavement through which a fluid, usually water, with an antifreezing agent is circulating. The collected energy can be stored as such or converted to any other form which suits the utility. There are three major benefits for the system: (a) if the heat can be collected with a reasonable efficiency and cost, it can be considered as the energy source, (b) a part of the stored heat can be utilised for heating the road in winter season to avoid ice formation, and (c) the extraction of heat in summer helps to reduce the thermal stress development and thereby rutting. Many constraints arise on embedding the pipes in the pavement. The major constraint is that it will affect the durability and sustainability of the pavement. ACS can only be employed when building new road or at the time of large scale maintenance of the existing road. Not only the amount of energy extraction but also the variation of temperature on the pavement surface is to be studied so as to avoid the development of thermal stress.

In order to design an efficient ASC there should be a payoff between the thermal and structural performance of the system. Optimum pipe depth, spacing, and flow rate for a particular pipe diameter have to be designed to have maximum heat extraction without causing structural failure in adverse conditions. Many researches have been done to predict the performance of the ASC numerically and experimentally. Some of the major works are described below. Zwarycz [1] designed a snow melting system operating between −16°C and 3°C and studied the performance. He observed an uneven heat transfer at the surface of the pavement. Loomans et al. [2] conducted numerical and experimental analysis to assess the thermal potential of asphalt pavements. He found that the effectiveness of this system is less as compared to that of conventional solar hot water heaters. Wu et al. [3] conducted a study in laboratory to find the effective heat exchanger that can extract maximum heat from the asphalt pavement. The results suggest that while using graphite content in the middle layer the temperature is reduced to a much lower value comparing to region that does not have graphite. Mallick et al. [4] presented the theoretical considerations obtained from his study that by selecting appropriate layer aggregates the harvesting of solar energy is feasible. Wu et al. [5, 6] had numerically and experimentally analysed the performance of full depth asphalt slab as a solar collector. Bobes-Jesus et al. [7] presented a literature review on the various parameters affecting the performance of asphalt solar collector.

Pascual-Muñoz et al. presented a new technology in which a multilayered pavement with a highly porous middle layer is used instead of a solar collector with an embedded pipe network. Excellent thermal efficiencies were obtained in the laboratory tests. Efficiency values from 75% up to 95% were obtained depending on the irradiance from the solar lamp, porosity of the intermediate layer, and slope applied to the collector. The authors also suggest that the addition of materials such as graphite can be used to enhance the thermal properties of the asphalt [8]. The influence of using different kinds of materials in the asphalt solar collector is studied by many researchers. Several experiments have been conducted to analyse the effect of raising the pavement thermal conductivity by the addition of aggregates of higher thermal conductivity such as graphite or quartz [4, 9]. This paper focuses on the combined structural and thermal analysis of asphalt solar collector having a fixed 20 mm pipe diameter. Various models are examined in COMSOL Multiphysics 4.2b to predict the thermal performance; structural analysis is conducted in ANSYS APDL. The models are redesigned iteratively to obtain an optimum design.

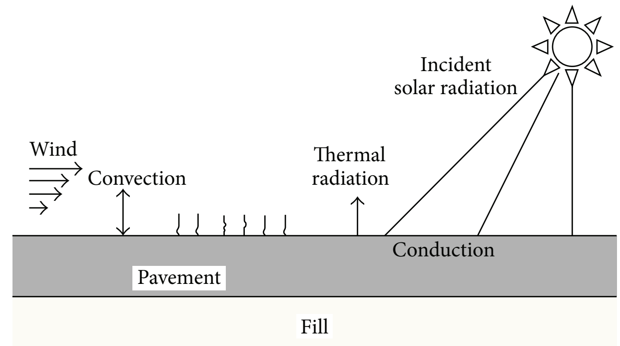


Figure 1: Various modes of heat transfer in asphalt pavement.

Computer simulation has become an essential part of science and engineering. Digital analysis of components is important when developing new products or optimizing designs because their real time experimentation is sometimes difficult and costly. Today a broad spectrum of options for simulation is available; researchers use everything from basic programming languages to various high-level packages implementing advanced methods. A computer simulation environment is simply a translation of real-world physical laws into their virtual form. COMSOL is all about to have a simulation environment that included the possibility to add any physical effect to your model. It is a flexible platform that allows even preliminary users to model all relevant physical aspects of their designs. COMSOL is equipped with a lot of packages for different studies. The package useful for our study is the Heat Transfer Module, with customized physics interfaces for the analysis of heat transfer. Arbitrary couplings to other applications modes in COMSOL Multiphysics are possible within Heat Transfer Module; this is particularly relevant for systems based on fluid-flow as well as mass transfer. On the other hand ANSYS APDL is a well-proven module to solve structural system that has complex parameters. It can give a clear-cut idea about the structural performance of a system with close tolerance to that of real time data. In this work we choose COMSOL for thermal analysis and ANSYS APDL for structural analysis.

2. Energy Balance in Asphalt Pavement

The temperature distribution of an asphalt pavement is affected directly by the thermal environment conditions to which it is exposed. The primary modes of heat transfer include incident solar radiation, thermal and long wave radiation between the asphalt pavement surface and the sky, convection due to heat transfer between the pavement surface and the fluid (air or water) that is in contact with the surface, conduction inside the pavement, and the radiation heat loss from surface. Figure 1 shows the various heat transfer modes in a heat conducting asphalt pavement exposed to solar radiation.

