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Geothermal pavements: 3D numerical modelling for the long-term thermal performance

Chaussées géothermiques: modélisation numérique 3D pour la performance thermique à long terme

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ABSTRACT: Geothermal pavements are one of the most promising energy geo-structures used for building thermal control, though these have not been studied extensively. They utilise sub-surface structures to exchange heat with the ground and therefore, provide thermal energy in addition to structural stability. This research focuses on exploring the thermal potential of geothermal pavements based on a validated 3D finite element (FE) numerical model developed specifically for this study. This numerical model is employed to evaluate the long-term (annual) thermal performance of a geothermal pavement system under thermal loads for a typical residential building under temperate climate conditions, using Adelaide, South Australia (SA) as a case study. Both a traditional system configuration as well as a hybrid system are considered in this study. It was found that a geothermal pavement, with a total pipe length of 480 m, or a hybrid system with a pipe length of 320 m and an auxiliary heating system, can meet the required space heating and cooling demands. In addition, the influence of surface layer thermal conductivity on the performance of such pavement system is investigated. Results show that a pavement surface with a higher thermal conductivity (1.3 W/ m·K) has an overall better system performance, although the difference is not extreme. However, a pavement surface with a lower thermal conductivity (0.3 W/ m·K) performs better during transition months (November, April, and May).

RÉSUMÉ: Les chaussées géothermiques sont l'une des géo-structures énergétiques les plus prometteuses utilisées pour le contrôle thermique des bâtiments, bien qu'elles n'aient pas été étudiées de manière approfondie. Ils utilisent des structures souterraines pour échanger de la chaleur avec le sol et, par conséquent, fournissent de l'énergie thermique en plus de la stabilité structurelle. Suite Cette recherche se concentre sur l'exploration du potentiel thermique des chaussées géothermiques à partir d'un modèle numérique 3D aux éléments finis (FE) validé développé spécifiquement pour cette étude. Ce modèle numérique est utilisé pour évaluer la performance thermique à long terme (annuelle) d'un système de chaussées géothermiques sous charges thermiques pour un bâtiment résidentiel typique dans des conditions climatiques tempérées, en utilisant Adélaïde, Australie-Méridionale (SA) comme étude de cas. La configuration du système traditionnel ainsi qu'un système hybride sont considérés dans cette étude. Il a été constaté qu'un revêtement géothermique, avec une longueur totale de tuyau de 480 m, ou un système hybride, avec une longueur de tuyau de 320 m, et un système de chauffage auxiliaire, peuvent répondre aux besoins de chauffage et de refroidissement des locaux. De plus, l'influence de la conductivité thermique de la couche de surface sur les performances d'un tel système de chaussée est étudiée. Les résultats montrent que la surface de la chaussée avec une conductivité thermique plus élevée (1,3 W / m·K) a une meilleure performance globale du système, bien que la différence n'est pas extrême. Cependant, la surface de chaussée avec une conductivité thermique inférieure (0,3 W / m·K) fonctionne mieux pendant les mois de transition (novembre, avril et mai).

KEYWORDS: ground source heat pump (GSHP); geothermal pavement; numerical modelling; heat transfer; thermal performance

1 INTRODUCTION

Global warming and the fossil fuel crisis are among the most pressing issues in our modern society. Thus, it is imperative to pursue clean and renewable energy resources, thereby alleviating the reliance on fossil fuels for tackling climate change. Ground source heat pump (GSHP) systems are receiving increasing attention recently as a promising solution to contribute towards satisfying the future energy demand. GSHP systems utilise the ground as a heat source/sink to air-condition (heating and/or cooling) buildings by means of ground heat exchangers (GHEs) and this heat can be further upgraded via a heat pump if necessary. GSHP systems are known for their high efficiency with a typical coefficient of performance (COP) value of four to five indicating that every unit kW electricity input can produce 4 to 5 kW heating/cooling energy (Narsilio et al., 2014). However, conventional GSHP systems have limitations due to high installation costs associated with drilling deep boreholes or the need for large trenching areas. This earthwork constitutes the major additional cost compared to traditional heating and cooling systems (Qi et al., 2019).

