Thermal performance of a controllable pavement solar collector prototype with configuration flexibility

Thermal Performance of a Controllable Pavement Solar Collector Prototype with Configuration Flexibility

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Abstract

Solar energy harvesting as a renewable and sustainable energy source has been widely investigated in recent years across engineering fields. The use of Pavement Solar Collectors (PSC) can lead to clean energy production, an increase in road safety, prolong the service life of asphalt pavement, and can mitigate the Urban Heat Island (UHI) effect. This study describes a controllable large-scale research PSC prototype with high configuration flexibility, and full monitoring capability at the University of Antwerp, Belgium. Since small- or laboratory-scale setups do not reflect the behavior of actual projects, the present paper investigates the thermal response of a large-scale PSC in the Western European climate, including heating load, heat extraction capacity, and asphalt surface and profile temperature changes during heating and cooling experiments.

The study shows that a low supply temperature compared to high (14 °C vs. 28 °C) can reduce the depletion rate of the stored thermal energy in borehole thermal energy storage up to 7 times. The sensitivity analysis indicates that an increase in flow rate from laminar to transient regime requires twice as much thermal power compared to the same flow rate changes within transient and turbulent regimes. The maximum average daily efficiency of the PSC could reach 34% with a flow rate of 4 l/min. The experimental results showed that increasing the pipe length from 50 m to 200 m reduces the cumulative power extraction capacity by up to 48%. Furthermore, the PSC system shows great potential in reducing the asphalt surface temperature (up to 12 °C) to mitigate the UHI effects. Finally, the PSC system effectively controls the temperatures of the interface zones to reduce the rutting distress in the summertime and lower the potential of cold thermal crack developments and brittle shear failure behavior in wintertime.

Keywords: Renewable energy, Energy harvesting, Solar energy, Urban Heat Island, Pavement Solar Collector (PSC), Asphalt pavement

Abbreviations: BTES, Borehole Thermal Energy Storage; SD, Standard Deviation; HEAL, Heat Exchanging Asphalt Layer; CyPaTs, Cycle Pavement Technologies; PSC, Pavement Solar Collector; STES, Seasonal Thermal Energy Storage,

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1. Introduction

In recent years, harvesting renewable and sustainable energy from asphalt pavements using new technologies has been studied in several research areas [1-3]. This is mainly to discover a suitable replacement for fossil fuels (i.e., solar energy) to tackle the high demand for energy due to global population rise, urbanization, and environmental problems.

Pavement Solar Collectors (PSC) are promising technologies to extract thermal energy from an asphalt pavement in roads, parking lots, and airports. The high temperature of the asphalt pavement surface in the summertime, heat capacity of asphalt mixtures, and high absorption of solar irradiation are the reasons that asphalt pavement has great potential as massive solar collector [4]. The PSC systems extract thermal energy by circulating cold fluid through embedded pipes in the asphalt pavement in the summertime and store the harvested energy in seasonal thermal energy storage (STES) systems. The extracted heat can partially be used to provide snow- or ice-free road surfaces to increase road safety in the winter, while additional heat can supply district heating networks for domestic or industrial applications [5, 6]. PSCs are able to reduce the seasonal temperature gradient of asphalt pavement, thus increases service life of the pavement [7]. As a secondary result, pavement distresses, such as top-down cracking, rutting, and fatigue cracking, can be reduced by regulating the asphalt temperature throughout different seasons [8]. Finally, since these systems effectively lower asphalt pavement temperature by harvesting thermal energy, PSCs can potentially mitigate the development of the Urban Heat Island (UHI) effect [9, 10].

There has been extensive research on the thermal performance of the PSC systems in small-scale or laboratory test setups [11-13] and actual large-scale projects [8, 14]. In a recent study [15], over 50 large-scale PSCs were reviewed to evaluate different aspects of these systems, including their system configuration compared to the small/lab-scale setups, applications in different projects, estimated cost, and long-term performance analysis. In addition to the experimental setups, simulation models are also essential to assess the feasibility and performance of PSCs due to the high expense of large-scale projects to evaluate the sensitivity of design parameters and overall system performance [15]. Studies over the past two decades have provided important information on the modeling of the PSCs in order to provide a better understanding of such systems. Although simulation tools simplify the PSCs systems and can suffer from an extensive computational run time [16], they offer reasonably accurate models to investigate anti-icing or snow melting capacity [17, 18], thermal energy output [14], validation of experimental models [19], and long-term thermal performance and efficiency of PSC systems [20].

The small- or laboratory-scale solar collectors have a simple configuration without a need for components such as a heat pump, heat storage, and weather station. The construction cost of small/lab-scale setups can be dramatically reduced due to smaller size and eliminating the above-mentioned components. Another advantage of the small/lab-scale systems is that the environmental conditions can be controlled in laboratory tests (e.g., air temperature, wind velocity, etc.) or have less disturbance effect compared to large-scale projects (e.g., shadow from trees or buildings nearby) [8]. Also, the small-scale systems can be easily relocated (small size) to different environments for parametric studies [7]. However, these small setups do not reflect the behavior of actual projects. Due to the small dimension and consequently short pipe length, the difference between inlet and outlet temperature of water becomes too small, resulting in a higher measurement error. Moreover, heat loss monitoring and calculations, heat storage flow measurements, heat pump power consumption, and weather station reliability are other exclusive features of large-scale systems that are not studied in small setups. Furthermore, several aspects of large-scale projects that are not possible to observe in small setups (e.g., coupling heat pump and energy storage) highlight the occurrence of certain challenges concerning large-scale PSCs.

PSC prototypes with actual size are essential to perform comprehensive evaluations over different thermal aspects of such systems. The actual size projects provide a better understanding of PSC systems' thermal and structural performance since simplification assumptions will be limited in the modeling and validation framework. The large-scale PSCs are constructed with different configurations, control system, monitoring, and automation components compared to the small/lab-scale systems since certain challenges can be expected due to scale effect or origin of the small setups (e.g., existence of structural loads). One of the drawbacks of large-scale PSCs is, although the system configuration can highlight important aspects of PSCs, in most cases, these systems are uncontrollable and unmonitored [21]. Hence, a relatively large-scale yet controllable and fully monitored system is an ideal prototype to investigate various aspects of PSC systems.

This study provides a comprehensive description of the Heat Exchanging Asphalt Layer (HEAL) prototype, a large-scale research system constructed for research purposes with high configuration flexibility and full monitoring capability at the University of Antwerp, Belgium. The present paper aims to study the thermal response of HEAL system in the Western European climate, including heating load (in cold season), heat extraction capacity (in summer), and asphalt surface and profile temperature changes in both heating and cooling experiments. Due to its system configuration, the sensitivity of design variables and operational parameters, such as length, flow rate, supply temperature, are investigated in identical experiments resulting in an established thermal performance comparison with available results from the literature.

This paper has been divided into five parts, starting with this introduction section. The second part provides a detailed description of the large-scale HEAL prototype. Section three describes the layout of the performed experiments to evaluate the thermal response of the HEAL system. This thermal response includes power extraction or depletion, and asphalt surface and profile temperatures in both heating and cooling modes. Section four discusses the summary of findings and compares the primary outcomes with other studies in literature, focusing on the potential reasons for the differences in performance of large-scale prototypes. Finally, the main conclusions are summarized and presented in section five to highlight the potential of further research in the field of PSCs.

2. Heat Exchanging Asphalt Layer Prototype

The Cycle Pavement Technologies (CyPaTs) project was designed and constructed in 2017 on a bicycle path on Campus Groenenborger at the University of Antwerp. Five innovative technologies were executed in the CyPaTs[1] project to further research and demonstrate these technologies to the road construction sector in Belgium. The large-scale research prototype of HEAL is one of the innovative technologies implemented in the CyPaTs project.

The PSC systems can be constructed, besides in regular roads, in bridge decks, pedestrian sidewalks, inclined planes, bicycle paths, parking lots, roundabouts, access ramps, hospital entries, airport aprons and parking areas for the prevention of snow and ice accumulation on road surfaces [12, 22]. In the planning phase of the HEAL system, several factors were considered to choose the location of the HEAL prototype, including immediate access from the university building for monitoring purposes, no major loading on the bicycle path, and limited effect on the local traffic in case of technical issues (e.g., leakage of water). Besides, due to the fact that the bicycle path is not heavily loaded, structural

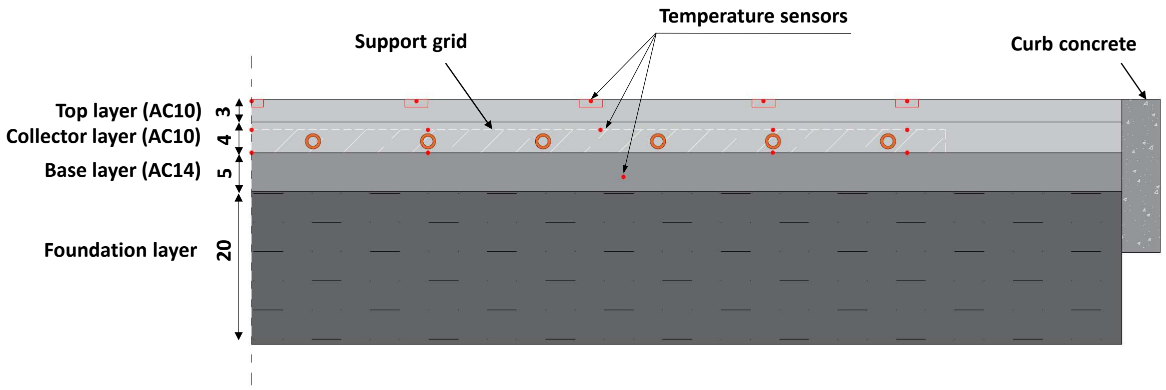
[1] https://www.uantwerpen.be/en/research-groups/emib/rers/projects/highlighted/cypats/

damages will be eliminated, resulting in longer service life and no expected issues for resurfacing (i.e., normal road needs to be resurfaced after 10-15 years). As a result, the extensive cycle path network and popularity of cycling in Belgium was an initiative to construct the HEAL prototype on a controlled bicycle path to benefit from the aforementioned reasons.

