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Numerical simulation of heat recovery from asphalt pavement in Finnish climate conditions

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ABSTRACT

A 3-dimensional mathematical model of asphalt pavement system was developed, based on the fundamental energy balance, to calculate temperatures beneath asphalt surface using hourly measured solar radiation, air temperature and wind velocity data. The modelling was conducted to predict the heat retention under the asphalt surface to seek an optimum position of pipe tubing to maximise the heat extraction considering the Nordic winter conditions for future infrastructure projects. The model results show good agreement with the experimental results conducted in a span of three months (June–Sept) notwithstanding the simplification of the model i.e. thermal properties unaffected by changing moisture content, perfect contact between different layers and homogeneous and isotropic thermal properties of materials (asphalt, sand and gravel). The findings indicated that the positioning of the heat extraction tubes under the asphalt layer will be dictated by the application. For heat extraction, pipes closer to the surface are ideal for maximal heat absorption during summer, however, in winter the outer temperature may effect properties the pipes. Parameters including pipe diameter, positioning of the pipes and flow rate were analysed. Temperature increase of up to 10 °C gain was observed for piping closer to the asphalt layer and 6 °C for pipes position at deeper from the asphalt layer. This model could be used in future to optimise critical variables for successful implementation of asphalt heating concepts.

1. Introduction

Ongoing aims regarding climate change and environmental protection, such as reduction of fossil fuel consumption and greenhouse gas emissions has propelled the development of new technologies and improvements of old ones. Renewable energy sources provides a cleaner energy alternative. Solar energy is abundant energy resources that be harvested using heat collectors or solar panels [1]. Additional, solar energy can be collected from the asphalt layer during the hot seasons. Asphalt surfaces absorb significant amounts of solar radiation on a daily basis, up to 40 MJ/m^2 over the course of a day during summer, which causes high temperatures in the pavement structure [2].

Heat harvested using a heat exchanger system embedded in the pavement structure can have potential benefits. First it can provide clean and low cost thermal energy to surrounding buildings, secondly, the energy collected in the summer can be stored to be used for other purposes such to melt the ice and snow off of the asphalt pavement in winter and finally saves the asphalt from large temperature changes that can cause structural damage like rutting or hardening asphalt pavements [3]. This can also reduce heat island effects and hence reduce cooling needs (as shown e.g. in Greece). Further, it may also improve air quality because asphalt warming can cause volatile organic compounds emissions [4,5].

Heat recovery from asphalt layer is promising technology for utilisation the most shallow geothermal potential with important side effect of reducing “urban heat island effect” (UHI). The urban heat island effect has significant impact on environment and quality of life of urban inhabitants [6–9]. Furthermore, high temperatures reached in summer have negative influence on the lifespan of asphalt layer [10]. Given the available thermal potential, many applications can be identified in which the thermal energy recovered from the asphalt layer can be used through Asphalt Mounted Solar Collectors [11]. The potential usage of Asphalt Mounted Solar Collectors is coupling with geothermal storage systems so that it can be used to defrost critical areas of highways or bridges [12] without using fossil fuels or chemically or mechanically aggressive materials for the asphalt layer. Worldwide there is an increasing interest in similar applications [13,14]. The Swiss government has supported the development of the SERSO system in a research grant [15]. Its purpose was to collect thermal energy from

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asphalt surfaces in the hot season and store it in rock for reuse during the cold period of the year to defrost bridges. A similar approach is presented in a study conducted by Gao et al. [16]. Other studies have proposed the connection of Asphalt Mounted Solar Collectors with geothermal systems De Bondt [17] to regenerate them thermally for situations in which thermal energy extracted during the cold season is higher than the one reintroduced in the soil during hot season. In these cases, the connection of Asphalt Mounted Solar Collectors with deeper geothermal systems for their regeneration where imbalance of heat budget was proposed [17]. The study presented in this paper provides good basis for reliable estimation of validated heat fluxes (and temperatures) in the asphalt layer and soil subsurface. The future work on improvement of knowledge of heat transfer in the most shallow zone is ongoing in a local scale (3D model to about 30 m depth) by coupling Comsol Multiphysics describing physical processes on the top boundary (depending on climate) with FEFLOW code Diersch [18] simulating heat transfer in variably saturated rock environment with artificial layers (asphalt).