Energy geo-structures (EGS) as an advancement over traditional GSHP systems is gaining traction among researchers and some practitioners. EGS incorporate high density polyethylene (HDPE) piping to underground structures to exchange heat with the ground in addition to their structural stability. Current research developed an understanding on utilising foundation piles (Brandl, 2006, Bourne-Webb et al., 2016, Makasis et al., 2018a), retaining walls (Makasis et al., 2020, Shafagh et al., 2020, Barla et al., 2020) and tunnel linings (Bidarmaghz and Narsilio, 2018, Adam and Markiewicz, 2009) to serve as GHEs with little additional cost, and achieve a dual purpose. Although having EGS can reduce the capital cost significantly, the design, implementation and the thermal provision of the system depends largely on the site layout and underground structure geometry. Therefore, in certain cases, having a hybrid configuration comprising of an auxiliary system to fulfil the shortfall in thermal demand is more suitable.

This research aims to investigate the design of geothermal pavement systems. Exponential growth in the human population has led to rapid urbanisation resulting in a greater need for transportation, thus, the idea of having geothermal pavements is promising. Geothermal pavements take advantage of existing earthworks for road construction by placing the horizontal GHEs under pavement surfaces at a relatively shallow depth (less than 1m), thereby, reducing the capital costs of GHE installation. The majority of the research focussed on utilising geothermal pavements for road maintenance purposes, such as de-icing or controlling pavement surface temperatures (Eugster, 2007, Muñoz-Criollo et al., 2016, Zhao et al., 2020). As such, the scope of geothermal pavements for thermal control of buildings remains largely unexplored in the available literature. Furthermore, the influence of placing GHEs at a shallower depth compared with other traditional horizontal GSHP systems has not been sufficiently studied to date.

The main aim of this research consists of accurately modelling the shallow GHEs in order to study their thermal performance. Although several analytical solutions and experimental studies (Lamarche, 2019, Jeon et al., 2018, Gan, 2013) have been undertaken to investigate the thermal performance of traditional horizontal GHEs (buried at depths of 1-3m), current research lacks knowledge on very shallow horizontal GHEs (less than 1m) and their modelling techniques. Researchers are moving towards numerical models to obtain deeper understanding on the GHE heat transfer process, because of their wider applicability and fewer constrains in exploring geometry and configuration compared to laboratory or field-scale experiments (Li et al., 2017, Kayaci and Demir, 2018). Li et al. (2017) investigated the thermal performance of several horizontal system configuration based on a 3D finite element (FE) they developed that used local geological data, such as ground temperature and soil properties, as design inputs for improving modelling accuracy. The limitation of their numerical model is that it relied upon the assumption of isotropic soil properties for saving computational time (Kayaci and Demir, 2018).

Although researchers had performed studies on geothermal pavements form a heat transfer perspective, their results were based on pilot or lab-based experimental data dealing with short-term performance (del-Castillo-García et al., 2013, Tota-Maharaj et al., 2011). However, models for having GHEs placed at a depth of less than 1m, as is the case of geothermal pavement system, are yet to be explored extensively. To bridge these gaps, this research developed a 3D FE numerical model of geothermal pavements, based on non-uniform soil properties and local geological data to assess the thermal performance of the system. This model is successfully validated with full-scale experimental data collected at a site in Adelaide, South Australia (SA). The long-term thermal performance of such pavement system under both traditional standalone and hybrid system configurations are assessed in conjunction with the thermal load of a typical residential building in Adelaide, SA (temperate climate). Note that the literature highlighted that higher thermal conductivity benefits the GSHP system performance through parametric studies (Li et al., 2017, Kim et al., 2016). However, these past studies only focused on homogenous and uniform ground soil thermal conductivity (or averaged soil thermal conductivity) on the GHE thermal behaviour. Considering the proximity of the installation of GHEs to the ground surface, as well as the non-uniform soil layers in this research, the influence of different surface soil thermal conductivities on the system is explored herein. Thus, apart from a traditional asphalt pavement, this research assesses the potentials of incorporating reclaimed asphalt pavement (RAP), which has a relatively lower thermal conductivity, as geothermal pavement system surface layer.

2 METHODOLOGY

This research developed a validated numerical model to undertake the analysis. Detailed 3D FE numerical modelling approaches were utilised, incorporating the governing equations to simulate the thermal performance of such system under annual thermal loads of a typical residential dwelling located in Adelaide (SA). In addition, the thermal potential of the pavement system under a balanced load case is assessed by introducing a hybrid system approach, which incorporates the proposed system with an auxiliary heating system such as a gas furnace to meet the remaining demand of the required thermal loads. To obtain more knowledge about the effects of pavement surface thermal conductivity on the system performance, the thermal conductivity value of the surface layer is varied to represent a reclaimed asphalt pavement (RAP) which is a widely used recycled pavement material and has a relatively low thermal conductivity value of 0.3 W/ m·K.