Table 1: Properties of material.

Layer	Density, ρ (kg/m^3)	Thermal conductivity, k (W/mK)	Specific heat, C_P (J/kgK)	Young's modulus, E (Mpa)	Poisson ratio, μ
HMA (layer 1)	2600	1.83	920	3500	0.4
Base (layer 2)	2600	1.83	920	3500	0.45
Subgrade (layer 3)	2200	1.7	1800	2800	0.45
Copper tube	8700	400	385	1.1×10^5	0.34

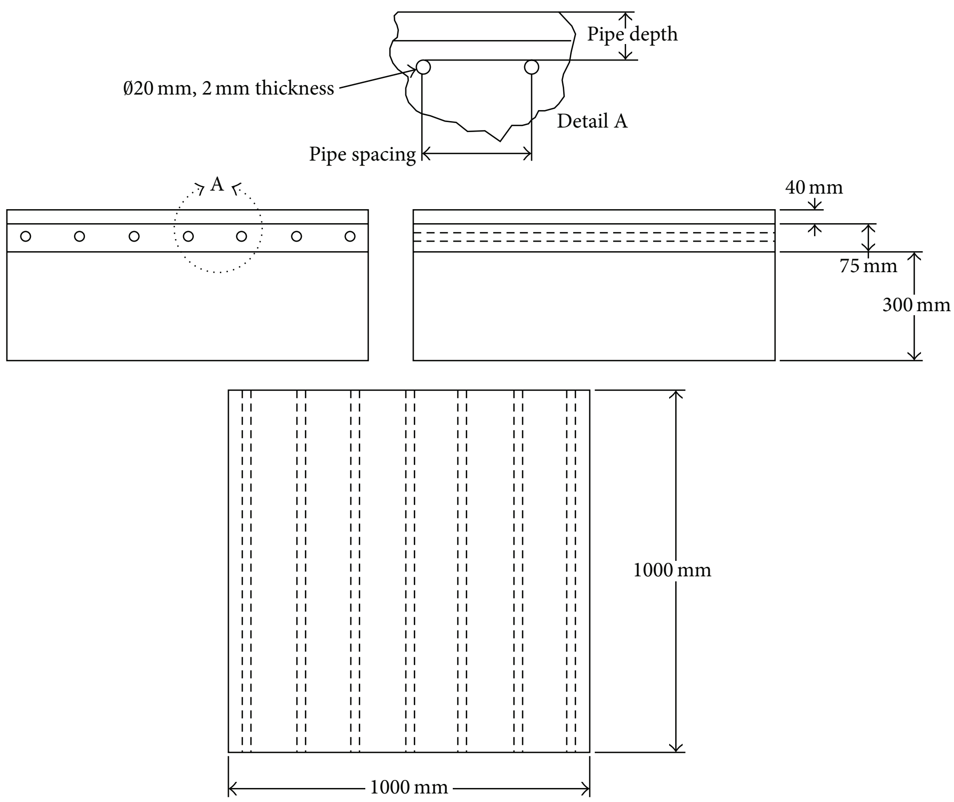


Figure 2: Straight pipe arrangement.

3. Thermal Analysis

From the literature it is clearly observed that the properties of asphalt surfaces strongly depend on temperature. One of the important factors in deciding the life of the pavement is its thermal response to solar radiation. A uniform temperature along the surface is a better option to avoid the thermal failure. Our interest is to find out the optimum pipe spacing and pipe depth in asphalt pavement so as to make an almost uniform temperature distribution in asphalt pavement surface. In order to find out the temperature variation within the asphalt pavement and the amount of energy extracted by the circulating water we conduct simulation on various models with different pipe spacing, pipe arrangement, and pipe depth and at different flow rates. Figures 2 and 3 show the structure of the asphalt pavement we chose for our study purpose. The pavement structure has a dimension of 1000 mm × 1000 mm with a total depth of 415 mm. The structure is inclusive of three layers as shown in Figure 4. The thermal properties of each layer are given in Table 1. Two types of pipe arrangements are possible: straight pipe and serpentine. Straight pipe is commonly used due to its advantage in providing more uniform temperature at surface. Serpentine arrangement can lead to nonuniform temperature in asphalt layers; this is proven in our analysis. The blockage to pipe may lead to the overheating of surface in case of serpentine arrangement, but in case of straight pipe arrangement blocking of a single pipe will not affect the system.

In the asphalt structure, studies are conducted by varying the pipe spacing(s) and pipe depth d, keeping the pipe diameter fixed at 20 mm diameter and thickness of 2 mm. The thermal analysis is conducted in COMSOL Multiphysics 4.3b, Heat Transfer Module. COMSOL Multiphysics is a finite element analysis, solver, and simulation software for various physics and engineering applications, especially coupled phenomena, or multiphysics.