In light of such high potential benefits of asphalt heat extraction, research studies have been extensively carried out to predict the heat energy output. Loomans et al. [19] has proposed the concept to extracting solar energy from asphalt pavements [19]. Vuye et al. [20] and co-workers performed developed a modelling framework to predict the heat energy output temperatures and performed a laboratory scale experimentally for verification [20]. The results showed the experiment and simulation surface temperature of asphalt lie closely together with slightly higher from the simulation. The discrepancies were attributed to the uncertainties in the thermal properties of the material and the position of the thermocouples. However, the experiment was conducted on a 1 m^2 slap, therefore, this limits the laterally dissipation of heat, hence a higher heat retention within slap. As concluded by the authors, a comprehensive study of all geometrical and weather parameters needs to be conducted [20]. Similarly, Gao et al. [21], studied the influence of air voids on the cooling performance of the porous pavement [21]. Here, a simulated sunshine experiment and a finite element virtual experiment were used to evaluate the cooling effect. It was found that voids can reduce the heat absorption, heat conduction, and heat dissipation capacity of a porous asphalt mixture and thus affect the cooling effect of porous asphalt pavement. In both research studies, a good agreement between experimental data and the modelling framework with respect to pavement temperatures, the scale of the experiment does not mimic the weather conditions of an actual asphalt surface. Therefore, in this paper, a modelling framework is developed, and validated based on the experimental data conducted on the parking lot at University of Vaasa.

In university of Vaasa, the temperatures beneath the asphalt layer and similar lawn covered field were monitored for several years period. Measurements were made with help of distributed temperature sensing (DTS) method from vertical boreholes. Temperatures at a depth of 0.5 m under the asphalt layer were noticed to be very promising for heat collection from May until September. The temperatures at that depth are 10 °C–14 °C in May, rising to 26 °C in July and then falling back to 15 °C–16 °C in September. Heat of this five-month period would be preferable to be stored since the heating demand is very low during summer even in Finland. Mäkiranta et al. (2019) suggest either a purpose-designed storage deeper under the asphalt or a bedrock heat battery. Those could act as a seasonal thermal energy storage (STES). Storage would be loaded by heat gathered under the asphalt layer during the summer and then the heat would be utilised for heating of buildings nearby during cooler season [22]. To maximally tap from this energy, the position of the heat collector as well as the flow parameters ought to be optimised.

Thus, this work utilised the calibrated model developed to predict the total energy output, factors that may affect heat collections were considered including the position of the pipe underneath the surface, the pipe diameter, working fluid flow rate and the distance between the pipes. Input data to the model were hourly measured values for solar radiation, air temperature, and wind velocity from Vaasa.

2. Methodology

An overview of the governing equations and boundary conditions (BC) is first described before model development itself is discussed.

2.1. Heat transfer

The principle behind this model is based on a transient energy balance of the asphalt pavement, which includes heat transfer via conduction, convection and radiation. It is noteworthy to point that heat process such as micro-scale radiation between particles, convection in the pores, phase change processes depending on the season, condensation and vaporisation take place on the surface of the asphalt surface. However, in this study these processes are not taken into consideration because it takes place in small scale processes thus negligible in relation to the volume of the structure under consideration [23].

In this study, solar radiation from the sun to the surface, convective heat to and from asphalt surface and heat conduction via the stratified ground layers are considered, at the surface, mathematically expressed:

$$-\lambda T_{i,j} = \alpha_{sw} q''_{sw} + \epsilon\sigma(T_{sr}^4 - T^4) + h(T_a - T) \tag{1}$$

here, the first term on the right hand side represent heat energy from short-wave (solar) radiation gains, α_{sw} – absorptivity coefficient and q''_{sw} solar irradiation. The second term is thermal (long-wave) radiation heat flux between the asphalt surface and surrounding matter, ϵ and σ denotes the emissivity of the pavement and Boltzmann's constant whilst T_{sr} denotes the hypothetical temperature of the surroundings that absorb and emit radiation and can be expressed as

$$T_{sr} = T_{db}(0.004T_{dew} + 0.8)^{0.25}. \tag{2}$$

Here, T_{db} and T_{dew} are atmospheric dry-bulb temperature in K and dew-point temperature °C, respectively. The third term account for the heat convection across the asphalt surface. The empirical Bentz model that is a function of wind speed was employed to estimate the heat transfer coefficient, h to characterise the thermal boundary layer above the asphalt [24].

$$\begin{aligned} h &= 5.8 + 4.1 \cdot v_w \quad \text{for} \quad v_w \leq 5 \text{ m/s} \\ h &= 7.2 \cdot v_w \quad \text{for} \quad v_w > 5 \text{ m/s} \end{aligned} \tag{3}$$

Here, v_w is the wind speed. The wind speeds used in the model were obtained from a neighbouring meteorological department in Vaasa [25]. The difference between mean air speed and near-surface air velocity as a result of friction and uneven/rough surfaces is ignored. Finally, the last term in Eq. (1) accounts for conductive heat transfer, λ as thermal conductivity.