2.1 *Finite element model*

The numerical modelling of the geothermal pavement system was performed using the FE package COMSOL Multiphysics (COMSOL, 2018), focusing on the GHE embedded in the pavement. This model incorporates governing equations of both fluid flow (momentum and continuity) and heat transfer (energy balance). Conductive heat transfer mainly occurs in the soil materials, including ground, GHE pavement structure backfills and the HDPE pipe walls, while convective heat transfer dominates in the carrier fluid within the HDPE pipes. The 3D numerical model has been developed within The University of Melbourne, and successfully validated with observation data from a full-scale field study in Adelaide, SA (Motamedi et al., 2020). Details of this developed model and validation process can be found in Gu et al. (2020).

2.2 *Model geometry and parameters*

The meshed finite element model, geometry and configuration can be seen in Figure 1 and the material properties are summarised in **Error! Reference source not found.** This geothermal pavement design comprises of a 0.05 m surface layer (asphalt), 0.3 m thickness of base layer with a mix of gravel (0.25 m) and fine sand (0.2 m), the remaining layer is a subgrade layer (high plastic clay). A single GHE circuit consisting of 8 legs of HDPE pipes, and having an outer diameter of 25 mm (SDR11) is placed at a depth of 0.5 m below the surface and connected in series meandering in an area of approximately 4m × 20m. The total length of the GHE circuit is 160.4 m with a spacing of 600 mm between the centre of the pipes. Moreover, a constant fluid flow rate of 12 L/min is applied to the inlet of the circuit. Ground water flow is not considered in this research due to the local site conditions in Adelaide, SA as well as the GHE being buried at very shallow depth.

Table 1 Material properties

Materials	Description	Density (kg/m^3)	Specific heat capacity [J/(kg·K)]	Thermal conductivity [W/(m·K)]	Thickness (m)
Asphalt	Road surface	2400	850	1.3	0.05
Gravel	Base	2200	944	1.4	0.25
Fine sand	Base	2240	1185	1.8	0.20
Clay	Subgrade	2100	840	1.9	-
Water	Carrier fluid	998	4158.5	0.58	-

2.3 *Model assumptions, initial and boundary conditions*

To obtain meaningful results, it is important to have appropriate assumptions, initial and boundary conditions. Initial and boundary conditions of the geothermal pavement system are shown in Figure 1 and summarised below:

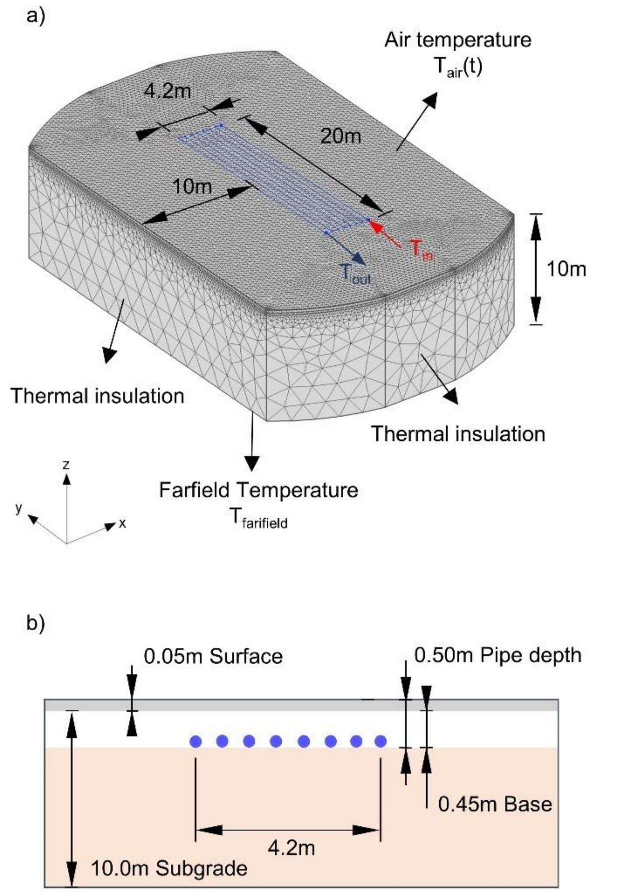


Figure 2. Model geometry: a) meshed 3D FE numerical model; b) section view of the model (not to scale).