Bicycles are an integral part of the transportation system and a sustainable alternative for individual motorized transport in many European countries. The EU commission works on integrating cycling into the multimodal transport policy, including reinforcing cycling aspects and increasing road safety concerning cycling [23]. Belgium was ranked third in Europe with 327 km of traversed bicycle kilometers per person per annum [24]. Also, the city of Antwerp is listed as one of ten international bicycle-friendly cities, having 702 km of cycle paths on a total of 1649 km of roads. The HEAL system offers a chance for a cyclist to use their bicycle safely on freezing and snowy days. The main objective of the HEAL project is to investigate the thermal (e.g., long-term thermal output) performance of the PSC systems. As a result, the thermal response can be used to evaluate the structural performance as well. Although there have been several studies in the literature regarding the thermal performance of the PSCs (e.g., snow melting ability and energy harvesting potential), these studies mainly focused on the small/laboratory-scale systems. Hence, further research on the performance of the large-scale PSCs is essential due to their innate differences (e.g., more complex system configuration and construction challenges) compared to small/lab-scale.

2.1. Design Configuration and Construction of HEAL

The total area of the HEAL is nearly 65 m^2 (14 m x 4.6 m) with four heat exchange sections (8.5 m x 1 m each) and two reference sections of 30 m^2 (i.e., without heat exchange layer). The asphalt pavement was placed in three layers with two different asphalt mixtures (see Figure 1). The top layer (3 cm) and the collector layer (4 cm) are constructed using a dense asphalt mixture with a maximum aggregate size of 10 mm (i.e., AC 10), while the base layer (5 cm) is composed of an AC 14 mixture. The asphalt base layer was placed on a 20 cm compacted unbound aggregate layer. In the construction stage, the collector layer (together with an embedded network of pipes and support/reinforcing grid) and the top layer were placed one day after the placement of the base layer. Therefore, the network of pipes and support/reinforcing grid was placed and sprayed with bitumen before paving the collector and top layer. Spraying emulsion increases the adhesion between pipe-grid structure and asphalt mixture, improves heat transfer, and provides allowable movements due to differences in coefficients of thermal expansion (Figure 2 - a).



The polyethylene pipes are supported by a reinforcing grid that was developed by the Dutch contractor Ooms [25, 26] for exact positioning and to provide support against excessive machinery loads during construction and protect the pipes from potential damages during/after construction (Figure 2 - b). The polyethylene pipes used in the HEAL prototype have a 20 mm outer diameter (D_{out}) and 13 mm inner diameter (D_{in}). These pipes are positioned at 15 cm center to center spacing (P_s) and embedded 4.5 cm below the surface (P_d) in a serpentine configuration.

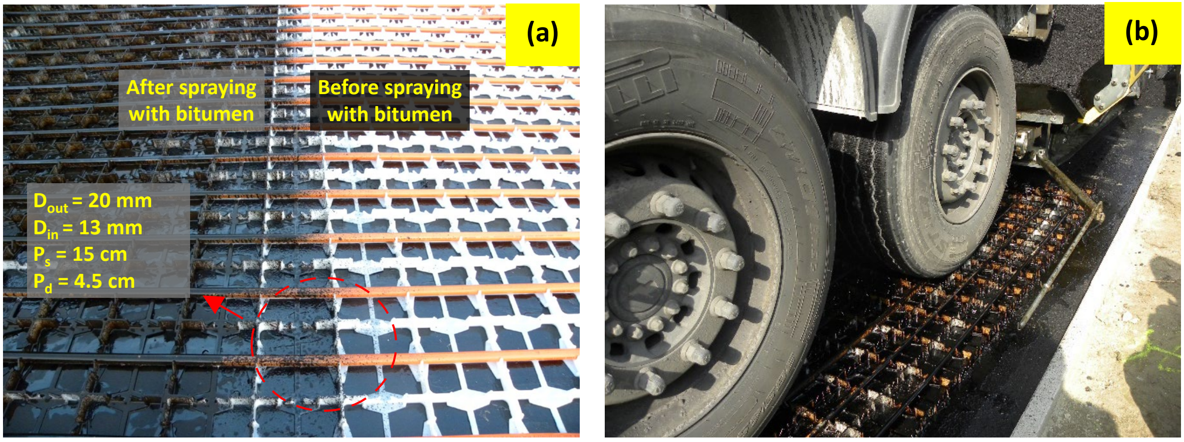


Figure 2. The pipe and grid structure in HEAL (a) geometrical specifications (b) during asphalt placement; with D_{out} = outer diameter of pipes, D_{in} = inner diameter, P_s = pipe spacing, P_d = pipe embedment depth

The HEAL system can be divided into four main parts; the heat exchanger section (i.e., collector), technical unit, borehole thermal energy storage (BTES), and control system (including measurement devices and sensors). The schematic layout of the HEAL prototype with details on temperature sensors' location and different heat exchange sections is presented in Figure 3.

The heat exchanger section was designed and configured into four interconnected sections. The pipe length for each of these sections is around 50 m that can provide a combination of different scenarios of 50 m, 100 m, or 200 m pipe length through a series connection with other sections (see Figure 4). Therefore, depending on the project settings and purpose (e.g., harsh snow or freezing temperature), the heat exchange sections can be automatically or manually switched between 4 x 50 m (parallel configuration), 1 x 200 m long (series configuration), or 2 x 100 m long pipe network (a combination of parallel and series). The aim of having different configurations of the collector section is to study the thermal performance of the HEAL system in various modes such as full power (i.e., activating the entire system) or partially powered. Furthermore, the system behavior can be investigated in the same weather conditions while using different parametric settings (e.g., different flow rates for each parallel pipe section).

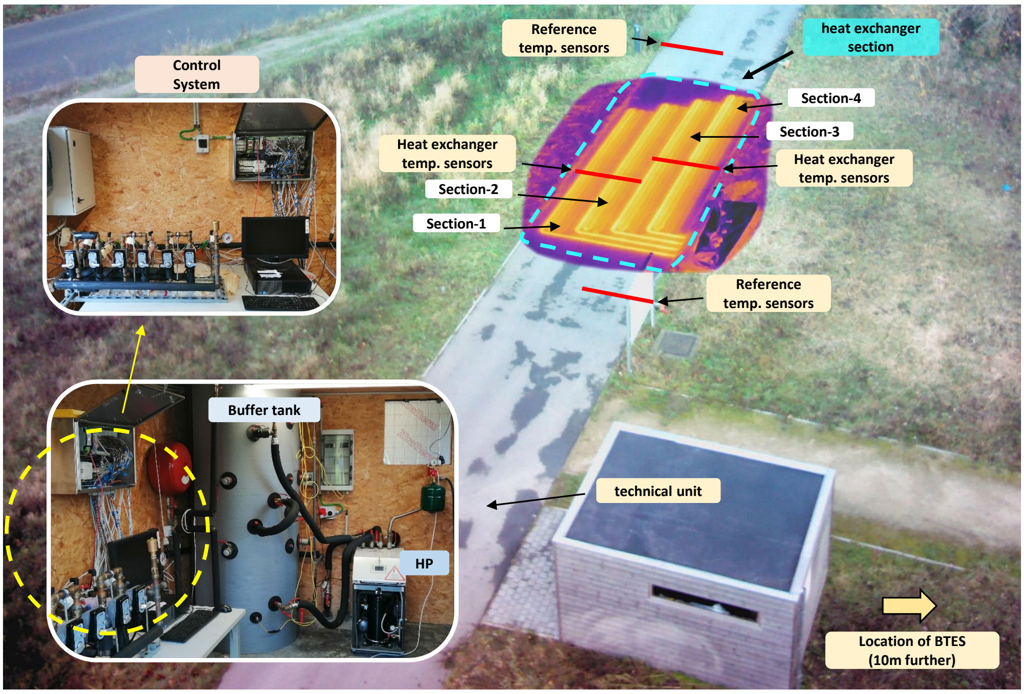


Figure 3. The layout of the HEAL prototype

The technical unit includes a reversible Heat Pump (HP), buffer storage, water pump, expansion tanks, control system, weather station, and control computer. The HP pumps back the stored heat from the BTES to the heat exchanger section in the wintertime. Moreover, if the temperature of the stored heat is not enough to provide the required thermal energy for the HEAL (e.g., harsh snow), the HP increases fluid temperature through a compression and expansion process. Moreover, a buffer storage located in the technical unit with a capacity of 1000 liters is connected to the heat exchanger sections and the HP. The main purpose of the buffer storage is to be able to activate the HEAL system in alternative supply temperatures and to ensure that the HP has a stable runtime. In the case of inadequate storage capacity, thus limited thermal power of BTES systems, auxiliary buffer storage might be necessary for large-scale projects [27]. Besides, since the buffer storage provides us with the flexibility of mixing water at a wide range of supply temperatures, the HP will have less frequent ON/OFF switches, resulting in an increase in the lifespan of the HP. The buffer tank collects the incoming water from the heat exchanger section (outlet) and can either increase or decrease water temperature using energy provided from the HP through the bottom, top, or both coils inside the buffer tank. By combining the HP and BTES in the system configuration, the supply temperature can reach up to around 35°C at its current settings in wintertime.