In Comsol Multiphysics software, the solar and ambient wavelength dependence of emissivity model is used to account for differing emissivities in different wavelength bands. Experimentally measured solar flux at the surface were is used in the modelling as presented in Çuhac et al. [1].

2.2. Flow problem

The continuity and momentum equations is used to calculate the pressure and velocity of an incompressible fluid system as outlined

$$\rho\nabla(\mathbf{u}) = 0 \tag{4}$$

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla[-p + \mu\nabla\mathbf{u}] \tag{5}$$

here u denoting the velocity and p pressure, μ and ρ represents the dynamic viscosity and density of the working fluid, respectively. The transient heat energy equation for fluid flowing

$$\rho AC_p\mathbf{u} \cdot \nabla T = \nabla \cdot Ak\nabla T + f_D \frac{\rho A}{2d_h}\left|\mathbf{u}\right|^3 + Q_{wall} \tag{6}$$

where A is the cross section area available for flow, d_h is the hydraulic radius, f_D friction factor, C_p the heat capacity at constant pressure.

Table 1
Thermal properties of the soil, [1,29].

Material	λ^* [W/m · K]	c_p [kJ/kg · C]	ρ [kg/m^3]
Asphalt	1	0.92	2400
Gravel	1.8	1.50 (dry)	1680
Sand	1.8	0.84 (dry, 20 °C)	2660
Clay	1.2	0.88 (10% moisture)	1600 (dry)

1 Thermal conductivity data were obtained from parametric fitting.
* Sand and gravel is mixed in ratio 1:2

The second term on the right hand side corresponds to friction heat dissipated due to viscous shear. Q_{wall} represents external heat exchange through the pipe wall. The radial heat transfer from surroundings is given by

$$Q_{wall} = (hZ)_{eff}(T_{ext} - T) \tag{7}$$

here, Z is the wetted perimeter of the pipe, h_{eff} is the overall heat transfer coefficient including the contributions of internal film resistance and layered wall resistance and T_{ext} is the external temperature outside of the pipe. The wall thermal conductivity of 400 W/m · K and a thickness of 2.23 mm were used in the simulation. The film resistance can be calculated using [26]

$$h = Nu\frac{k}{d_h} \tag{8}$$

Where, d_h is the hydraulic radius. $d_h = 4A/Z$. Nu is Nusselt number defined for turbulent flow as

$$Nu = \frac{(f_D/8)(Re - 1000)Pr}{1 + 12.7(f_D/8)^{1/2}(Pr^{2/3} - 1)} \tag{9}$$

here Pr is the Prandtl number $= C_p\mu/k$.

Pipe flow module provides 'Wall-Heat Transfer' feature that couples the temperature in a pipe to the temperature in a 3D surrounding, thus the flow problem is coupled to the thermal problem. The pipe flow module models the 3-D pipe as 2D curves, i.e., instead of a tube, a line is modelled. The physics interfaces in the module define the conservation of momentum, energy, and mass of a fluid inside a pipe or channel. The flow rate, pressure, temperature, and concentration fields are modelled as cross-section averaged quantities, so that they only vary along the length of the pipes [27]. A uniform mass flow rate and pressure outlet were prescribed for pipe inlet and outlet, respectively. Pressure loss due to bends were ignored. A no-slip velocity boundary condition was pipe wall was set. The working fluid is assumed to be pure water with a constant inlet temperature of 10 °C.

2.3. Model development

The simulation model is carried out using the hourly climate data of incident shortwave solar irradiation, air temperature and wind velocity. The radiation data for the climate file were obtained measured data as described in Çuhac et al. [1] while as the air temperature and wind speed is obtained from the nearby meteorological station, Klementtilä Vaasa [1,25].

The same dimensions as presented in the experiment design in Çuhac et al. [1] is kept in this study: a stratified layers of asphalt layer, a mixture of gravel and sand layer, and clay. The thickness of the asphalt layer is 8 cm, 60 cm layer consisting of the gravel and sand layer in a ratio of 1:2 and the underlying clay layer. It is assumed that these materials behave as a homogeneous material with isotropic thermal properties. The density and heat capacity of the material obtained from literature are depicted in Table 1. The thermal conductivity were obtained through fitting to experimental data. It is noteworthy to note that the thermal conductivity has been shown to vary with respect to the moisture content [5,28].

The pipe loop that acts as a heat exchanger is buried under the asphalt as shown in Fig. 1 below.