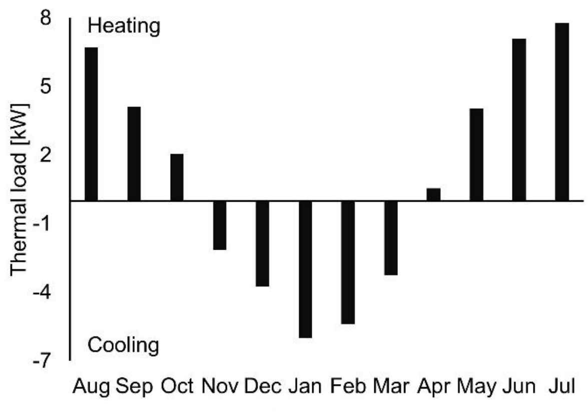
- Assuming fully developed fluid flow within the pipes, therefore, the fluid flow and heat transfer occurring in the fluid are analysed as a 1D problem.
- The *initial* temperature of both ground and the farfield boundaries are equal to the measured undisturbed ground temperature for different depths $T_{farfield}(z)$ (Table 2).
- Thermal insulation, which renders a zero net-flux, is prescribed to the farfield side boundaries of the numerical model. To avoid any boundary influences on the GHEs, the distance between the edge of GHEs and the outer boundary is determined as 10m (similar results can be achieved while assuming fixed temperatures over the simulation period at the boundaries). The bottom boundary of the model is set as a prescribed temperature.
- Considering that the shallow depth of the GHEs would be strongly influenced by seasonal fluctuation, the surface boundary of the model is designed as a time-dependent ambient temperature $T_{air}(t)$ recorded in Adelaide, SA.
- The time-dependent inlet fluid temperature $T_{in}(t)$ is computed a function of fluid temperature at the outlet point of GHE $T_{out}(t)$ and the input annual thermal loads.

Table 2 Measured farfield temperature – initial conditions

Depth (m)	Farfield Temperature (°C)
0.0	16.1
0.3	16.5
0.5	16.8
1.0	17.3
1.5 and below	17.5

2.4 *Thermal load distribution*

For the design life of a general GSHP system, the operating fluid temperature in the pipes must remain within a reasonable temperature range (typically between -5 and 40 °C), to be a functional system, the narrower the range is, the more efficient the system typically is (Makasis et al., 2018b). Thermal load distribution, which defines the amount of energy the GSHP system is required to extract from/reject to the ground, is one of the key parameters that determines the operating fluid temperature. In this research, annual thermal loads of a typical house in Adelaide, SA, as shown in Figure 2 is utilised to calculate the carrier fluid temperatures, and the average fluid temperature T_{fluid} (average from T_{in} and T_{out}, see Figure 1) is used for quantifying the circulated fluid temperature within the pipe. Furthermore, a hybrid system configuration is also considered (using the geothermal pavements to provide a baseload of 6kW and a gas furnace to supply heating shortfalls).



3 RESULTS AND DISCUSSION

Figure 1. Annual thermal load of a residential building in Adelaide, SA.

This section includes a discussion on the annual thermal performance of the geothermal pavement systems, both in terms of a traditional (section 3.1.1) and a hybrid system (section 3.1.2). Furthermore, to gain further understanding on the variation in thermal conductivities of pavement surface layer to the system, two types of pavement surface with thermal conductivity values of 1.3 W/ m·K and 0.3 W/ m·K are input to the pavement model for comparison (section 3.2).

3.1 *Long-term simulation on thermal performance*

In this section, the developed numerical model is employed to assess the long-term performance of the geothermal pavements with a case study centred on a typical residential building in the temperate climate conditions of Adelaide, SA. According to literature, unbalanced thermal loads can lead to thermal accumulation effects on the ground for vertical GHEs, therefore, impact on the system performance (Li et al., 2018). However, this is generally not the case of horizontal GHEs due to their shallow buried depth (Gu et al., 2021). Therefore, to save the computational time, a simulation of 1 year is carried for representing the long-term performance of the pavement system.