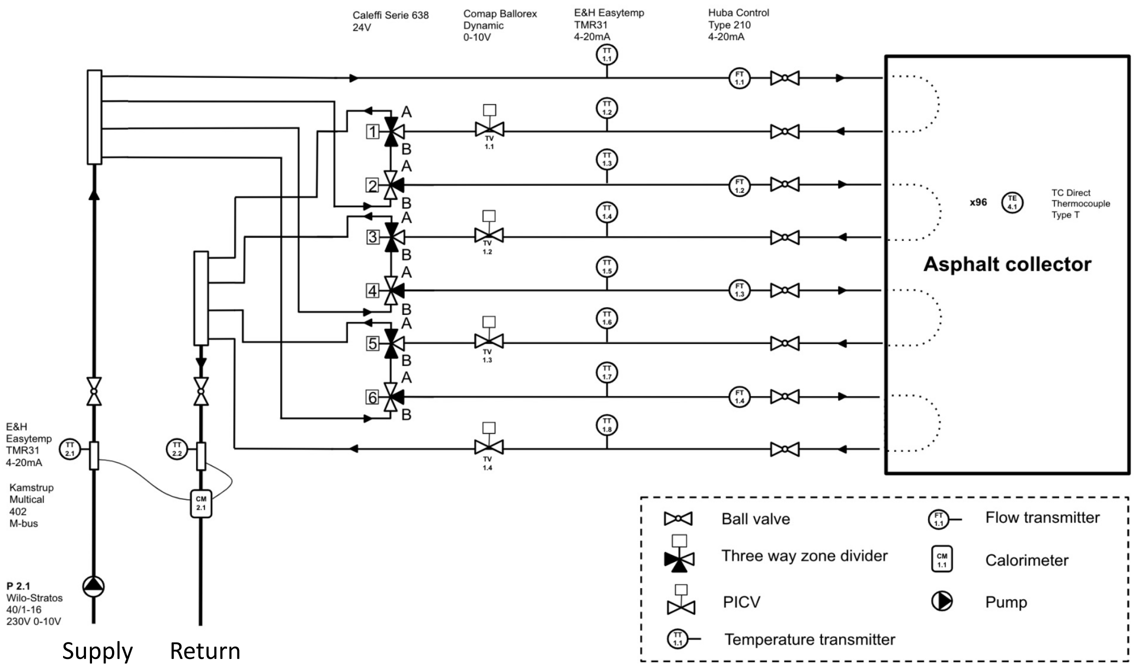


Figure 4. The schematic connection of HEAL sections with corresponding sensors and actuators [28]

2.2. System Control and Monitoring of HEAL

The control system in the technical unit includes flow transmitters, temperature sensors, pressure manometers, control valves, and regulators. The control system monitors (input and output parameters) and applies the necessary changes (e.g., activate or deactivate the heat exchanger sections). The measurement devices record supply and return temperatures, flow rates, and pavement temperature at different depths and are connected to a programmable logic controller (PLC) for real-time monitoring and control (Figure 4). The flow rates for both parallel and series configurations are adjustable (i.e., laminar, transient, and turbulent regimes) and can be automatically or manually switched by the control system. The maximum flow rate for the parallel configuration is 5 l/min (i.e., 20 l/min in total), while in series, it can reach up to around 2.5 l/min. The coils of the buffer tank are connected in series in order to optimize the transferred heat between the HP and buffer tank. Hence, a mixing valve sets the supply temperature by mixing water (i.e., at different flow rates) from the upper and lower part of the buffer storage (with different temperatures), and the water pump sends it to the collector through the control system. The schematic of the connections between HP, buffer tank and BTES is provided in Figure 5.

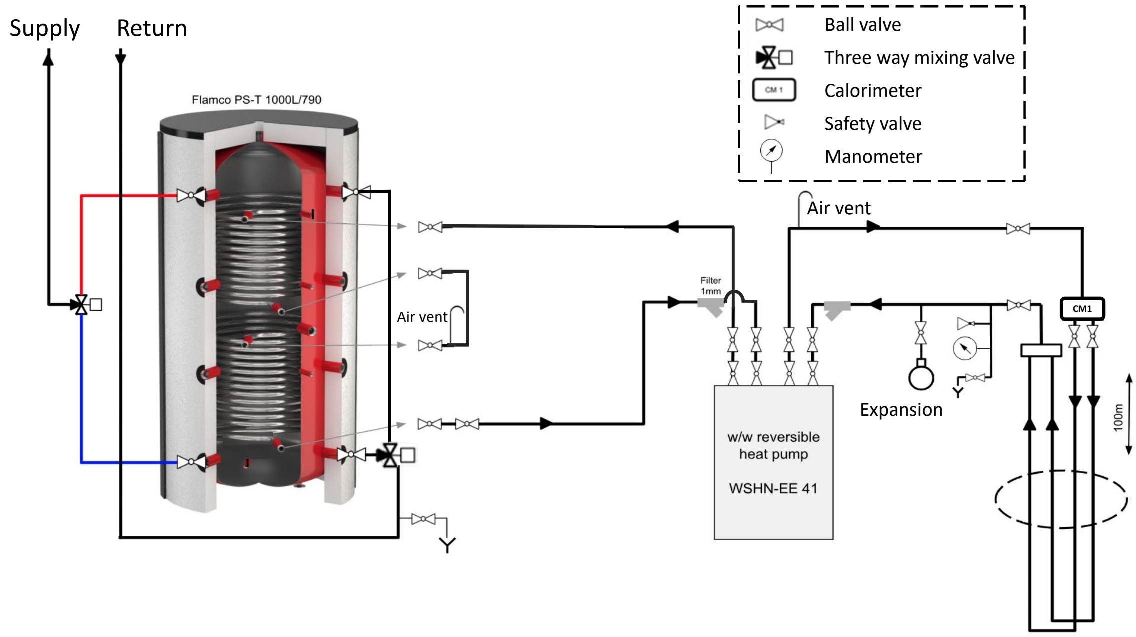


Figure 5. The schematic connection (P&ID) of heat pump with buffer tank and borehole energy storage (modified from [28])

To monitor the temperature profile of the asphalt pavement and compare the temperature variations in the heat exchanger and reference sections, 96 fast response PFA insulated thermocouples are placed in two reference sections and two within the collector part, all perpendicular to the traffic direction. Each of the temperature measurement sections includes 24 thermocouples that are placed at the near-surface, on top and bottom of pipes, in the collector layer, and in the base layer (Figure 1). Furthermore, a stand-alone weather station is installed at the technical unit to monitor and collect weather parameters at the project location. The weather station measures air temperature and relative humidity (41342VC/V.F. temperature probe), wind velocity and wind direction (85000 ultrasonic anemometer), solar irradiation (SR11 pyranometer), and barometric pressure (61202 Young). The data is collected using an individual data logger (CR1000) connected to the central system controller [29].

The large-scale PSC systems harvest thermal energy from solar irradiation, store and use it for different applications. Seasonal thermal energy storage is necessary to store the excess collected heat in the summer to compensate for the required heat during the cold months. A Borehole Thermal Energy Storage (BTES) can be constructed by excavating and drilling the ground to insert vertical or horizontal tubes, where the tubes, soil, and water act as heat exchangers, storage medium, and transfer fluid, respectively [27]. For this prototype, two boreholes were drilled to 100 m of depth as a vertical BTES system and filled with U-shaped pipes to form the heat exchanging surface with the surrounding soil. The BTES boreholes are filled with a water and anti-freeze mixture (i.e., monopropylene glycol). However, due to environmental concerns such as contamination of the groundwater table, no glycol mixture is used in the heat exchanger section of HEAL, as there could be a larger risk of leaking. The BTES is the thermal energy source of the HEAL (combined with the HP when necessary) during the winter period and acts as heat sink in the summertime. In summer, colder water passes through the pipes, gets heated, and is then collected in the buffer tank. Next, the HP captures the thermal energy from the warm water and pumps the heat into the BTES. A lack of remaining heat for snow melting purposes (e.g., long snow period or harsh snowstorm) or too low temperature of BTES for keeping the road surface temperature above 5 °C can be tackled by incorporating the HP to provide additional heat or increase the supply water temperature. This combination also offers more flexibility to the prototype. Although several studies [14, 15, 30] showed that the amount of extracted heat from PSC systems is sufficient for wintertime, a proper plan seems essential to balance the injected and depleted heat from BTES in order to keep the temperature of the soil in thermal equilibrium in the long term.

3. Methodology of designed experiments

The influence of geometrical and operational parameters on the performance of PSCs has been studied in several recent studies, and it is concluded that pipe spacing, embedment depth, asphalt thermal properties, flow rate, and pipe diameter are the most prominent parameters [2, 4, 18].

The fluid operation parameters (e.g., flow rate and supply temperature) directly impact the heat transfer between circulating fluid and asphalt pavement, in which an increase in flow rate or supply temperature (in wintertime) speeds up the heat exchange mechanism. As a result, an increase in flow rate will decrease the temperature difference between supply and return temperature. However, due to the lack of controlled studies, it can be questioned whether the increase in flow rate results in heat transfer efficiency (i.e., impact on surface temperature) [31]. In [14], Johnsson and Adl-Zarrabi showed that a higher flow rate leads to a larger temperature difference between supply and return temperatures, increasing heat extraction capacity of the PSC system. It should be noted that the magnitude of flow rate greatly differs in the literature studies. For instance, Masoumi et al. [16] and Zaim et al. [19] studied the variation of flow rate in the range of 0.2 - 1.6 l/min and 0.4 - 1.3 l/min in the small-scale setups. However, the studies of Johnsson and Adl-Zarrabi [14], and Saleh et al. [8] were performed with a much higher flow rate (i.e., up to 11 times) of 1.2 - 10.2 l/min and 6 - 18 l/min, respectively.

In addition to asphalt surface temperature and return temperature, variation of the flow rate affects the temperature profile of asphalt pavement. Although Bobes-Jesus et al. [4] stated that an increase in flow rate has no noticeable influence on temperature profile with depth, to date, the problem has received scant attention in the research literature. Zaim et al. [19] studied the impact of pipe arrangement on the thermal performance of PSC systems to maximize the return temperature and consequently achieve optimum thermal efficiency. They concluded that an appropriate pipe arrangement could increase both thermal efficiency and outlet temperature of PSCs. Research to date has not yet determined the impact of pipe length on the thermal behavior of PSCs. Up to this date, a systematic understanding of how PSCs contribute towards urban heating and global warming is still lacking despite several studies have reported on their potential application to mitigate the UHI effect [15].

This paper investigates the thermal performance of the PSC systems with a focus on a series of parametric studies. The HEAL prototype is controllable, fully monitored, and has a flexible configuration that provides the opportunity to design experiments to compare the system performance in several identical operational modes. Thus, the impact of several input variables (e.g., flow rate) on the thermal response of HEAL can be investigated in identical experimental conditions.

In this study, four experiments, two in cold seasons and a pair in the summertime, were designed to investigate the impact of various parameters on system performance. The first set of experiments is performed in the wintertime to study the effect of inlet temperature, flow rate, and system configuration on the required heating load to keep the asphalt surface ice/snow-free and on asphalt profile temperature variations. The experiments in the heating mode include two different supply temperatures, while each heat exchanger section has a different flow rate in laminar, transient, and turbulent regimes. Furthermore, one of the heating mode tests was planned to illustrate whether it is possible to increase the supply temperature by profiting from solar irradiation in cold seasons.

The second set of experiments was conducted in summer to assess the energy harvesting capacity, collector efficiency, and the influence of heat extraction from asphalt pavement on the surface and profile temperatures. Parallel and a series configuration were opted for the cooling mode experiments to study the impact of pipe length (and system configuration), flow rates, and flow regime. The flexibility of the HEAL system allows collecting the data in the series configuration simultaneously for the pipe length of 200 m, and at intermediate lengths of 150, 100 and 50 m, in which a constant turbulent flow rate equal to 2.5 l/min was pumped into the heat exchanger section. In the parallel configuration for both heating and cooling experiments, four different flow rates equal to 1, 2, 3, and 4 (l/min), covering laminar, transient, and turbulent regimes, were delivered to each of the four heat exchanger sections.