The mesh of the FEM is a combination of prismatic elements with a triangular base (for the middle part of the model), and tetrahedral elements for the end parts of the collector geometry. Larger elements were used parallel to the fluid flow and much smaller elements were necessary perpendicular to the fluid flow. The extremely fine elements mesh (minimum element size 4 mm and maximum size 50 mm) were used in and around the heat exchange pipes as shown in Fig. 1. The entire system is modelled in 3D using the finite element method, during which thin wall assumptions or other geometric simplifications are not applied. This approach allows for a comprehensive evaluation of the system. The position and orientation of the pipe is simulated to determine the highest possible outlet temperature and is the most pragmatic to construct.

3. Results and discussion

3.1. A comparison of experimental results to simulation results

The model described above was used to predict asphalt surface temperature profile evolution at various different depths in response to the weather variable periods. Temperature at 0.5 m, 1.0 m, 1.5 m and 3 m depths under the asphalt was measured as presented in Çuhac et al. [1]. The hourly climatic variables air temperature, wind speed for the study period were obtained neighbouring weather station and measured solar irradiation data were used in the modelling. A parametric study was performed to determine thermal conductivity of sand–gravel mixture and clay. Thermal conductivity of 1 W/m^{2}K, 1.8 W/m^{2}K and 1.2 W/m^{2}K respectively were found. These approximate values are in the range of literature values.

Fig. 2 shows the comparison of results between the measured temperature data and the simulated temperatures at predicted with the model, for a study period starting 24th June–12th September 2014. At 0.5 m deep a temperature over 25 °C was measured in the summer months, here, the model shows even a higher temperature can observed. The discrepancy can be attributed to non-continuous and sporadic time interval measurements of the data.

From the plot, it can be seen that in the first two weeks the model under predicts the measured data during the heat/cooling cycle of asphalt surface. This because the initial temperatures assigned in the asphalt layer, sand/gravel layer and clay were low i.e. 16 °C, 14 °C and 7 °C, respectively. Overtime as the model results and the measured moves towards a good agreement, notwithstanding the assumptions in the model that thermal properties were considered to be unaffected by changing moisture content, perfect contact between different materials and layers, homogeneous and isotropic layered materials. As expected, in 3 m depth, the heat transfer into the ground results in limited or no temperature fluctuations with respect to time. This is because with increasing depth, the increasing thermal mass of the soil renders the temperature at such depths independent of the heating and cooling cycles on the asphalt surface. However, there is still heat flux flowing into the ground. Closer to the surface, significant fluctuations were observed in the 0.5 m depth.

Fig. 3 shows the evolution of temperature over a period of six days. Simulation between two measured data points was performed. At t = 0, i.e. midnight there is no solar irradiation and maximum after midday. The change in surface temperature readily impacts the asphalt layer. On the day with less irradiation, cooling of the asphalt happens. As expected the impact of diurnal temperature variation significantly reduces as depth increases. As it can seen from the plot, the top surface i.e. the asphalt layer was significantly affects by the diurnal temperature up to a variation of 5 °C and with increasing depth the temperature change extent decreases gradually. However, over a long period of time (3) the temperature peak appeared lag as the depth increased; a hysteresis of heat transfer phenomena.

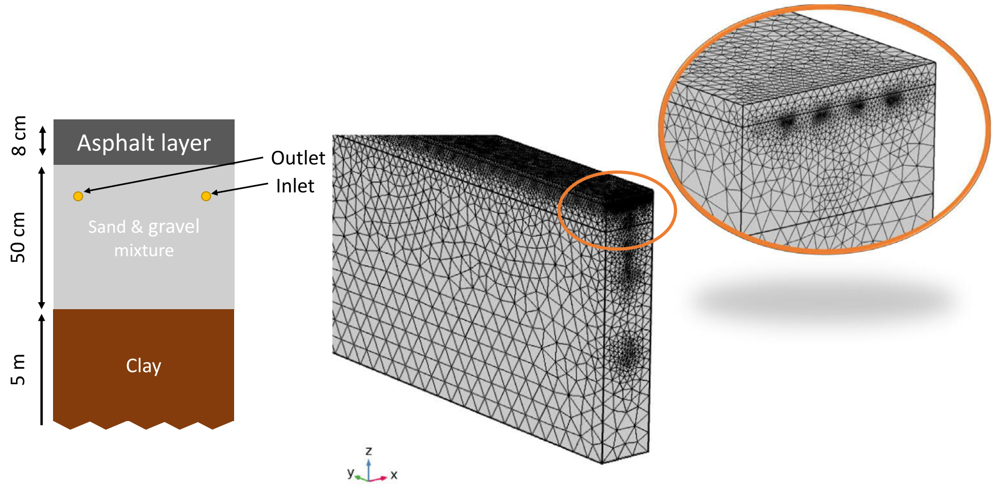


Fig. 1. A scheme of cross-sectional layers of the in the asphalt system and mesh of the model.