3.1.1 *Thermal performance of the standalone geothermal pavement system*

As mentioned in section 2.4, a GSHP system is defined as functional only if the average fluid temperatures T_{fluid} over the design life are within a reasonable operating range. In Figure 3, the maximum (T_{max}) and minimum (T_{min}) average fluid temperature T_{fluid} of having two identical GHE circuits to supply the annual thermal demands exceeds the acceptable operating range. Therefore, in this case, it was found that three identical design GHE circuits could satisfy the building thermal demand while maintaining a reasonable operating T_{fluid}. The maximum and minimum T_{fluid} when utilising these three GHE circuits to meet the demand are 33.9°C and -0.8°C, noting that an anti-freeze solution rather than plain water may be required, in this case, 15% of Propylene Glycol is recommended by IGSHPA guidelines (IGSHPA, 2009). In the modelling results, an average $\Delta T = |T_{in} - T_{out}|$ of about 1.7ºC was obtained.

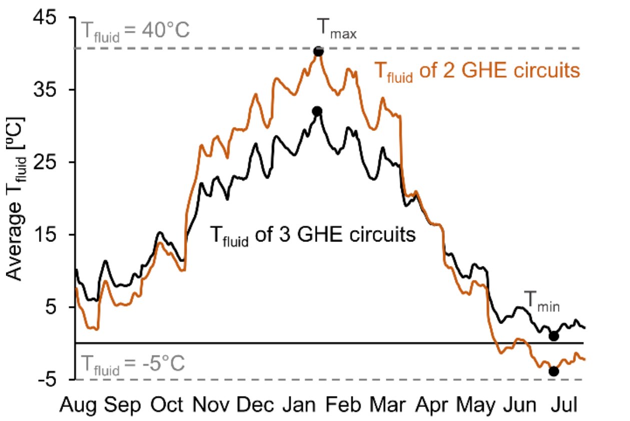


Figure 4. Average T_{fluid} resulting from a GSHP system with 2 and 3 GHE circuits to satisfy a typical residential annual thermal demand (for Adelaide, SA).

3.1.2 *Thermal performance of the hybrid geothermal pavement system*

Considering the common scenario of having a large residential development with multiple dwellings and a finite pavement area available, it may not be feasible to assign three GHE circuits per dwelling. Thus, a hybrid system is introduced here, as it can reduce the required construction area as well as may results in a more economic and better life cycle operation of the system. To secure the maximum amount of thermal energy supplied by the geothermal pavement per dwelling, as well as guarantee the acceptable system operating T_{fluid}., an iterative process is carried by varying the peak heating and cooling load capacity of a GSHP to determine a desirable hybrid system design.

In this study, a hybrid system which utilises the geothermal pavement system to supply a "baseload" of thermal demands that are lower than 6 kW (or 100% cooling and 89% heating), while the shortfalls are provided by an auxiliary system – a gas furnace. The resulted T_{fluid} (as well as the thermal load) is shown in **Error! Reference source not found.**. which has less extreme values and fluctuations compared to T_{fluid} obtained from the standalone pavement system. Though the number of days requiring an auxiliary system is 92 days per year, the hybrid system can supply 92% of overall thermal load using the geothermal pavements. In addition, with this hybrid system Wdesign configuration, it only requires two GHE circuits (instead of three GHE circuits for standalone system), which could serve more buildings in the hypothetical residential development with this geothermal design.

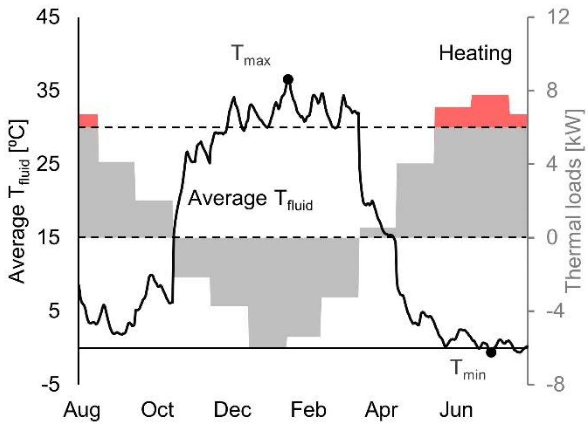


Figure 3. Average fluid temperature of the hybrid geothermal pavement system with balanced thermal loads. A baseload is satisfied by the GSHP system, while the balance load, by a smaller heat furnace.