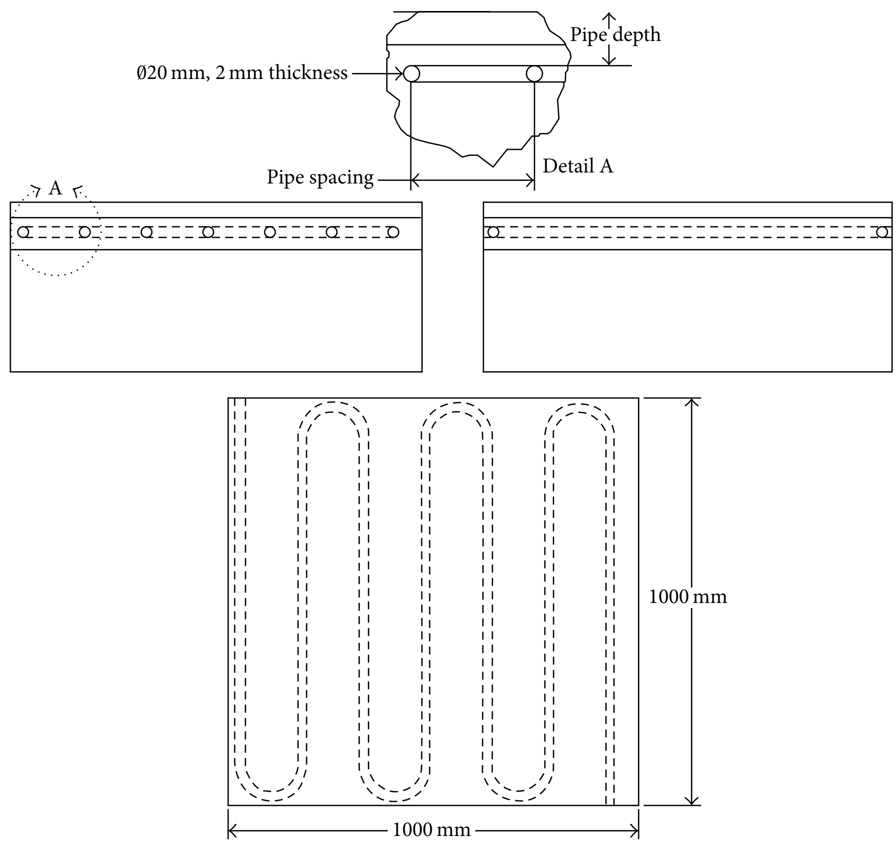


Figure 3: Serpentine arrangement of pipe.

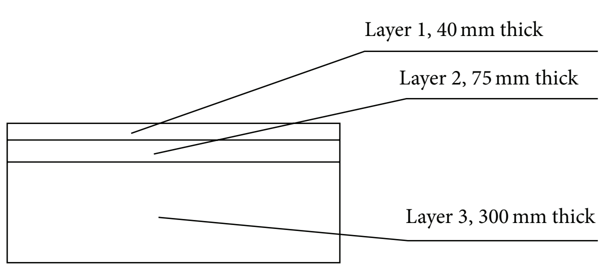


Figure 4: Model of pavement under study.

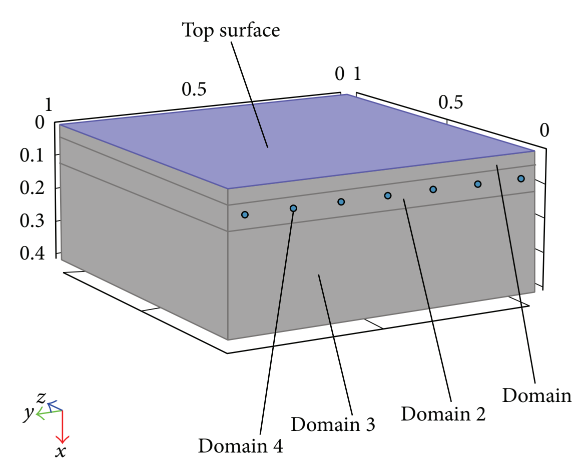


Figure 5: ASC model in COMSOL.

In the present study we choose Conjugate Heat Transfer-Laminar Flow Interface for our simulation. The Conjugate Heat Transfer-Laminar Flow Interface is used primarily to model slow-moving flow in environments where temperature and energy transport are also an important part of the system and must be coupled or connected to the fluid-flow in some way. The various modes of heat transfer between the asphalt layers, pipe fluid, and the external environment are as follows:

(i) conduction through asphalt layers;

(ii) conduction through embedded pipes;

(iii) convective heat transfer from pavement surface to ambient;

(iv) convective heat transfer from pipe wall to flowing water;

(v) radiation heat transfer from asphalt surface.

Initially a 3D model consisting of the asphalt layer and fluid domain is made using Autodesk Inventor 2013. The model is then imported to the COMSOL interface for thermal analysis. The asphalt solar collector model for study in COMSOL is shown in Figure 5 along with the domain details in Table 2.

Table 2: Domain details.

Domain 1	Top layer (HMA)
Domain 2	Middle layer (base)
Domain 3	Bottom layer (sublayer)
Domain 4	Water domain

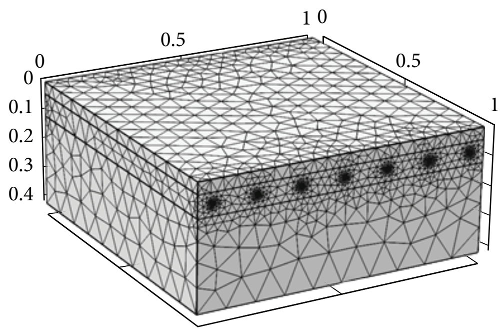


Figure 6: Meshed model.