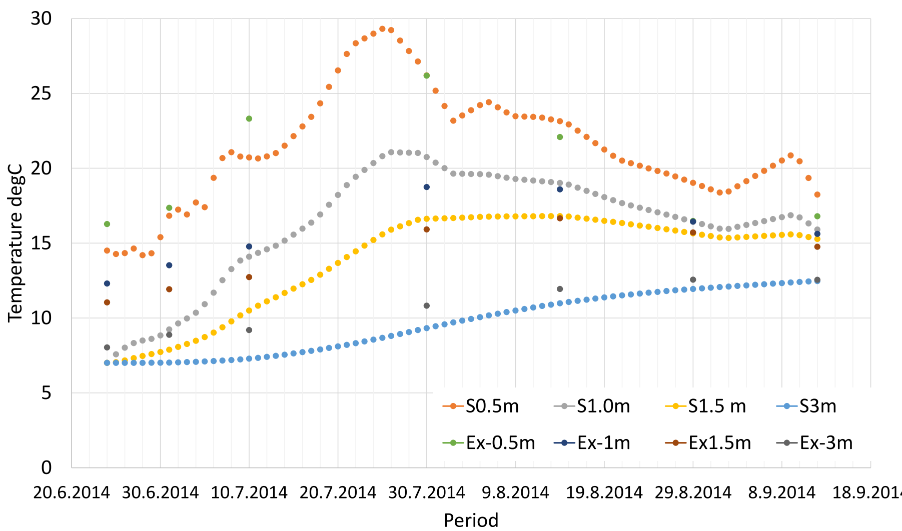


Fig. 2. Three months model validation for varied depth (0.5 m, 1 m, 1.5 m and 3 m) temperature profile evolution against experimental measurements at University of Vaasa.

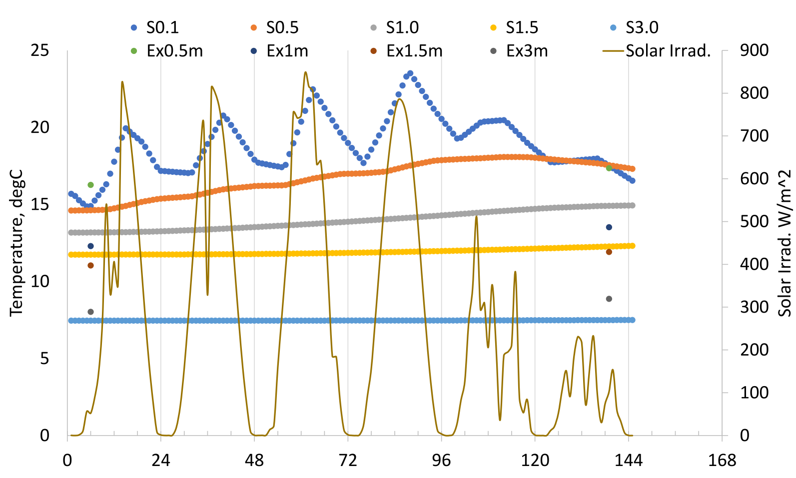


Fig. 3. A comparison between the measured temperature data and the simulated surface temperatures over a 6-day study period.

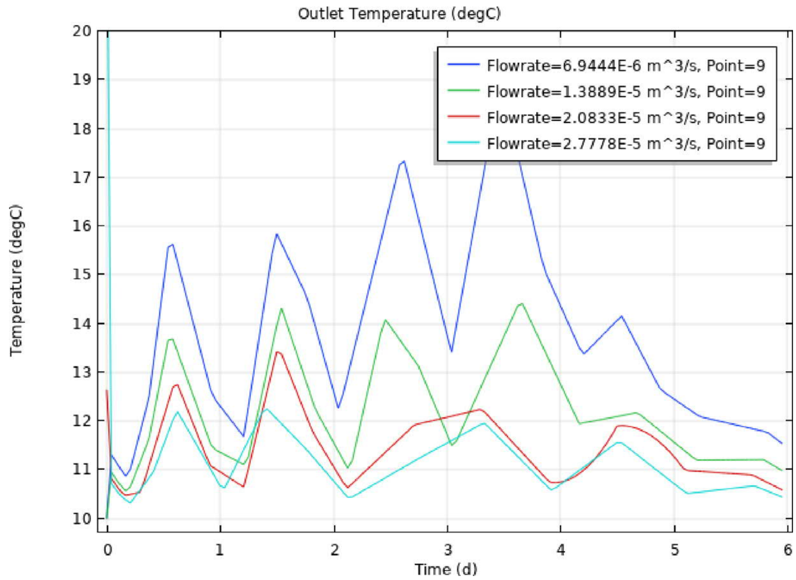
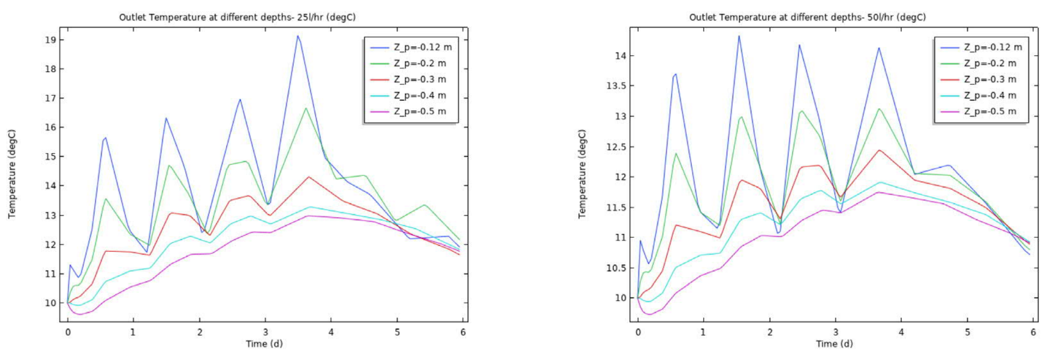