3.1. System response validation

In this part, the response of the four different HEAL sections is investigated and compared to check the reliability of the system for further parametric studies. This analysis is conducted in order to understand the HEAL response in identical system inputs and whether comparison results are valid. For this reason, the HEAL system was activated in the parallel configuration with a supply water temperature of 14+-0.5 °C for all four heat exchanger sections. In this experiment, three flow rates equal to 2, 3, and 3.85 l/min were used to validate the response of the different heat exchanger sections. As a result, output response of flow transmitters and return temperature sensors were examined in all four sections. Figure 6 - (a) shows the flow rate variations in the heat exchanger sections. There is a marginal difference in flow transmitter response in the four sections at the highest flow rate equal to 3.85 l/min, although it can be neglected in a large-scale system. The main explanation for this difference could be the calibration parameters of the flow sensors actuators that record the inlet flow.

Furthermore, the average supply and return temperatures of the four sections and standard deviations are shown in Figure 6 - (b). The supply temperatures are controlled with a mixing valve, and there is almost no difference between the supply temperatures going into the four sections (i.e., an average standard deviation of 0.07 °C). However, the return temperature of the heat exchanger sections has a slightly higher standard deviation with a maximum of 0.43 °C and an average of 0.20 °C. Therefore, the accuracy check illustrates that comparing different sections is reliable due to an insignificant error among the four heat exchanger sections.

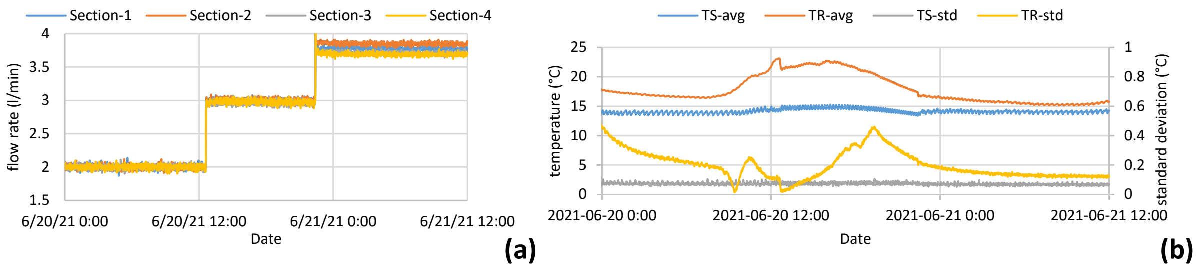


Figure 6. System response check (a) implemented flow rates of 2, 3, and 3.85 l/min; for the (b) average supply and return temperatures (left axis) and standard deviations (right axis)

3.2. Heating experiments

This section provides experimental results of the HEAL system in the heating mode, including low and high supply temperature tests to differentiate between the performance system in these two modes, heating load in different flow rates, and changes in asphalt surface and profile temperatures. The experimental results for high-temperature and low-temperature studies were collected between April 6^{th} and 8^{th} and March 4^{th} and 9^{th}, 2021, respectively.

For the high-temperature experiment, the Supply Temperature (TS) for all four sections was set to 28+-1 °C (Figure 7 - (a)). The high-temperature experiment was designed to compare the performance of the HEAL system with different flow rates in cold weather and optimize the system performance. Due to the fact that no thermal energy was collected into the BTES system in the previous summer, the temperature of the BTES was assumed (i.e., to calculate the thermal power consumption) around 12 °C from the thermal response test of the boreholes. Hence, the HP was activated to increase the temperature of the supply flow to achieve a higher temperature for the heat exchanger sections. As shown in Figure 7 - (a), the ambient air temperature (T_a) reached -0.5 °C and 6 °C in the coldest and warmest points in the period of the high-temperature study.

In this experiment, the heat exchanger sections were not operational before the activation of HEAL in order to achieve temperature stability in the system. In Figure 7 - (a), the Return Temperatures (TR) are related to flow rates of 4, 3, 2, and 1 l/min in the turbulent, transient, and laminar regimes. These different flow rates for sections 1 to 4 (Figure 3) were selected to investigate the impact of flow rate on the thermal performance of the HEAL system. Figure 4 - (a) shows that return temperatures from a section with a higher flow rate are larger than sections with a lower flow rate. The flow rate greatly affects the TR of a section directly associated with other aspects of the HEAL thermal behavior (e.g., surface temperature or energy consumption).

In the low-temperature setting, supply water (collected in the buffer tank) temperature was set to 14 °C for all heat exchanger sections. Since the return flow was placed at the bottom of the buffer tank, a direct short circuit with the bottom supply of the mixing valve was possible. Due to hourly changes in solar irradiation and ambient air temperature, the relative hot return flow mixed with the cold water at the bottom that increased the minimum supply temperature between 11 and 22 °C, as seen in Figure 4 - (b). As mentioned in Section 2, a mixing valve is normally used to control and deliver the requested supply temperature. In this particular experiment, the mixing valve was disabled to benefit from solar irradiation during the day and eliminate the need for HP to increase the TS of the circulating flow. Since the extraneous heat is gained from solar irradiation, the BTES will deplete at a lower rate. According to Figure 7 - (b), T_a varies between zero and -3 °C during the night and increases to 8 – 10 °C around noon. Similar to the high-temperature experiment, flow rates equal to 4, 3, 2, and 1 l/min are set for the four different heat exchanger sections to compare the thermal performance of HEAL system in the low-temperature setting.

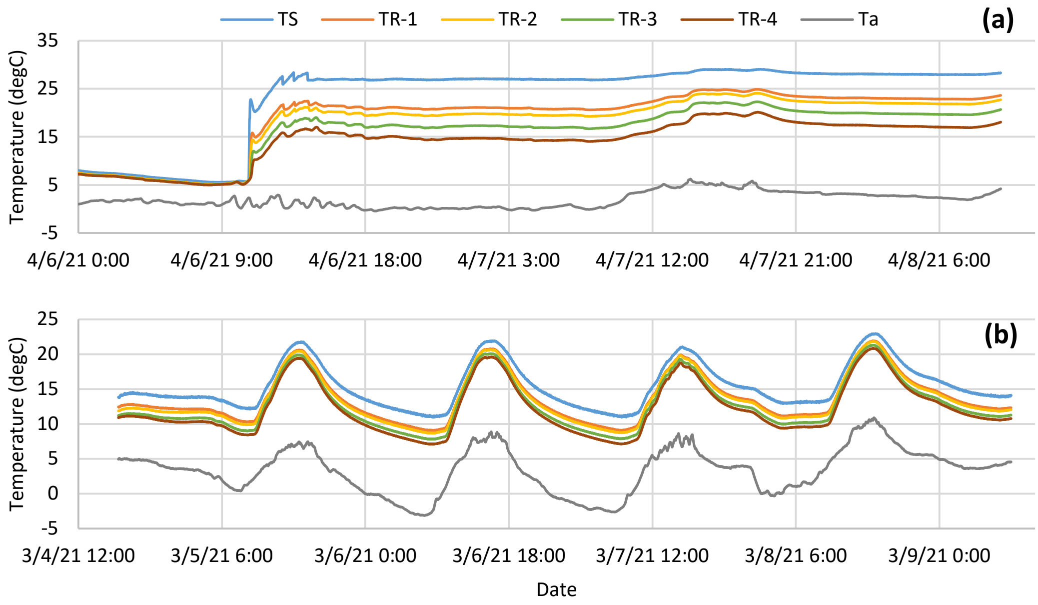


Figure 7. Heating experiments in (a) high-temperature (b) low-temperature water supply; with TS = supply temperature, TR = return temperature and Ta = ambient air temperature
High-temperature (TS=28°C, controlled), low temperature (TS=14°C, not controlled), TR1-4: flow rates 4,3,2,1 (l/min)

3.2.1. Thermal power consumption

The thermal power consumption of the PSC systems is an essential aspect of such systems since a seasonal balance between extracted and injected heat needs to be established. In the studied low-temperature and high-temperature heating experiments, the energy consumption of HEAL in different operational conditions (e.g., flow rates) is investigated. The momentary (i.e., logged via controller) injected or extracted power $q_{gain/loss}$ (kW) of the asphalt solar collector system are calculated according to Eq. (1) [13, 32]:

$$Q_{gain/loss} = \dot{m}\, c_{p,w}\, (T_{w,o} - T_{w,i}) \qquad (1)$$

where $\dot{m}$ (kg/s) is the mass flow rate, $c_{p,w}$ (J/kg.K) is the specific heat capacity of water, and $T_{w,o}$ (K) and $T_{w,i}$ (K) are the outlet and inlet water temperature of the PSC, respectively. To translate the calculated momentary power of the system to average hourly, the following Eq. (2) is used:

$$Q_{avg} = \frac{\sum_{s=1}^{n} Q_{gain/loss}}{n} \qquad (2)$$

where Q_{avg} (kW) is the average hourly power extraction or consumption (depending on season), and n (-) is the number of momentary recorded data in one hour.

The average hourly and cumulative power consumption of the different sections in low- and high-temperature flow experiments are given in Figure 8. The results from the high-temperature case show that the heat exchanger section with a higher flow rate requires more average hourly power (subfigure a), resulting in a higher cumulative consumption power of the section (subfigure b). For example, lowering the flow rate from 4 to 3, 2, and 1 l/min results in 10%, 23%, and 49% reduction in the cumulative power consumption. This comparison between cumulative power consumption highlights the fundamental impact of flow rate in calculating the required energy for snow melting in wintertime (as described in Eq. (1)).