Fluid domains are selected separately and the material was assigned as water. The pipe material for the purpose of the asphalt solar collector is selected as copper due to its high thermal conductivity. The pipe wall is built into the model by Highly Conductive Layer Feature in Heat Transfer Module. A layer thickness of 2 mm is provided in user interface with material as copper. The details of various input conditions for analysis are provided in Table 3. Analysis is conducted on different models with different pipe spacing and pipe depth. The details of models under analysis are given in Table 4.

The meshing of the entire domain was done by mesh tool in COMSOL with a physics controlled mesh sequence under normal size element. The entire module is meshed with free tetrahedral elements as shown in Figure 6. The details of element size and number are given in Table 5. In each model, the pipe diameter (20 mm) is made constant and thermal analysis was conducted and the surface temperature distribution was collected along the central line as shown in Figure 7 along with the outlet temperature of circulating fluid. The surface temperature can be directly obtained from the result of the analysis by 3D group plot tool. Cutlines are defined manually along the centre line to obtain the temperature along the cutline.

4. Structural Analysis

Strength of a system is determined by the weakest component. Embedding of tube system helps to reduce the thermal stress developed in the pavement. On the other hand the addition of weak elements will affect the strength of the pavement. FEA is the powerful proven method to analyse complex structures like asphalt pavements. Even though 3D structural analysis is superior to 2D plane strain analysis, the large longitudinal dimension makes it suitable for using 2D plane stress analysis with close results. This part of analysis helps to determine the effect of tube layouts in the pavement structure. Different models analysed in this paper are as follows:

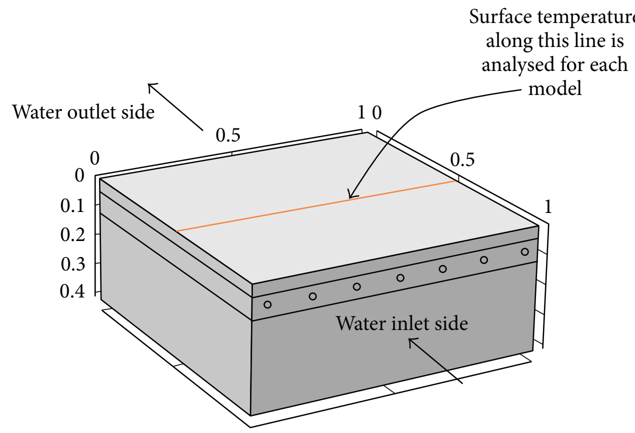


Figure 7: Surface temperature collection line and water inlet and outlet region in straight pipe arrangement.

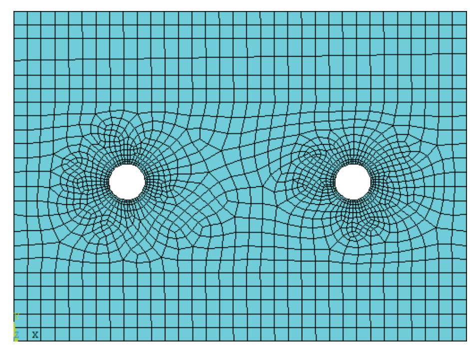


Figure 8: Finite element mesh for pipe spacing 150 mm at a depth of 75 mm.

(i) 200 mm long pavement with 100 mm tube spacing at a depth of 75 mm;

(ii) 300 mm long pavement with 150 mm tube spacing at a depth of 75 mm;

(iii) 300 mm long pavement with 150 mm tube spacing at a depth of 50 mm;

(iv) 400 mm long pavement with 200 mm tube spacing at a depth of 75 mm.

The depth of each layer is kept the same in all the models. The topmost HMA layer, middle base layer, and the bottom sublayer are considered to have a thickness of 40 mm, 75 mm, and 30 mm, respectively. The finite element mesh boundary condition, material properties, and load conditions are the same for all the analysis. Quad 4 node 182 is chosen as the plane element type. Figure 8 shows the finite element mesh of the model. The bottom layer of the pavement is assumed to be fixed to prevent both vertical and horizontal deflections. The boundary nodes along the sides of the model are constrained in the horizontal direction. Plane strain model used in this analysis assumes the thickness in longitudinal direction infinite. In all the analysis tyre pressure was taken as 0.7 Mpa, weight was supported by tyre as 25 kN, and the water pressure is 0.72 pa (which is considered as negligible). Figure 9 shows the load condition and constraints. Analysis is conducted on

Table 3: Input details for thermal analysis in COMSOL.

Thermal insulation	Bottom surface insulated
Pipe wall condition	No slip boundary condition
Initial temperature	T initial = 300 K
Heat flux input	800 W/m^2, general inward heat flux condition on top surface of model
Highly conductive layer	Boundaries of fluid domain selected layer thickness given as 2 mm, material copper
Convective heat flux	User defined heat transfer coefficient given as 20 W/m^{2}K on top surface, T_{ambient} = 300 K
Surface to ambient radiation	User defined emissivity = 0.7, T_{external} = 300 K
Water inlet temperature	T inlet = 298 K
Inlet water velocity	8 mm/sec–50 mm/sec

Table 4: Models analysed.