Fig. 4. The effect of volumetric flow rate on the outlet temperature.



(a) volumetric flow rate 100 l/hr (b) Volumetric flow rate 200 l/hr

Fig. 5. The positioning of the pipes under the asphalt subsurface.

3.2. Subsurface heat exchanger

A surface of 5 m by 0.5 m and 1 m (2.5 m^2 and 5 m^2 of heat exchanger) was simulated during a 6 day period. In order to design a complete asphalt heat exchanger, temperature profile under the asphalt surface and the position the pipes was studied. The inlet water temperature was kept constant at 10 °C, and half-inch pipe diameter pipe was considered. Firstly, the effect of different flow rates was studied to determine the heat extraction from the subsurface. Fig. 4 shows the water outlet temperature as a function of volumetric flow rate. Flow rates at 100, 150, 200, and 300 litres/hour was studied. These flows corresponds to Reynolds number of 2120, 3180, 4240 and 6360, respectively. As expected, water flowing at a low rate heats up to a higher temperature in comparison to high flows rates. This is attributed to retention time in the heat exchangers, i.e. for low flow rates the residence time is long thus a high temperature gain is noted and vice versa.

The positioning of subsurface heat is crucial due to interactions with the surface or environmental conditions. Fig. 5 shows the water outlet temperature for heat exchanger placed at different depth beneath the surface. The pipes were place 0.12 m, 0.2 m, 0.3 m, 0.4 m and 0.5 m below the surface.

From Fig. 5, the impact of the surface conditions are evident. During the day, the water outlet temperature is for the pipes layout closer to the surface grows unto 19 °C and equally less heat is absorbed in the evening when solar irradiation is minimal/not available. The impact of weather condition for pipe deep surface, i.e. over 40 cm is minimal. Similar observation were observed at different water inlet flow rate. This findings gives a guidance to application of heat extracted. Close to the surface, a larger heat is extracted that can be stored for utilisation during the winter season for heating the living spaces or melting ice on the pavement. However, weight and heavy moving vehicles can easily deform or destroy the piping. In the reverse, piped buried deeper have less chances of damage, however heat extraction is minimal.

The extraction of heat from the subsurface lowers soil temperature disproportionately depending on the position of the cold inlet stream and heated outlet stream. Fig. 6 show temperature contours for heat exchangers positioned at different depths.

In Fig. 6a, where the pipes are closer to the surface significant the temperature gradient is observed not only across the water inlet and outlet temperature but also on the surface. The heat exchange tubes placed deeper showed less or no significant temperature change on the surface. From these findings, positioning the tubes below 0.3 m below the surface seemed ideal for applications in heat collection and melting the ice during winter. As a consequence, a uniform surface temperature is maintained thus the thermal fatigue that is caused by uneven temperature and daily temperature cycling would be minimised [30]. Although an isotropic thermal properties conditions were assumed, the findings gives an insight into the temperature distribution in subsurface layers.