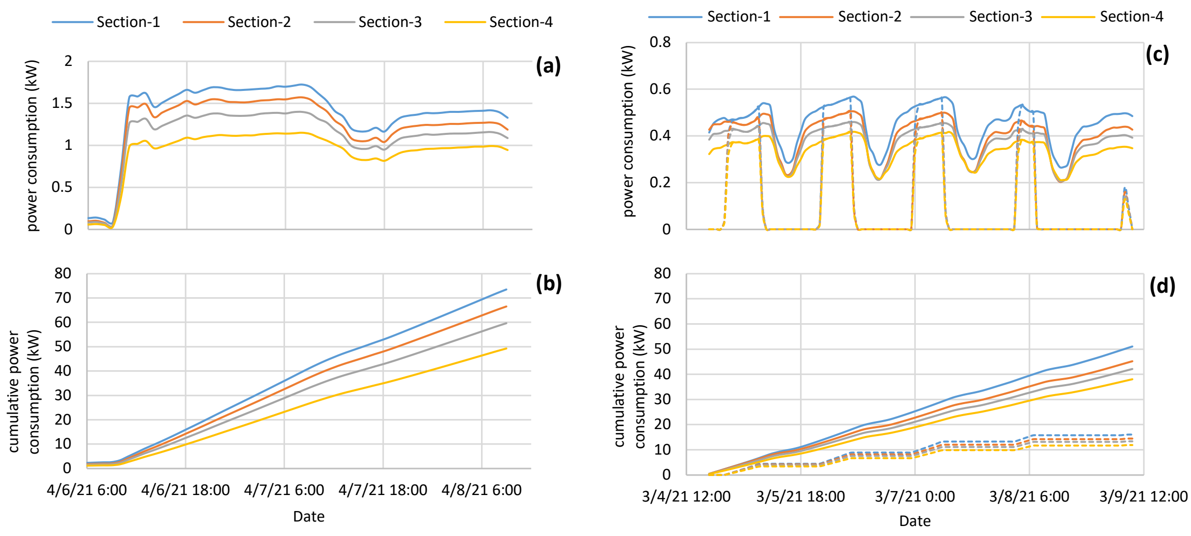


Figure 8. Average hourly (a and c) and cumulative power (b and d) comparison for (left) high-temperature and (right) low-temperature modes; dashed lines in (d) represent excluded solar irradiation in generated power

Furthermore, according to Figure 8 (b) and (d), the low-temperature scenario uses less heat power to provide ice-free asphalt surface than the high-temperature mode. The impact of both high- and low-temperature supplies on the surface of the asphalt pavement will be discussed in the following section. As mentioned in the previous section, in the low-temperature experiment, the mixing valve was disabled to maximize the impact of solar irradiation on the return temperature. As a result, heated return flow will be collected in the buffer tank even during cold days resulting in a lower depletion rate of the heat from the BTES. In Figure 8 – (c) and (d), the dashed lines represent the generated power only from BTES and HP (i.e., solar irradiation excluded), and total cumulative power consumption is 3.16 times higher compared to the case without the help of solar irradiation. In terms of cumulative power consumption for different flow rates, an increase in flow rate from 1 l/min (laminar flow) to 2 (transient), 3, and 4 l/min (turbulent flow) results in 10%, 20%, and 34% increase for total delivered power from HP, respectively.

It should be noted that in the high-temperature flow experiments, the solar irradiation on asphalt pavement increases the return temperature by 1.5-2 °C compared to 7-11 °C in the low-temperature case. Hence, it is reasonable to benefit from solar irradiation (on partially sunny days) in low-temperature experiments and optimize the inlet temperature according to the weather conditions. Although both low- and high-temperature flow scenarios provide an ice-free asphalt road surface, the average cumulative power for a total number of working hours shows that the power consumption of the high-temperature test was over 7 times higher compared to the low-temperature (i.e., with the combination of solar irradiation) experiment that should be taken into account in the long-term energy balance calculation of the system.

3.2.2. Effect on asphalt surface temperature

transverse thermal cracks that could extend the service life of the pavement. To this end, the surface temperature of four sections with different flow rates are compared with the surface temperature of reference sections (without HEAL system). The asphalt surface temperature plays an important role in the optimal control of HEAL system for anti-freezing. In this study, the threshold for asphalt surface freezing point was assumed as zero °C. Experimental results show that the HEAL system has successfully increased the asphalt surface temperature in both high- and low-supply water temperatures. However, the thermal response of heat exchanger sections is directly associated with the supply temperature flowing in the system (Figure 9).

In the high-temperature experiment, the minimum asphalt surface temperature in the reference section reached -2.5 °C, while the HEAL system increased the surface temperature in the coldest hours (between 21:00 and 9:00) between 4 and 8.5 °C for the lowest and highest flow rate, respectively. Moreover, solar irradiation around noon time increases the surface temperature. Hence, the conductive heat transfer mechanism in the asphalt pavement increases the profile temperature of the asphalt pavement and, consequently, the temperature of the circulating water (Figure 7 - (a)). Since the solar irradiation partly compensates for the required heating load (e.g., for snow melting), it is essential to use an intermittent operation mode [15] to optimize the heat loading of the HEAL system.

In the low-temperature experiment, the minimum surface temperature of the reference sections reached around -6.1 °C during the measurement period. In this experiment, the supply temperature from HP has an insignificant effect compared to solar irradiation during the daytime, resulting in the increase of the surface temperature of all four sections to the same level. The low-temperature supply successfully increased the surface temperature of asphalt pavement between 7.0 °C and 2.0 °C for the highest and lowest flow rate in different heat exchanger sections. Although the main aim of the low-temperature experiment was to increase the surface temperature of the asphalt pavement above zero (and it succeeded), an optimal control protocol (e.g., variable flow rate or intermittent operation mode) seems necessary to prevent potential freezing of the road surface.

A histogram of asphalt surface temperature data is provided in Figure 9 for high- and low-temperature experiments. The histogram compares four surface temperature bins regarding their operational time (in percent) in both the HEAL and reference sections. For example, in the high-temperature experiment (Figure 9 - (a)), during 32% of the experiment, the surface temperature of the reference section was below 0°C and susceptible to freezing. Also, the asphalt surface temperature was between zero and 2.5 °C (i.e., dew formation and high potential to have a slippery road) around 35% of the experiment period. However, by activating the HEAL system in the high-temperature water supply, we achieved a surface temperature above 2.5 °C in all four flow rates (discussed in previous sections) above 98% of operation time. In the case of the low-temperature experiment, around 40% of surface temperature data points are still below freezing point, and in total, 64% of surface temperature data are under 2.5 °C. Based on Figure 6 - (b), implementing a HEAL system with a low (laminar) flow rate (i.e., 1 l/min) did not successfully increase the surface temperature above the freezing point in almost 8% of the experiment time. Hence, the capacity of low-temperature supply to provide an ice-free road surface should be predicted using local weather data prior to defining an operational protocol in HEAL systems.

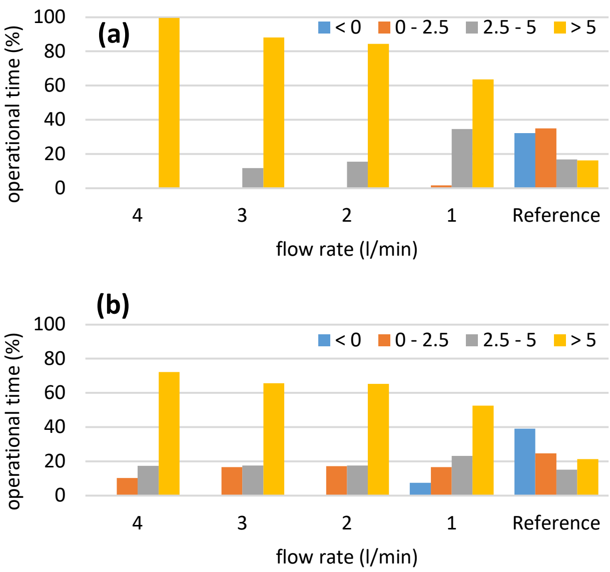


Figure 9. Asphalt surface temperature data histogram in (a) high-temperature (b) low-temperature supply mode

3.2.3. Effect on asphalt pavement profile temperature

The temperature measurements of the interface layers at the collector layer (i.e., between the top layer and collector layer) and base layer (i.e., between collector layer and the base layer) for both low- and high-temperature experiments are provided in Figure 10. These measurements compare the temperature response within the different heat exchanger sections and reference sections.

A histogram of the average temperature differences in the interface layers shows the classification of the data measurement points with regard to the operation time of the experiment. The temperature of collector and base layers interface significantly increase above 8 °C in the high-temperature mode (Figure 10). The temperature difference (relative to reference sections) in the interface of the collector layer in 68% of experiment time was more than 8 °C, while in the base layer even higher temperature differences were established, more than 78% and 58% of the time above 8 and 12 °C, respectively. On the other hand, low-temperature test results show that the temperature increase in the collector interface is considerably concentrated (around 82%) in the 4 – 6 °C category. For the base layer interface, the temperature increase was recorded approximately 76% of the operational time between 4 – 8 °C. It is noteworthy mentioning that the HEAL system increased the temperature of the collector layer interface more than the base layer interface since the effective radius of the heating system is closer to the collector layer interface. Moreover, the low-temperature flow is less effective in increasing the temperature of the interface. Hence, it is essential to estimate the effective heating distance in different asphalt layers of a HEAL system in the wintertime to increase the temperature of the interface layer to reduce the potential of cold thermal crack developments and brittle shear failure behavior.

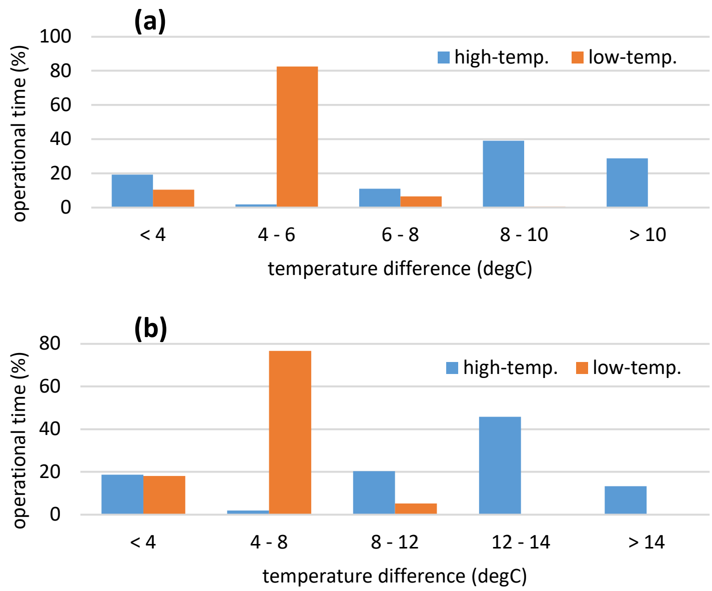


Figure 10. Histogram of interface layer temperature difference at (a) collector and (b) base layer for high- and low-temperature tests

3.3. Cooling experiments

Another aspect of the HEAL system is to cool down the asphalt pavement by circulating colder fluid and consequently extracting thermal energy from the temperature difference between asphalt and fluid. The experimental tests for the parallel configuration were performed between June 10th - 14th, 2021, and the series configuration was recorded between June 15th - 21st, 2021. The average supply temperatures into the HEAL system for the parallel and series configuration experiments were 16+-1.7 °C and 14+-0.55 °C, respectively.