3.2 *Effects of different pavement surface thermal conductivity*

Since the GHEs are buried at a shallow depth of 0.5m below the pavement surface, they are more susceptible to the changes in pavement surface temperatures. Therefore, it is crucial to explore the influence of pavement surface layer on the system thermal performance. It should be noted that this research only considers the influence of different surface layer thermal conductivities $\lambda_{surface}$ on the system while soil properties for rest of the layers remain unchanged for simplicity. Two types of pavement surfaces are studied here, first, a traditional asphalt pavement with a $\lambda_{surface}$ of 1.3 W/m K (which is also used in the previous analyses) and second, a RAP with a $\lambda_{surface}$ of 0.3 W/(m K) (DeDene et al., 2015). Being a recycled material, RAP is seeing a greater utilisation in pavement construction given its significant economic and environmental benefits.

The same thermal loads (Figure 2) are used for assessing the influence of different $\lambda_{surface}$ on the system performance. The comparison between the performance resulting from the two $\lambda_{surface}$ values is presented in terms of ΔT_{fluid} in Figure 5. For an easier interpretation, the plot for annual thermal load is also provided.

The value for ΔT_{fluid} is always plotted as a difference between the outlet fluid temperatures when λ=1.3 W/(m·K) to when λ=0.3 W/(m·K). Furthermore, ΔT_{fluid} is indicated in both heating (plotted in red) and cooling (plotted in blue) modes. According to the literature review, a higher surface layer thermal conductivity value would lead to better system performance. Based on this, ΔT_{fluid} should always have a positive value during operation in heating mode (red area must remain above 0°C), whereas, it should always have negative values in cooling mode (blue area must remain below 0°C). However, the results shown in Figure 5. show a slight variation to the predicted (in literature) behaviour. Moreover, the results overall show a ΔT of less than 2°C, which could be justified provided the other benefits of RAP.

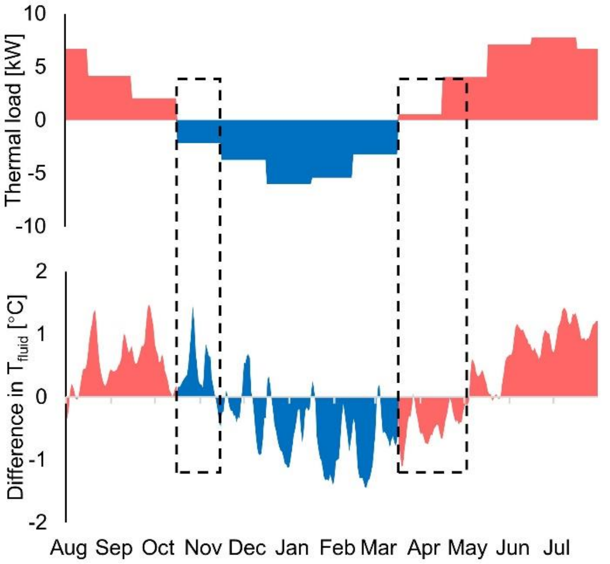


Figure 6. The differences in T_{fluid} ($\Delta T_{fluid} = T_{fluid}$ (λ=1.3) - T_{fluid} (λ=0.3)) for GHEs under RAP and conventional asphalt pavement surface. Red and blue colour represents heating and cooling thermal demands.

During certain months (November, April, and May), the RAP surface layer, with a lower thermal conductivity, demonstrates a comparatively better system performance. This has been highlighted in Figure 5. One reason behind observing these "unexpected" results could be attributed to the fact that, during these transition months, the T_{air} fluctuates frequently and the type of thermal demand suddenly changes. In these cases, having a low $\lambda_{surface}$ would insulate the ground from these abrupt changes in T_{air}, thereby benefitting the system performance. Additionally, the T_{fluid} with RAP surface performs a comparatively worse during the months prior to the transition, therefore, the surrounding ground temperatures is more favourable to the sudden changes in the thermal demands that occurs during transition months. This reason can be explained by considering pavement conditions on 2nd November, when the thermal demand reverses from heating to cooling (in the Southern Hemisphere). According to Figure 6, due to continuous heating demands in previous months, the sub-surface temperature under RAP surface is much lower (Figure 6(a)) compared to the case with a higher $\lambda_{surface}$. Besides, a low $\lambda_{surface}$ makes the surface behave similar to an insulation layer, that promotes more heat to exchange between the ground and the GHEs, rather than ground surface, thus, leading to a larger/deeper influence region, going down to 2.3m below surface for the RAP surface, and only 1.8m below surface for the higher thermal conductivity surface. This cooler ground would be beneficial while cooling demand is required. In addition, T_{air} on a cooling day should be much higher and the less conducting RAP surface prevents the ground from absorbing additional heat from the surround air. This makes the ground more amicable to receiving the rejected heat, thus, resulting in more efficient heating compared to the other discussed scenario (λ=1.3 W/(m K)).