Size of model	Arrangement and short notation
1000 mm × 1000 mm, s = 200 mm, d = 75 mm	Serpentine (pipe diameter 20 mm), 200 × 75 serp
	Straight (pipe diameter 20 mm), 200 × 75 str
1000 mm × 1000 mm, s = 150 mm, d = 75 mm	Serpentine (pipe diameter 20 mm), 150 × 75 serp
	Straight (pipe diameter 20 mm), 150 × 75 str
1000 mm × 1000 mm, s = 100 mm, d = 75 mm	Serpentine (pipe diameter 20 mm), 100 × 75 serp
	Straight (pipe diameter 20 mm), 100 × 75 str
1000 mm × 1000 mm, s = 150 mm, d = 50 mm	Straight (pipe diameter 20 mm), 150 × 50 str

Table 5: Mesh details.

Domain	Domain 4 (water)	Overall
Minimum element size	0.0193 m	0.1 m
Maximum element size	0.0644 m	0.018 m

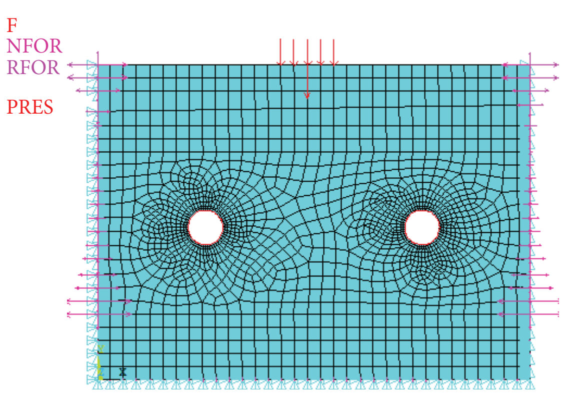


Figure 9: Load applied at the midsection.

each model at three different load conditions. In the first analysis external loads are applied at the surface in line with the tube centre, in the second conditions the loads are applied at the surface in midplane of the tubes, and in the third the loads are applied nearer to one tube.

5. Results and Discussion

The result obtained from our analysis is shown in Figure 13 in a line graph. From the graph it is clearly understood that the surface temperature variation for serpentine fashion is very high. For the cases of serpentine models, 200 × 75 serp, 150 × 75 serp, and 100 × 75 serp, the temperature varies from 318 K to 328 K. In case of 200 × 75 serp model the temperature varies from 320 K to 327 K; there is an initial reduction in surface temperature in serpentine arrangement due to large temperature difference during the initial time of flow. Once the water is heated during its path along the pipe by extracting heat from asphalt layer through copper pipes, its temperature gradually increases and in later stages it cannot be able to absorb more energy from asphalt layers. The final result due to this is gradual increase in asphalt surface temperature from inlet to outlet along centre line. Hence the performance of serpentine arrangement is poor in providing uniform surface temperature. We can see the effect of straight pipe arrangement on asphalt surface temperature variation for different models, 200×75 str, 150×75 str, and 100×75 str. Clearly it is more uniform than serpentine arrangement, but there is some regular asphalt surface temperature variation from pipe to pipe in the straight pipe arrangement. In case of 200 × 75 str the surface temperature variation is within 320 K to 322 K. On reducing the pipe spacing from 200 mm to 150 mm, keeping pipe depth the same, surface temperature reduced due to more heat absorption from surface to flowing water in pipe. But still there is a regular variation in surface temperature between pipes as in previous case of 200 × 75 str arrangement. To find the dependency of depth on the surface temperature we conducted an analysis on 150 × 50 str arrangement where the depth is reduced to 50 mm. The result obtained is not much satisfactory; even the surface temperature that reduced the temperature variation between pipes still exists. A 100×75 str arrangement can make the temperature variation more uniform within 317.5 K. Temperature variation within asphalt layers for 100 × 75 str arrangement solved by COMSOL is shown in Figure 10. The temperature distribution within the pipes where water is flowing is shown

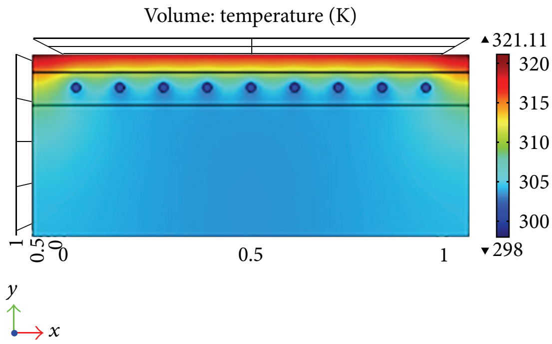


Figure 10: Temperature variation within asphalt layers for 100 × 75 str arrangement.

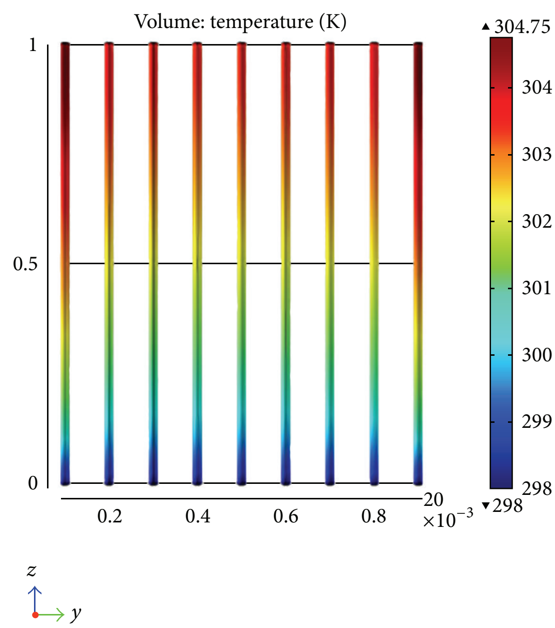


Figure 11: The temperature distribution within the pipes.

in Figure 11. The maximum temperature obtained at outlet by analysis is 304.7 K, that is, a 6.7°C temperature rise.