In Figure 11, the experimental results from the parallel and series tests are provided. Different flow rates are set for the four sections in the parallel configuration (Figure 8 – a) to compare their thermal performance. On the other hand, the series configuration aims to compare the various aspects of thermal response with identical flow rates but different pipe lengths. As shown in Figure 11, the ambient air temperature (T_a) was 19.17 °C (SD, 5.32) and 22.59 °C (SD, 4.65) for parallel and series tests. In Figure 11 – (a), the TR 1-4 are related to sections 1 to 4 with flow rates of 4, 3, 2, and 1 l/min. In the series experiment, TR-50 m, 100 m, 150 m, and 200 m are associated with a different pipe length of the HEAL system, with a constant turbulent flow rate of 2.5 l/min. As a result, in the next sections, the thermal performance of the HEAL system with a focus on energy extraction efficiency and impact on asphalt pavement temperature is compared both within parallel and series configurations and between the two scenarios.

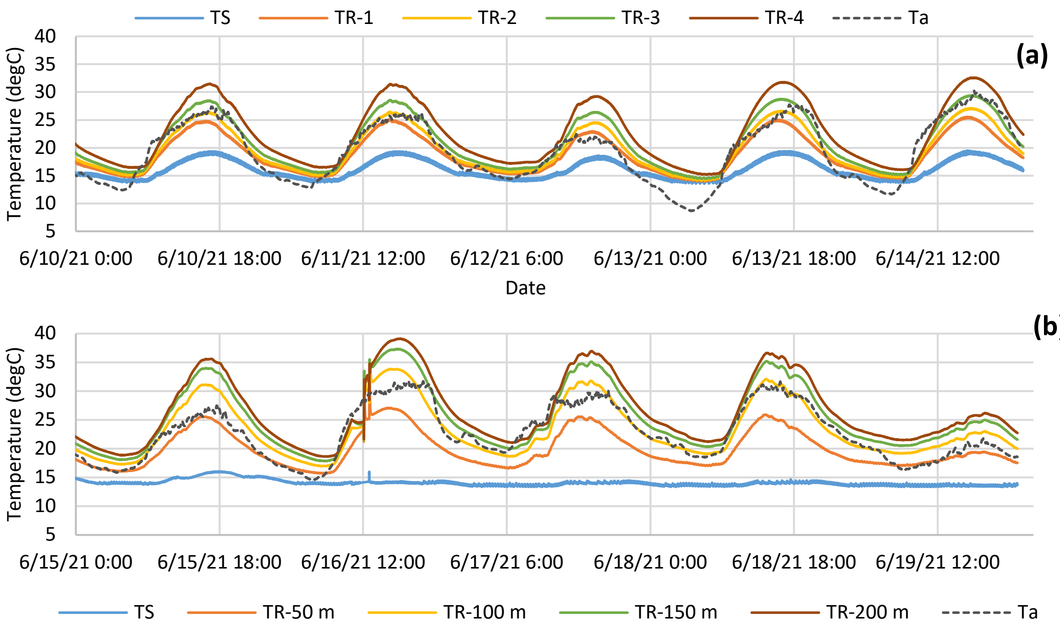


Figure 11. Cooling experiments in (a) parallel and (b) series configuration; with TR-X m = return temperature for X length of pipe

3.3.1. Heat collection

The ability of HEAL system to extract thermal energy from asphalt pavement and its potential to provide clean energy for domestic or industrial use is studied in this section. This part of the study highlights the energy extraction capacity, average daily efficiency of the HEAL system in different system configurations and compares the findings with relevant literature studies. The efficiency of the pavement solar collector is defined differently in the literature [20, 30, 33]. In this study, the efficiency of the collector is calculated based on the ratio between the extracted energy and the thermal energy of the incident solar irradiation using Eq. (3), according to [20]:

$$\eta_{avg} = \frac{Q_{gain}}{Q_{sw}} \tag{3}$$

where Q_{gain} is the total sum of hourly or daily extracted thermal energy from the HEAL system, and Q_{sw} is the total hourly or daily incoming solar irradiation on the heat exchanger sections, as measured by the pyranometer installed on top of the technical unit. Also, the average daily efficiency $\eta_{day,avg}$ is defined to compare the efficiency of the collector on different summer days as plotted in Figure 12.

Figure 12 shows the cumulative thermal energy extracted from asphalt pavement and $\eta_{day,avg}$ values for the parallel and series tests. A glance at the results shows that the $\eta_{day,avg}$ for the parallel configuration achieved around 25% efficiency while it was 20% for the series configuration. The lower efficiency of the series configuration is mainly due to the lower flow rate of the series mode since the water pump installed in the HEAL system has limited pump head to circulate the fluid into the longer pipe network (more pressure losses). Although this can be questioned as a practical issue in the design stage, it is directly related to the selection of HEAL system configuration in its operational stage since longer pipe networks require a water pump with a higher pump head. In Figure 12 - (a), the actual $\eta_{day,avg}$ is calculated based on the experimental results, and in order to reach the maximum $\eta_{day,avg}$ of

34%, all four sections should be supported with the flow rate of 4 l/min. An artificially high $\eta_{day,avg}$ as a result of low solar irradiation on the asphalt surface [14] (e.g., cloudy days) is observed in the series mode (as shown in Figure 12 – (c) and (d)), where the efficiency reaches a value of 40% on June 19th. Previous literature studies have shown a wide range of energy harvesting efficiency for the PSC systems [15]. Although energy harvesting efficiency of PSCs has been estimated to be between 20% and 30% in various studies [20, 34, 35], research studies achieved up to around 50% energy harvesting capacity of the incident solar irradiation on the road surface [14, 36]. This study also confirms that the energy harvesting capability of large-scale PSCs is not only determined by the geometrical properties and geographical location of the installed systems, but also on operational conditions such as fluid flow and weather parameters (e.g., cloudiness).

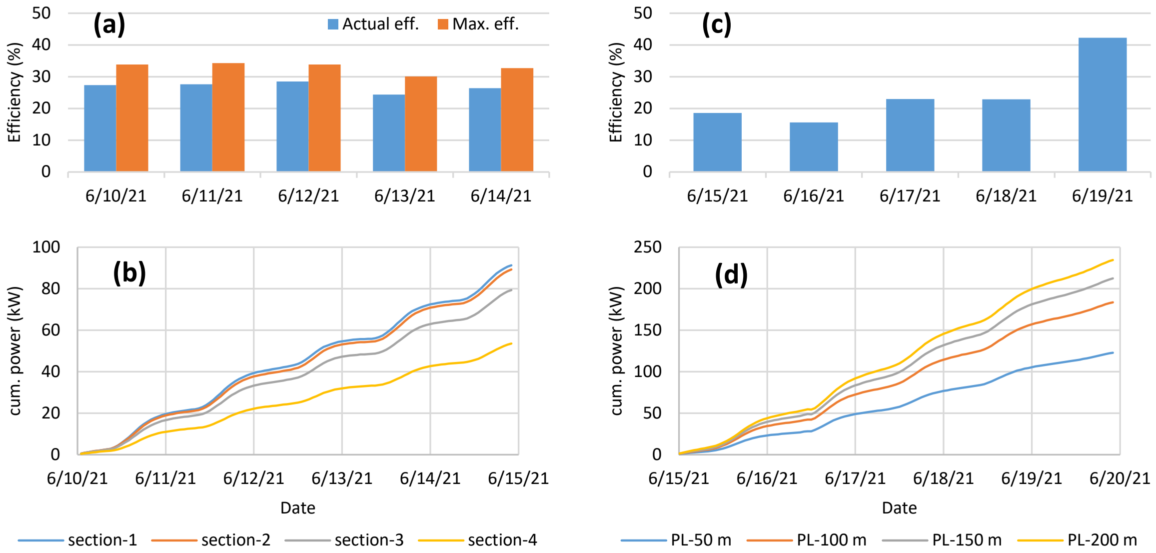


Figure 12. Cumulative heat extraction and average daily efficiency for (a and b) parallel (c and d) series configurations

The section with a higher flow rate (e.g., section-1) achieved the highest cumulative power. Moreover, and as can be expected, according to Figure 12 – (b) transient and turbulent flows are more effective in the heat exchange between circulating water and asphalt. The results show that an increase of flow rate from 1 to 2 l/min increased the cumulative collected power by around 48%, while an increase from 2 to 3 l/min and 3 to 4 improved the cumulative power by only 12% and 2%, respectively. For the series configuration, it can be seen that the cumulative power rises with the increase of pipe length. This is evident since the circulating fluid will have more time to exchange heat with warmer asphalt. However, to make a robust assessment regarding the impact of pipe length on the thermal response of HEAL system, a comparison between the sectional increase of pipe length is paramount. As a result, the cumulative extracted power from the HEAL system is divided by the pipe length to compare the collected power per running meter of pipes. The cumulative power per pipe meter is calculated at 2.45 kW/m for a pipe length of 50 m (PL-50 m) and drops by 25% to around 1.83 (kW/m) for 100 m. With a further increase of the pipe length to 150 and 200 m, the power per meter of pipe is reduced by 42% and 52% to 1.41 and 1.17 (kW/m) in comparison with the 50 m pipe network. Hence, the impact of pipe length on the total heat collection is immense and should be carefully selected at the design stage.

3.3.2. Effect on asphalt surface temperature

As mentioned in the introduction section, one of the objectives of the HEAL system is to reduce the surface temperature of asphalt pavement to mitigate the urban heat island (UHI) effect in the summertime. Several studies claim that PSC systems do not significantly influence the surface temperature of the asphalt pavement [8], however some reported in vice-versa [37, 38]. The current study investigates whether these systems can decrease pavement surface temperature and evaluate the impact of HEAL in parallel and series configuration to highlight the effect of operational variables (e.g., flow rate and pipe length) on the temperature reduction of the asphalt surface. For this reason, the temperature difference between four sections (parallel configuration) and pipe lengths (series configuration) with respect to reference sections are calculated and presented in the histogram shown in Figure 13.