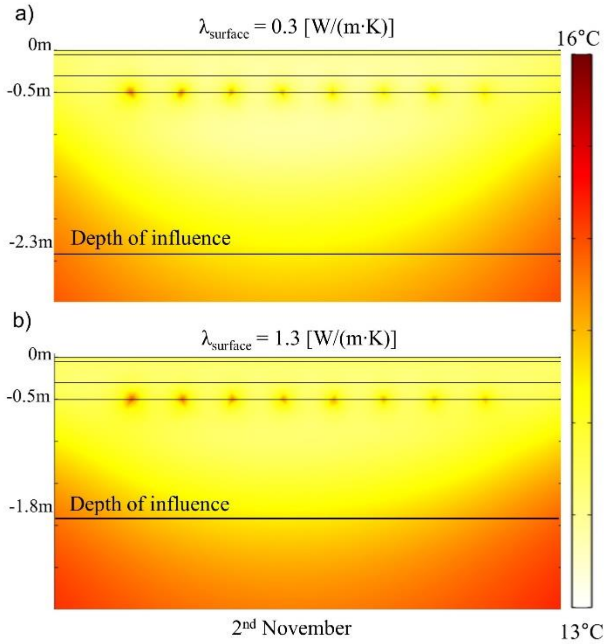


Figure 5. Temperature distribution at cross-section of the GHE (XZ-plane) on the 2nd Nov under a) RAP surface; b) traditional asphalt pavement surface.

4 CONCLUSIONS

Energy geo-structures are gaining increased attention as an alternative to provide space heating and cooling in an effort to combat the issue of climate change. Some of the most common energy geo-structures are energy piles, energy tunnels, and energy retaining walls. While a wealth of knowledge can be found on these energy geo-structures, limited information exists pertaining to geothermal pavements. This research utilises numerical modelling to explore the thermal potential of using geothermal pavement systems which have been largely overlooked by researchers to date. This study explores the long-term thermal behaviour of such pavement systems in both conventional (standalone) and hybrid configurations. The former configuration relies solely on the GSHPs to meet the thermal demand while the later consists of a combination of geothermal pavement, that provides a baseload, and an auxiliary gas furnace for meeting the shortfall. In addition, the effects of variations in pavement surface thermal conductivity on the system performance have been explored to develop a deeper understanding. Key findings are summarised below:

- Under design thermal loads similar to a typical residential building in Adelaide (SA) (mild temperate climate conditions), three GHE circuits (with a total pipe length of 480 m) of the geothermal pavement system seem sufficient.
- Adopting a hybrid system can reduce the number of GHE circuits from three to two (320 m pipe length), this significantly reduces the required area for the GHEs, thus, creating a possibility for catering to more surrounding buildings. Though a total of 92 days would require an auxiliary system, the GSHP system can supply more than 90% required thermal loads (100% of cooling and 89% of heating demands).
- It is imperative to understand the pavement surface thermal properties as the thermal conductivity of pavement surface layer has significant influence over

- the system performance (since the depth of surface layer is only 0.05 m).
- The majority of the simulation results show an agreement with the predictions based on literature review that higher soil thermal conductivity values are correlated to better GSHP system performance. However, this difference could be justifiable and moreover, during transition months (when air temperature may fluctuate more than usual and frequent reversal in operating mode is observed), RAP surface with lower conductivity exhibits a better system performance.

Overall, this research carries out a comprehensive study of exploring the thermal potential of using geothermal pavement systems, and results indicate that it is worthwhile to investigate these systems in a greater detail. Further studies could explore the potential of developing an artificially programmed continuously fluctuating thermal demands that can take full advantage of geothermal pavements with RAP.

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