Now when we consider the fact of outlet temperature variation in case of different models, we can see a maximum temperature is attained by the serpentine arrangement as shown in Figure 12. The water outlet temperature is higher in three serpentine arrangement cases when compared to straight pipe arrangement. Maximum temperature of 322 K is attained by 100 × 75 serp arrangement, which is a 24°C rise compared to inlet.

It is important to consider the structural aspect also because reducing pipe spacing and reducing pipe depth will lead to damage of pipes and road surfaces due to loads exerted from vehicles. The result from structural analysis also needs to compare to fix the spacing and depth. On analysing different models with different pipe spacing and depth, the results show all the models were under safe operation. Figures 14 and 15 show the von Mises stress distribution in the 150 × 75 str model examined. From the plot it is clear

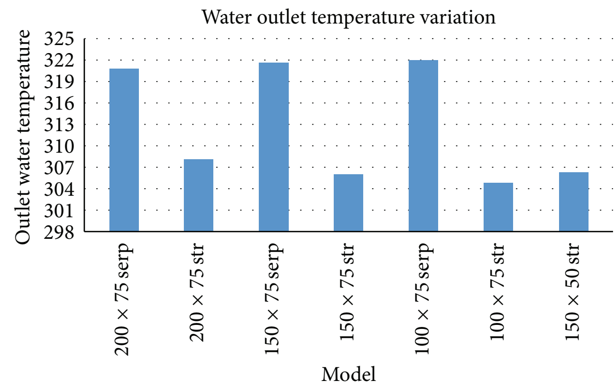


Figure 12: Outlet water temperature for different pipe arrangements.

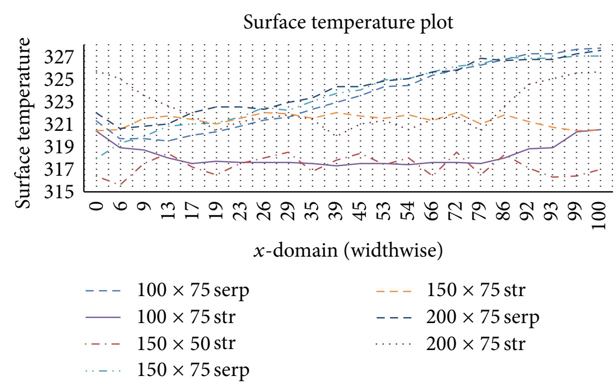


Figure 13: Surface temperature collection line and water inlet and outlet region in straight pipe arrangement.

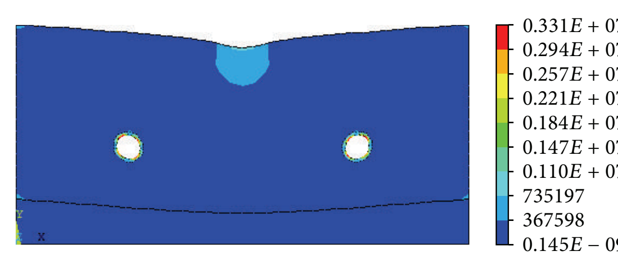


Figure 14: Stress distribution when load is applied at the middle.

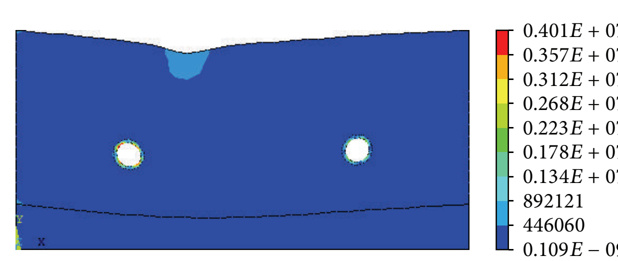


Figure 15: Stress distribution when load is applied eccentrically.

Table 6: Result of stress analysis.

Model	Load applied on surface in line with the tube	Load applied at midplane	Load applied eccentrically between the tubes at surface
100 × 75 mm	0.23×10^7 pa	0.298×10^7 pa	0.314×10^7 pa
150 × 75 mm	0.287×10^7 pa	0.31×10^7 pa	0.41×10^7 pa
150 × 50 mm	0.41×10^7 pa	0.285×10^7 pa	0.41×10^7 pa
200 × 75 mm	0.291×10^7 pa	0.33×10^7 pa	0.490×10^7 pa

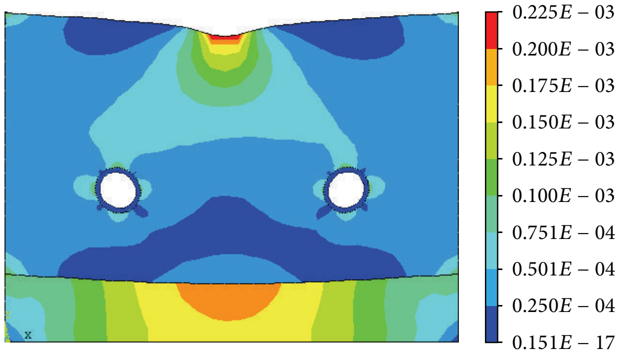


Figure 16: Strain distribution.