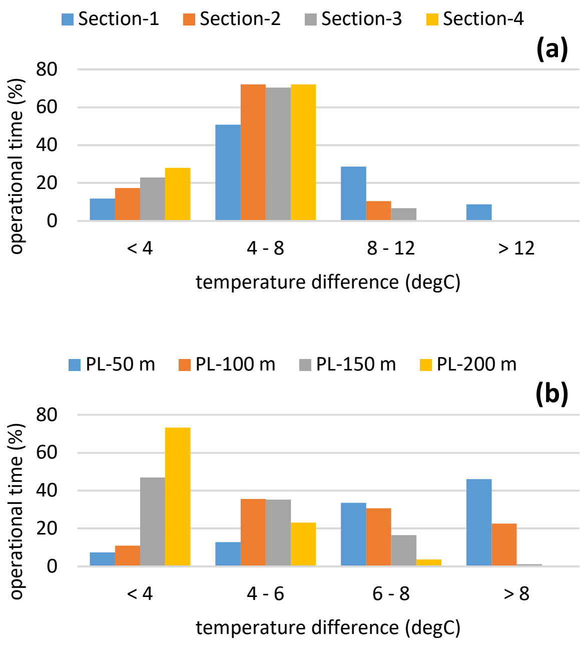


Figure 13. Histogram of asphalt surface temperature differences in: (a) parallel and (b) series configurations

The temperature differences have been classified into multiple groups on the basis of the operational time of the experiment. Evidently, a section with a higher flow rate resulted in lowering the surface temperature more effectively. Figure 10 – (a) shows that section-1 achieved a temperature reduction of the asphalt surface between 4 - 8 °C during more than 50% of its operational time. This section could reduce the surface temperature around 37% of the time above 8 °C, which is a significant achievement in using HEAL systems to mitigate the UHI effect. Although other sections with lower flow rates also positively impact surface temperature reduction, the temperature difference class is more concentrated (above 70%) between 4 - 8 °C. It is noteworthy mentioning that the temperature of the asphalt surface reaches its peak around 14:00 – 16:00 in summer days, and the cooling effect of HEAL on the asphalt surface is maximum between 18:30 - 19:30, which can be explained with the high (heat) thermal capacity of the asphalt pavement.

The series configuration in Figure 13 – (b) shows a more non-uniform surface temperature reduction than the parallel configuration. For the 50 m pipe length, the surface temperature reduction is around 46% of operational time above 8 °C. With the increase of pipe length to 150 m, the effectiveness of system in surface temperature reduction becomes limited to 6 °C, and surface temperature difference concentrates in below 4 °C category at almost 47% operational time. Therefore, the temperature difference of surface layer decreases in each 50 m increase of pipe length, resulting in an uneven temperature distribution of asphalt surface. In terms of pipe length, the effectiveness of the HEAL system in lowering surface temperature reduces with an increase in pipe length. Hence, pipe length is an important design variable to increase heat collection capacity, decrease asphalt surface temperature, and mitigate UHI.

To assess the inconclusive findings in the previous studies regarding the impact of PSC systems on the UHI effect, this study proves that the HEAL system can significantly reduce the pavement surface temperature. The results of the cooling experiments illustrate that circulating flow rate and pipe length have a measurable effect on the surface temperature reduction in PSC systems. Since the geometrical and operational conditions are either unclear or not well-defined in previous literature, a point-by-point comparison is challenging. Saleh et al. [8] observed that the PSC system could reduce the surface temperature by only 2 °C, while the influence of the project's pipe length remains unclear since it dramatically impacts surface temperature reduction. Finally, it can be expected that small- or lab-scale experiments encounter scaling limitations to predict the actual effect of PSC systems in mitigating UHI. The findings of the current paper and more recent research in the literature [10] demonstrate that increasing the flow rate has a significant effect on the surface temperature reduction in PSCs, although earlier studies claimed otherwise [25, 39].

3.3.3. Effect on asphalt pavement profile temperature

In line with regulating the seasonal temperature gradient in the asphalt pavement, the HEAL system also cools down the temperature of the interface zone between different layers in the asphalt pavement. A histogram of temperature differences (related to the reference sections) in the collector and base layer interface is provided in Figure 14.

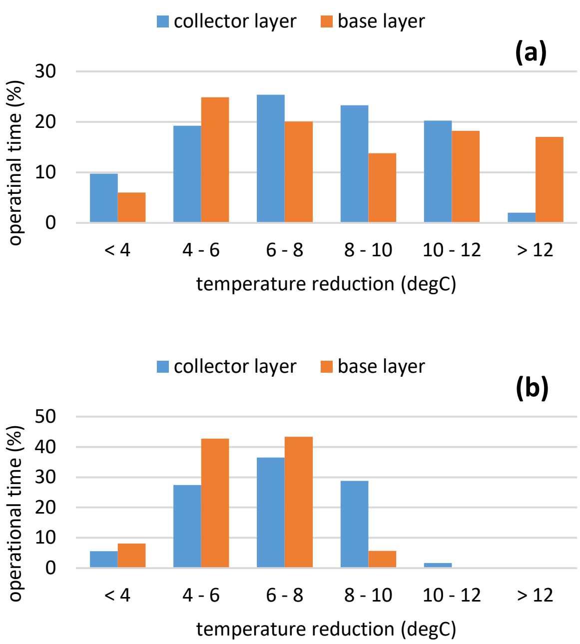


Figure 14. Histogram of temperature differences in interface layers (a) parallel (b) series configurations

This histogram categorizes average temperature differences of the sections with different flow rates (parallel configuration) and different pipe lengths (series configuration) in terms of the total operational time. Figure 14 – (a) demonstrates that the HEAL system cools down the interface temperature of the collector layer by 8 °C over 45% of the time and by 6 °C around 70% of the experiment period. It is vital to state that the HEAL system could potentially diminish the base layer's interface temperature by more than 12 °C (around 20% in this experiment), which is crucial to prevent shear failure and rutting development in the interface layers [40]. Majidifard et al. [41] studied the sensitivity of various parameters on the rutting performance of asphalt pavement and concluded that test temperature has the most significant influence on the rut depth together with the type of asphalt mixture and asphalt binder replacement (i.e., the ratio of the recycled binder to the total binder). The presented experimental and predicted results indicate that reducing test temperatures by 6 °C (between 64 and 58 °C) and 12 °C (between 64 and 52 °C) results in around 70% and 87% decrease in rutting depth of asphalt pavement.

The series configuration has a less effective cooling impact on the interface layers since the temperature difference is densely concentrated below 8 °C. This configuration shows that the HEAL system has the most influence on collector and base layer interface temperature reduction in the 4 – 10 °C and 4 – 8 °C categories, respectively. Hence, a comparison between the configuration modes reveals that the parallel configuration is more effective on average temperature reduction of the interface zones, thus a shorter pipe length is suggested to lower the temperature of interfaces successfully.

4. Discussion of results

The present study investigates different aspects of the thermal response of a PSC system. The thermal energy harvesting and consumption of these systems is important to define a seasonal balance in case a BTES or other STES system is used. As discussed in Sections 3.2.1 and 3.3.1, supply temperature, flow rates, and pipe length are critical operating parameters for the heating loads of the HEAL prototype. Although an evident strategy to optimize the heat loading of the HEAL system is to maximize the energy harvesting capacity and minimize the energy consumption, advanced strategies to optimally control the road de-icing systems already exist in the literature [42, 43].

4.1. Heat extraction rate and power consumption

The heat collection tests demonstrate that mean hourly heat gain (in the 2nd week of June) was around 0.773 kW (for one section only) for the highest flow rate (4 l/min) to reach its maximum heat extraction capacity. This value is relatively lower than the mean hourly heat gain of 1.031 kW (in the 3rd week of June) for the shortest pipe length in the series test. It should also be noted that the average ambient air temperature was around 3.42 °C higher in the latter experiment, resulting in a higher mean hourly heat gain. In a large-scale experimental study conducted by Johnsson and Adl-Zarrabi [14], it was shown that the daily average heat extraction rate ranged from 4 to 10 kW between May to August 2018. This study was performed in Östersund, Sweden with specific geometrical configurations and operational parameters (e.g., higher flow rate) to have a better understanding of PSC system performance in Scandinavia. In the current study, however, the mean daily heat gain is 2.65 kW, and the maximum achievable (by applying maximum flow rate in four sections) mean daily heat extraction rate is 3.06 kW. The operational conditions such as supply temperature, flow rate, geometrical properties, etc., are known to be associated with this difference in heat extraction rate of large-scale PSC systems.

Furthermore, the minimum power consumption for the wintertime to guarantee an ice-free road surface was 0.746 and 0.119 kW, for the high- and low-temperature modes with flow rates of 1 and 2 l/min, respectively. The analysis results showed that very low flow rates are not suitable to increase the interface layer temperature and further benefit from the HEAL system to reduce the potential of cold thermal crack developments and brittle shear failure behavior.

In this study, the mean hourly heat gain and power consumption are calculated for representative warm and cold months in order to evaluate the HEAL prototype's seasonal energy balance. The maximum hourly heat extraction rate in the parallel configuration was calculated 0.773 kW for one section (90.94 W/m^2) and can be compared to the average hourly power consumption of a heat exchanger section with 0.129 kW (15.17 W/m^2), in the low-temperature mode with flow rate 2 l/min to provide ice-/snow free road surface. Although the experiments of the current study are limited to a number of days, a comparison between average hourly heat gain and power consumption shows that applying a low-temperature supply in wintertime could save above 80% of the collected heat in the summertime for the same number of operational days. This finding is in confirmation with the literature, where Baetens et al. [44] state that 20% of the harvested heat could be enough for power consumption in wintertime for road surface temperature regulation. As a result, the remaining excess heat in the storage can be used for various applications such as providing (preheated) domestic hot water and heating system of the nearby buildings. Nevertheless, the direct integration of the extracted low-temperature heat in a district heating network remains a major challenge for researchers to pursue in relevant studies.

There are prominent features in the energy harvesting capacity of large-scale PSC projects, including geometrical parameters of the system (e.g., pipe depth, length, spacing), operational conditions (e.g., fluid flow, fluid type, supply temperature), weather parameters, and system properties (geographical location, asphalt materials). This broad range of parameters result in an arduous performance comparison between different projects since each is unique in its design and operational conditions. Therefore, further investigation on the sensitivity of design and operation variables is essential using a flexible and controllable large-scale research prototype.