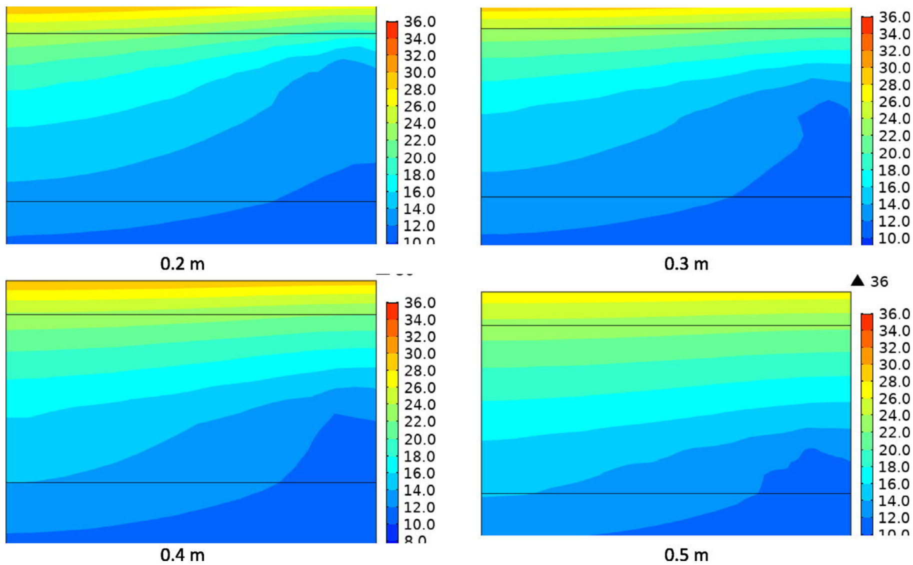
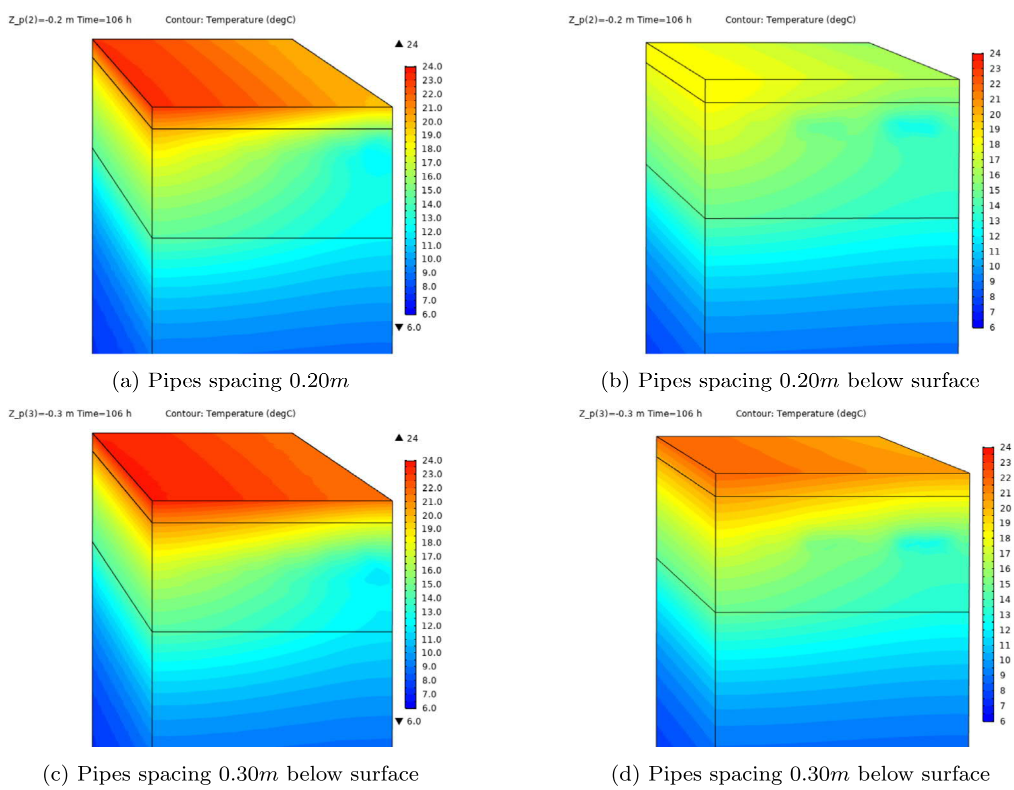


Fig. 6. The positioning of the pipes under the asphalt subsurface.



(a) Pipes spacing 0.20m (b) Pipes spacing 0.20m below surface

(c) Pipes spacing 0.30m below surface (d) Pipes spacing 0.30m below surface

Fig. 7. The effect of the pipes spacing on subsurface temperature distribution.

The spacing between the piping have a larger influence of the water outlet temperature as well as temperature distribution under the subsurface. Fig. 7 shows gradual change of temperature from the cold inlet to hot outlet stream. However, for the pipes far part, i.e. 20 cm, the space in between the pipes have high temperature. Subsurface temperature beneath a closely spaced pipes seems lower compared to the widely spaced pipes. This can be attributed to the larger heat absorption area thus higher liquid outlet temperature.

