Future roads and mobility

The use of a large-scale prototype to investigate the actual performance of a Heat Exchanging Asphalt Layer

Ghalandari Taher[1], Vuye Cedric[1], Couscheir Karolien[1], Jacobs Geert[1], Severins Ian[1], Van den bergh Wim[1], Baetens Robin[1], Ceulemans David[1], Verhaert Ivan[1], Guldentops Gert[2]

[1]University of Antwerp, [2]Simpson Gumpertz & Heger, Inc.

Abstract

In October 2017 a large-scale prototype for a Heat Exchanging Asphalt Layer (HEAL) was constructed in a cycling path, together with other innovative technologies, such as Fibre Bragg Gratings to monitor the stress and strains, and fiber-reinforced asphalt in the top layer. The HEAL prototype consists of 30 m², 8.5 m x 3.5 m, and includes four circuits of pipes, 50 m of length each, placed in a collector layer. Additionally, two boreholes with a depth of approximately 100 m have been installed next to the cycling path so that heat can be extracted from the HEAL during summer and is available during winter to keep the cycling path ice and snow-free. By using an additional heat pump an overall better efficiency will be obtained. Different sensors to monitor the temperature of the asphalt and fluid were installed, together with a weather station that captures the most important weather parameters, such as wind speed, outside temperature, solar radiation, … By changing the way the different circuits of pipes are connected, it is possible to investigate the influence of total pipe length and pipe layout. Also, the input temperature and flow rate of the water will be controlled and varied during the experiments. An overview of the complete design, including all sensors and electromechanical devices, is given in this paper. Furthermore, some details are included from an extended Finite Element Model which will be validated using the experimental results from the large-scale prototype.

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1. INTRODUCTION

In recent years, concerns on the renewable energies and use of these energies instead of limited energy resources such as fossil fuels have increased. Increase of population, lifestyle changes, shifting more and more rural to urban areas, enhanced the worldwide demand for energy. According to [1], from 1980 to 2018, the world population increased from 4.45 to 7.63 billion, and at the same time, energy consumption per capita increased from 62.3 to 76.0 GJ [2]. These results show that the total energy consumption almost doubled in the period of 40 years. This leads to the idea of shifting from non-renewable energy to renewable energy resources. In the past years, multiple research has been devoted to find and develop substitute energy resources for conventional sources of energy. Energy harvesting from pavements is one of these new approaches.

Energy extraction from an asphalt pavement can be categorized in several major groups: solar radiation absorption (solar electrical, solar thermal) and mechanical to electrical conversion. In the mechanical to electrical conversion type, mechanical energy from cars passing on the road is transformed into electricity. Solar radiation on the pavement could be captured, transformed and stored for multiple purposes. Solar to electrical and thermal conversion approaches could be utilized in such a way in order to store energy in the desired form of energy.

In the solar thermal approach, the asphalt pavement is usually called an Asphalt Solar Collector (ASC) or Heat Exchanging Asphalt Layer (HEAL). In a HEAL, the asphalt pavement absorbs solar radiation on its surface. Furthermore, a network of pipes is embedded in the pavement with a fluid circulating in them. Water is the most used flowing fluid used in the pipes (similar in the current study), however, recent studies [3-6] investigated using air instead of water. Air as the circulating fluid is used to avoid potential of water leakage from pipes in case of improper construction or damages during the operational time. The energy is harvested from the temperature differences between the hot asphalt layers and circulating cold water which is pumped from an outside source. The extracted energy could be stored in a borehole or aquifer during summer and pumped back in the winter for safety (to increase asphalt temperature for snow- or ice-free asphalt surface) or clean-energy (to provide domestic hot water, cooling/heating of neighbourhood buildings) purposes.

Because of the dark colour of the asphalt, a significant amount of solar radiation can be absorbed on its surface which can reach up to 40 MJ/m² over the course of a day during summer [7]. This solar radiation absorption can increase the temperature of the asphalt up to 70°C [8]. The absorbed heat energy could be potentially extracted using a heat exchanger system embedded in the pavement structure, e.g. a heat exchanging asphalt layer (HEAL) system. According to literature, the possible output of energy extraction from a HEAL varies between 0.5 and 0.8 GJ/m² per year. It is estimated that around 20% of harvested energy is used for the operation of the asphalt collector, and the remaining 80% is available to provide clean energy for residential and nearby buildings.