4.2. Supply temperature versus flow rate

According to the performed heating experiments in this study, although a low-temperature mode (i.e., supply temperature of 14 °C) depletes almost 7 times less thermal energy than a high-temperature supply (i.e., supply temperature of 28 °C), it can provide an ice-free asphalt surface in wintertime. It was concluded that it is reasonable to use a low-temperature supply on partially sunny days and benefit from solar irradiation to lower the depletion rate of the stored thermal energy in BTES. The sensitivity analysis of flow rate shows that an increase in flow rate from 1 (laminar) to 4 l/min (turbulent) results in 49% and 34% higher power consumption (hydronic heat supply) in high- and low-temperature modes. The analysis of the results demonstrated that the influence of flow rate also depends on the flow regime. In the high-temperature mode, an increase of flow rate from laminar to transient regimes (1 to 2 l/min) increases the power consumption by around 21%, where it was calculated as only 11% and 10% for flow rate variation between transient to turbulent (2 – 3 l/min), and within turbulent flows (3 - 4 l/min). On the other hand, an increase of flow rate from 1 to 2 l/min (i.e., laminar and transient regimes) increased the cumulative power harvesting capacity by around 48% in the summertime. The cumulative power rise was calculated as only 12% and 2%, increasing from 2 to 3 l/min and 3 to 4, respectively. As a result, an increase in flow rate results in heat transfer efficiency of PSC systems as shown by previous studies in the literature [8, 10, 14].

4.3. Pipe length (system configuration) and flow rate

In terms of system configuration, the average daily efficiency for the parallel and series configurations was around 25% and 20% and can be increased to a maximum of 34% in parallel configuration by supplying all sections with the highest flow rate of 4 l/min provided by the water pump. The thermal response of PSCs to pipe length is not studied in the literature. This study established that increasing the pipe length from 50 m to 200 m reduces the cumulative power extraction per pipe meter by 52%, from 2.45 to 1.17 (kW/m) in the series configuration. Therefore, it is of utmost importance to configure and determine the ideal pipe length of the PSCs during the design stage to achieve an optimal heat harvesting efficiency from the asphalt pavement.

4.4. HEAL influence in mitigating surface UHI

The effective use of PSC systems cools down the upper layers of the asphalt pavement due to heat extraction. Hence, the sensible heat flow to the atmosphere decreases, mitigating the UHI effects [6, 45, 46]. Dakessian et al. [47] demonstrated that PSCs reduce pavement surface temperature considerably using small-scale and simulation studies. Nevertheless, Saleh et al. [8] concluded that the change in flow rate influences the asphalt surface temperature only slightly. Although several studies have shown the potential of PSCs to reduce the UHI effects [10, 38], the experimental data from large-scale projects are rather controversial, and there is no general agreement about the impact of PSC systems in mitigating the UHI effects. Studies on the mitigation of the UHI effects indicate that reducing the asphalt surface temperature could reduce ambient air temperature slightly above the asphalt pavement and at the pedestrian level [38, 48].

The present study shows that PSCs are capable of reducing the asphalt surface temperature by 8 - 12 °C (and mostly 4 - 8°C) when the ambient air temperature was 19.17 °C (SD, 5.32) and 22.59 °C (SD, 4.65). Besides, the influence of system configuration, flow rate, and pipe length on the surface temperature reduction is studied systematically. Hence, it could conceivably be hypothesized that PSCs potentially mitigate and reduce the UHI effects by collecting heat from the asphalt pavement.

4.5. Impact of HEAL on pavement temperature profile

There has been no detailed investigation of the impact of PSCs on the temperature profile of asphalt pavement. A previous study expressed that an increase in flow rate has no noticeable influence on temperature profile with depth [4]. Using experimental results, the present study shows that the temperature of collector and base layer interface have been increased with more than 8 °C in both heating and cooling tests. Depending on the supply temperature and system configuration, the temperature difference could rise further up to 12 °C in the interface zones. It was concluded that the low-temperature supply and longer pipe length (series configuration) are less effective in controlling the temperature of the interface zones. Therefore, controlling the temperature of collector and base layer interfaces could be an important benefit of PSCs to reduce the potential of cold thermal crack developments and brittle shear failure behavior during the wintertime, and rutting development and shear failure in in the interface layers zone during the summertime.

4.6. Service life of asphalt pavement

Previous literature studies showed that the compound thermal-induced and load-induced strains reduce the performance of pavement [49]. Besides, since rutting distress in asphalt pavement directly results from thermal-induced stresses, more frequent maintenance is necessary for pavements exposed to higher temperatures [50]. The effect of (seasonal) temperature gradient and maximum temperature of the asphalt pavement on the formation of distresses, and consequently their impact on the service life of the pavement is significant [6, 51]. As a result, one of the primary goals of using

PSC systems is to regulate temperature fluctuations in the asphalt pavement to reduce pavement distresses such as top-down cracking, rutting, and fatigue cracking to extend the service life of the pavement. Although it is claimed that PSCs are able to increase the service life of the pavement between 3-5 years depending on traffic load, weather conditions, mixture material, etc. [6, 47], a detailed service life extension analysis, including methodologies and assumptions is missing in the literature. It is noteworthy mentioning that most of the constructed large-scale PSCs in Europe and unmonitored, and no data is available regarding the service life of the pavement or issues after construction of systems (e.g., leakage, local failure). The lifetime of the entire system highly depends on regular maintenance (e.g., yearly) and inspections of the mechanical and electromechanical installations such as valves, transmitters, pumps, etc.

Furthermore, a proper structural and geometrical design of PSC systems can ensure to keep the (potential) structural damages in an acceptable range for roads. As an example, the embedment pipe depth is a crucial design parameter that should satisfy a trade-off between harvesting maximum heat (pipes closer to the surface) and minimum structural damage (pipes deeper in asphalt). Hence, several measures can be taken to ensure structural safety, such as preliminary load-induced strains/stress calculations or using a thicker top layer in the asphalt pavement. Moreover, more regular maintenance of the surface layer is suggested in order to seal surface cracks and avoid water infiltration (for pipes protection). To guarantee a longer service life of the system and pipe networks, shorter resurfacing intervals (e.g., 7 years) can be planned.

5. Conclusions and future work

This paper describes a fully monitored large-scale Heat Exchanging Asphalt Layer (HEAL) research case study with flexible system configuration. This study aims to explore the heating and cooling mode responses of HEAL system in the Western European environment. The thermal performance includes heating load, energy harvesting efficiency, the impact of heat injection and harvesting on asphalt surface temperature, and asphalt pavement profile temperature. The main advantage of HEAL prototype is its flexible system configuration that enables us to perform simultaneous sensitivity assessments for the design and operational parameters in the same experiments. As a result, a robust thermal response is established within the HEAL prototype which can be compared to other studies in the literature.

In this study, two experiments are designed and performed during cold season, emphasizing supply temperature, flow rates, and system configuration. The analysis results show that using a lower supply temperature (e.g., 14 °C) on sunny (and partially sunny) days diminishes the depletion rate of the stored thermal energy in BTES, guaranteeing an ice-free asphalt surface in wintertime. It should be noted that an appropriate system configuration is necessary to collect the heated return flow (by solar irradiation) in a storage tank. Besides, sensitivity analysis demonstrated that an increase in flow rate from laminar to transient regime results in almost two times higher power consumption compared to the same magnitude of flow rate variation between transient and turbulent or within turbulent regimes. In the high-temperature (i.e., inlet temperature of 28 °C) tests, the power consumption increases by around 21% when the flow rate increases from 1 (laminar) to 2 l/min (transient). The power consumption increases only 11% and 10% for flow rate variation between 2 - 3 l/min (transient to turbulent) and 3 - 4 l/min (both turbulent), respectively.

The experiments for summer include parallel and a series configurations to assess the impact of pipe length (and system configuration), flow rates, and flow regimes on the energy harvesting capacity, efficiency of the collector, and the influence of heat extraction from asphalt pavement on the surface and profile temperatures. The calculated average daily efficiency for the parallel configuration is higher compared to a series configuration which is a direct result of the higher flow rate (i.e., lower pressure loss in shorter pipe length) pumped into the heat exchanger sections. In the parallel mode, it was observed that a maximum average daily efficiency of 34% could be reached using the highest flow rate equal to 4 l/min. In terms of pipe length, a precise length should be designed and selected since longer pipe network results in lower cumulative power per pipe meter. It was found that the cumulative power extraction capacity can decrease by half, from 2.45 to 1.17 (kW/m), when the pipe length changes from 50 m to 200 m.

The HEAL system aims to increase the asphalt pavement temperature in the wintertime and improve road safety by means of providing a snow/ice-free surface. The test results demonstrate that both high- and low-temperature supply successfully increased the asphalt surface temperature above zero °C to prevent ice formation on the road surface. However, applying very low flow rates in the laminar regime (e.g., 1 l/min) for the low-temperature supply is not suggested on cold days since the heat exchange did not meet the required amount to keep surface temperature above 0 °C during the whole experiment time. Furthermore, the experiments show a great potential of PSCs to reduce asphalt temperature and consequently mitigate the UHI effects. The asphalt surface temperature was reduced noticeably up to 12 °C during 37% of operation time in the parallel configuration using a turbulent flow rate of 4 l/min. The range of surface temperature reduction is lower in a series configuration, which highlights the importance of pipe length in the effectiveness of HEAL system in surface temperature reduction. Finally, the HEAL system also effectively controls the temperature at the asphalt pavement interface layers. The performed experiments show that such a system is able to cool down the interface layers on hot days to regulate seasonal temperature gradient in the asphalt pavement and reduce the asphalt rutting in the collector and base layers during the summertime. Moreover, increasing the interface layer temperature in the wintertime will lower the potential of cold thermal crack developments and brittle shear failure behavior in interface layers.

Our future work includes to further the numerical and experimental investigations of PSC technologies (i.e., HEAL prototype) in mitigating surface and air UHI effects. The work analysis will incorporate two different weather and climate data with HEAL system configuration to test on the system capability to improve the UHI effects for the case of temperate city versus hot arid city.

Acknowledgments

This research did not receive any form of funding from public agencies, commercial, or not-for-profit sectors. The first author would like to acknowledge the University of Antwerp for the doctoral funding. The authors of this paper would like to give special thanks to Ing. Robin Baetens for his endless efforts to make the HEAL system operational. Finally, special gratitude is also given to Ing. Lucas Verheyden for his valuable works to improve the prototype.

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.

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