3.2.1. Effect of liquid flow rate and pipe dimension

The liquid volumetric flow rate and pipe diameter both influence the heat extraction from the subsurface. Fig. 8 shows the outlet temperature at different liquid flow rate. As expected the lower flow rate result in a high outlet temperature because of longer residence time in the heat exchanger. In the results presented in Fig. 8, the pipe diameter is kept constant. For a given volumetric flow rate, change in the pipe diameter inversely effect the flow rate and consequently the residence

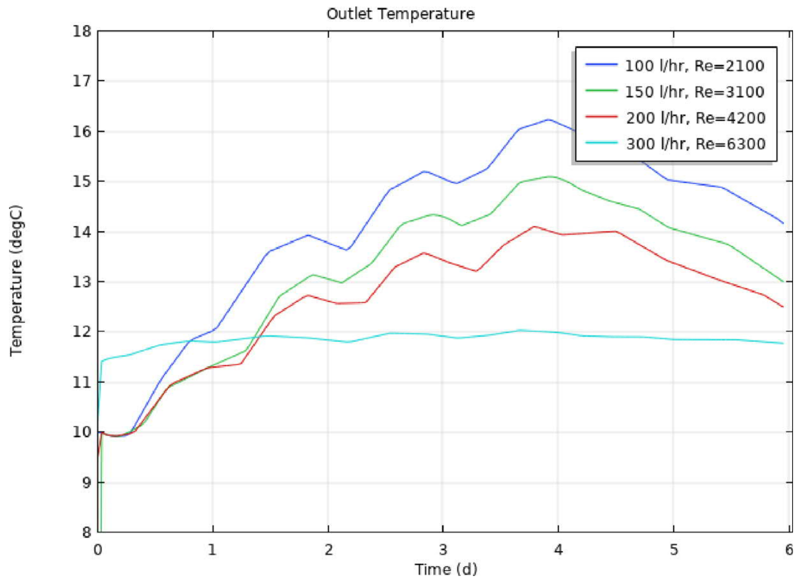


Fig. 8. The influence of volumetric flow rate on the outlet liquid temperature.

time. The Reynolds Number can be used to analyse the effects of both the pipe diameter and the flow rate.

4. Discussion

Experimental and simulated temperature data from pipe with flowing water in asphalt pavement were compared. The experimental data were collected from open-air asphalt surface in Vaasa Finland subjected to solar radiation as described in Mäkiranta and Hiltunen [22]; Çuhac et al. [1]. The simulated results obtained from finite element models show good agreement with the experimental results. The models were used to evaluate the effect of different parameters i.e. liquid flow rate, the position of the heat extraction pipes and the dimensions of the pipes on the heat extraction.

Firstly, the positioning the pipe closer to the surface higher heat extractions was realised and converse is true. For Finnish climatic conditions that experience subzero temperature during winter and over 20 °C during summer. The position of heat extraction pipes is prone to external temperature influence. During the summer months, the heat energy can be harvested using a heat exchanger system, be stored in possibly borehole thermal energy storage for potential use in different applications including deicing the surface during winter months. The harnessing of heat energy by transferring the solar radiation energy from the pavements to a fluid cools down the asphalt surface hence reduces cracking due to thermal fatigue, reduced heat emission from the pavement to air and fatigue due to oxidation of the binder [3].

Pipe diameter and liquid flow rate both affects the heat harvested by solar irradiation. Lower liquid flow rate through the piping implies longer residence time in the heating circuit thus high temperature is observed. The pipe diameter shows significant influence on the temperature distribution around the pipes because of the large surface area for heat conduction. Therefore, a larger distance between adjacent pipes should be considered in the design. From a practical point of view, the control parameter for the functioning of the heat harvesting by transferring solar radiation energy to a fluid is the liquid flow rate assuming the fluid inlet temperature is kept constant. The position of the pipes and the pipe diameter cannot be altered once installed. Therefore, the use of model could help in design and adoption and thus a better use of technology for obtaining sustainable pavements and harnessing renewable energy.

5. Conclusions

In this paper, a modelling framework is developed using a finite element method to predict the thermal parameters influencing heat absorption transferred from solar radiation to working fluid beneath the asphalt layer. The model results show good agreement with the experimental results conducted in a span of three months notwithstanding the following assumptions in the model; thermal properties unaffected by changing moisture content, perfect contact between different layers and homogeneous and isotropic thermal properties of materials (asphalt, sand and gravel). Temperature increase of up to 10 °C gain was observed for piping closer to the asphalt layer and 6 °C for pipes position at deeper from the asphalt layer. The position to lay the pipes underneath the asphalt found to be dictated by the application of the heat extraction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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