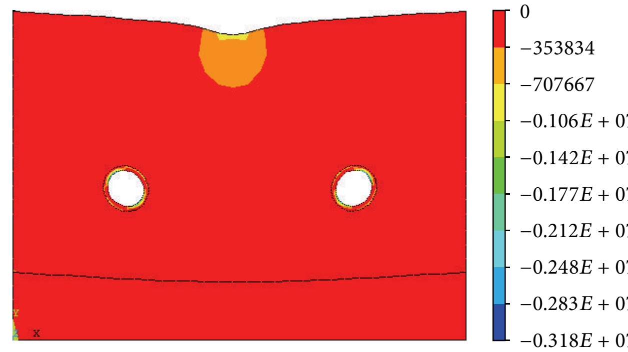


Figure 17: Third principle stress.

that the maximum stress is developed at the interface of copper tube and within the tube. Within the asphalt the stress is within permissible limit [10]. Since the temperature is maximum at the surface of the pavement the stress value decreases with depth and becomes maximum at the interface between the pavement and the copper tubes. This shows that the possible mode of failure may be because of fatigue and creep. Within the copper the maximum stress developed is 0.490×10^7 pa, which is for the model 200 × 75 str when the load is applied eccentrically between the tubes at the surface. This value is very small when compared to the safe stress for a copper tube [11]. Table 6 shows the result of von Mises stress in different models. Figure 16 shows the strain distribution in the model. From the result it is clear that the maximum strain is at the layer just below the application of load. The value is in the order of 0.0001 which is negligible. The deformation is in the order of micrometres. For further analysis the first, second, third, and fourth principle stresses have been plotted. From the analysis the maximum value is obtained for the third principle stress as shown in Figure 17.

6. Conclusions

The numerical study conducted on ASC shows that both the pipe depth and pipe spacing strongly influence the temperature distribution within the pavement. Within a certain limit the structural stability is not affected much. As the structural and thermal properties of ASC are subjected to vary with prevailing temperature condition, mix proportions, and compactness of the pavements, the exact performance can only be predicted by conducting real time experiments on large models. Numerical study is enough to predict the behaviour of such system under certain assumptions. As an initial study numerical analysis is conducted on asphalt models with different pipe length and pipe spacing [100 × 75 mm, 150 × 75 mm, 150 × 50 mm, and 200 × 75 mm] and pipe arrangement by keeping both pipe diameter and flow rate constant. The result of analysis proves that reducing the pipe spacing will improve the quality of temperature profile at the surface of the pavement. At a spacing of 100 mm and depth of 75 mm nearly a uniform temperature profile is obtained on the pavement surface. Even more quality will be obtained if we go on reducing the spacing but it will reduce the solidity of the pavements. This added-up weak component will reduce the strength of the road pavement. As the pipe depth reduces more energy can be extracted. In order to maintain a structural safety a depth of 75 mm is advisable. Serpentine arrangements are not advisable as the temperature at the pavement surface increases linearly inducing large thermal stress in the pavements. Hence we conclude that the optimum spacing and depth as 100 mm × 75 mm straight arrangement.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

The authors thank Jesseela S, Assistant Professor in Mechanical Department, Government Engineering College, Kozhikode, for her support and valuable advice during this research.

References

[1] K. Zwarycz, *Snow Melting and Heating System Based on Geothermal Heat Pumps at Goleniow Airport, Poland*, Reports, The United Nations University, 2012.

[2] M. G. L. C. Loomans, H. Oversloot, A. de Bondt, R. Jansen, and H. van Rij, “Design tool for the thermal energy potential of asphalt pavements,” in *Proceedings of the 8th International IBPSA Conference*, vol. 8, pp. 745–752, Eindhoven, The Netherlands, August 2003.

[3] S. Wu, M. Chen, H. Wang, and Y. Zhang, “Laboratory study on solar collector of thermal conductive asphalt,” *International Journal of Pavement Research and Technology*, vol. 2, no. 4, pp. 130–136, 2009.

[4] R. B. Mallick, B.-L. Chen, and S. Bhowmick, “Harvesting energy from asphalt pavements and reducing the heat island effect,” *International Journal of Sustainable Engineering*, vol. 2, no. 3, pp. 214–228, 2009.

[5] S. Wu, H. Wang, M. Chen, and Y. Zhang, “Numerical and experimental validation of full-depth asphalt slab using capturing solar energy,” in *Proceedings of the 4th International Conference on Bioinformatics and Biomedical Engineering (iCBBE ’10)*, pp. 1–4, Chengdu, China, June 2010.

[6] W. Shaopeng, C. Mingyu, and Z. Jizhe, “Laboratory investigation into thermal response of asphalt pavements as solar collector by application of small-scale slabs,” *Applied Thermal Engineering*, vol. 31, no. 10, pp. 1582–1587, 2011.

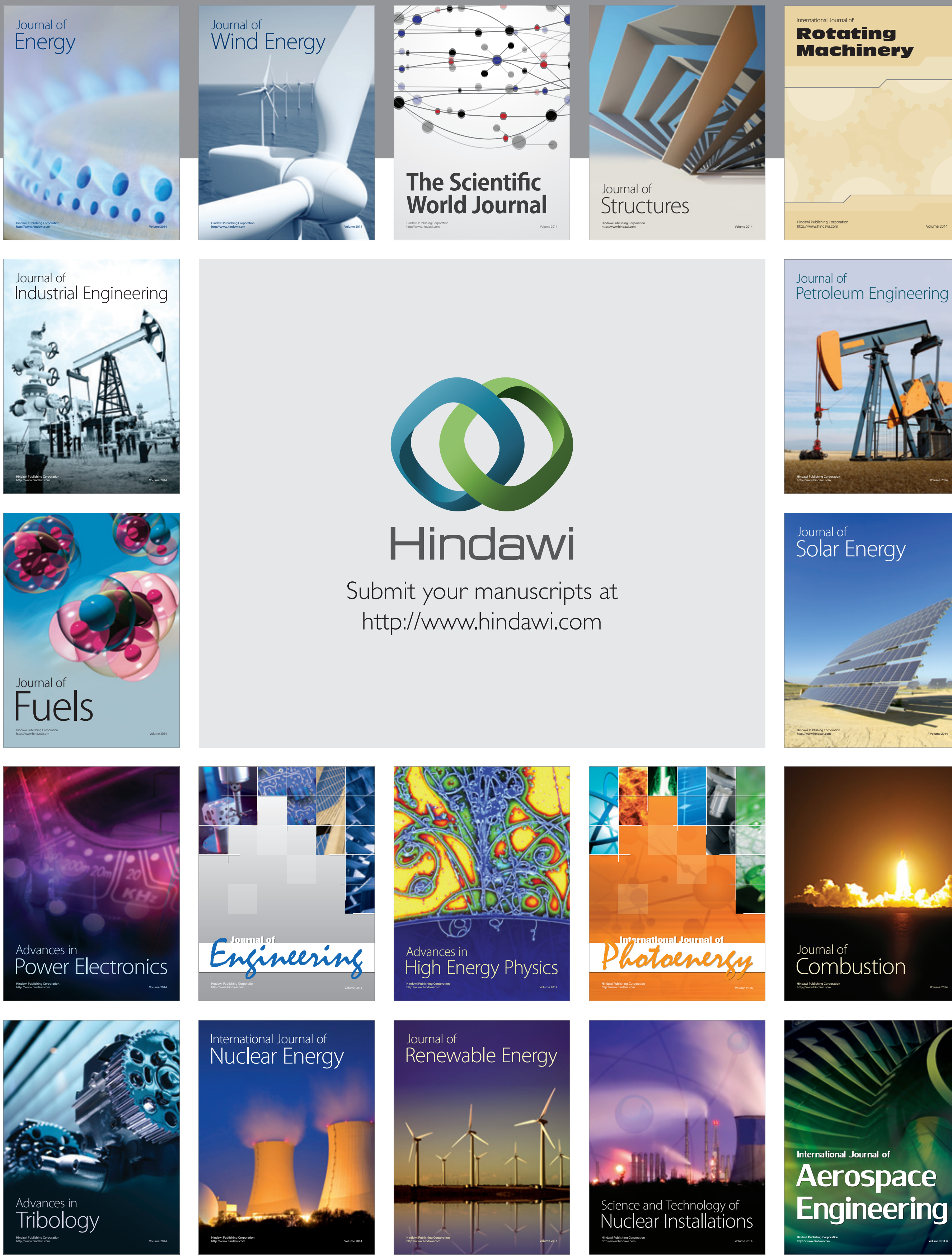
[7] V. Bobes-Jesus, P. Pascual-Muñoz, D. Castro-Fresno, and J. Rodriguez-Hernandez, “Asphalt solar collectors: a literature review,” *Applied Energy*, vol. 102, pp. 962–970, 2013.

[8] P. Pascual-Muñoz, D. Castro-Fresno, P. Serrano-Bravo, and A. Alonso-Estébanez, “Thermal and hydraulic analysis of multilayered asphalt pavements as active solar collectors,” *Applied Energy*, vol. 111, pp. 324–334, 2013.

[9] H. Wang, S. Wu, M. Chen, and Y. Zhang, “Numerical simulation on the thermal response of heat-conducting asphalt pavements,” *Physica Scripta*, vol. 3, 2010.

[10] AASHTO, *Guide for Design of Pavement Structures*, American Associates for State Highway and Transportation Officials, Washington, DC, USA, 1993.

[11] I.S.I.2825-1969, *Code for Pressure Vessel Design*, Bureau of Indian Standards, New Delhi, India, 1969.


Journal of Energy
Journal of Wind Energy
The Scientific World Journal
Journal of Structures
International Journal of Rotating Machinery
Journal of Industrial Engineering
Hindawi
Submit your manuscripts at
http://www.hindawi.com
Journal of Petroleum Engineering
Journal of Fuels
Journal of Solar Energy
Advances in Power Electronics
Journal of Engineering
Advances in High Energy Physics
International Journal of Photoenergy
Journal of Combustion
Advances in Tribology
International Journal of Nuclear Energy
Journal of Renewable Energy
Science and Technology of Nuclear Installations
International Journal of Aerospace Engineering