Furthermore, another aspect of a HEAL system is to increase the service life of asphalt pavement. A HEAL system aims to control seasonal changes in asphalt pavement temperature in order to decrease the potential of pavement distresses such as top-down cracking, rutting and fatigue cracking. The service life of asphalt pavement can be increased by 5 years if the maximum temperature is decreased by 5°C [9], which shows such pavement distresses are a direct or indirect effect of a temperature gradient on the asphalt pavement service life. In recent years, there have been several small-scale as well as large-scale experimental and numerical studies on the feasibility and performance of ASCs [7,10].

In order to further investigate the actual real-life performance and return-on-investment (ROI) of a HEAL, a large-scale prototype was conceived and constructed on a bicycle path, as part of the CyPaTs[1] project [11-13], which was constructed in 2017 at Campus Groenenborger at the University of Antwerp. In this paper, first, the detailed design and components of the large-scale HEAL prototype are described. Then, a finite element (FE) based model of the HEAL project is discussed in order to predict the thermal behaviour of the HEAL. Finally, output results from the FE model will be validated with those from the large-scale prototype, as authors expect to have the first experimental results available by the conference date.

2. LARGE SCALE PROTOTYPE DESIGN

In September 2017, a bicycle path was constructed on the Campus Groenenborger at the University of Antwerp. This project is named CyPaTs (Cycle Pavement Technologies) and contains several new and innovative technologies. Five innovative technologies were implemented in the CyPaTs bicycle path to serve two main reasons: as a demonstration for the road construction sector and as part of current research projects. These innovative technologies include: an asphalt solar collector (HEAL project), a Fiber Bragg Grating (FBG) monitoring system [14,15], fiber-

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

reinforced asphalt, the ROAD_IT system including a thermographic line-scanner and real-time tracking application [16,17], and non-destructive technologies for quality assessment (thickness and density measurements using a MIT-SCAN and Pavement Quality Indicator (PQI)). For more information and details of each implemented technology and research project, one can refer to the website of the research group Road Engineering Research Section (RERS[2]) and published papers [11-13].

The design procedure of a HEAL system depends on the expected performance of the system. A HEAL could be potentially constructed as a part of parking lots, bicycle paths, bridge decks and urban streets (to reduce the urban heat island effect [9]). In each case, design requirements and performance expectations are noticeably different. As an example, in a bicycle path design, safety in traffic is an important element compared to energy extraction performance, but for a parking lot case, one expects to have a better insight in energy output performance rather than traffic safety.

In recent decades, the bicycle turned out to be a sustainable transportation alternative for private cars. In many European countries, cycling is not only a recreational activity but also a means of transportation. In the Netherlands, Germany and Denmark, cycling has succeeded over private cars in the past three decades [18], in which Belgium is ranked third in Europe regarding the number of traversed bicycle kilometres per person per annum (327 km) [19]. In Belgium, approximately 21% of commuters live within a 5 km distance from their work, and 39% of commuters have to commute in a radius of fewer than 10 km. In 2001, 6.2% of commuters regularly used a bicycle as their main mode of transport [20]. Due to the importance of safety and extensive availability of cycling paths in Belgium, the HEAL project was implemented on a cycling road. Although advantages of implementing HEAL system in asphalt roads are studied and proved in literature, there remain challenges in a HEAL project. A high initial cost and difficulty in recycling are limitations of HEAL. An improper construction could result in leakage of pipes resulting in a less durable pavement, and subsequently complication to repair [21]. Moreover, the complex distribution of stresses around the pipes is a concern related to the presence of the pipe network in the heat exchange layer due to the stiffness difference between polyethylene pipes and asphalt mixture. Although the presence of pipes in the asphalt can result in a lifetime reduction, providing a support grid diminishes the adverse effects of complex stress distribution around the pipes [20]. Besides, to evaluate whether the HEAL system is a cost-effective investment or not, a cost-benefit analysis (CBA) and ROI are required. Using information from the large-scale prototype, a long-term LCA and LCC analysis could be investigated to evaluate the overall sustainability of the HEAL concept [22].

The HEAL prototype is constructed in a total area of 14 m x 4.6 m including reference sensors and reference sections, where the heat exchange layers and pipe networks are placed in an imaginary rectangle of 9.6 m x 4.0 m (Figure 2). Due to the similar pattern of the pipe sets, an individual block of pipe sets is measured as 8.5 m x 1.0 m. Hence, the large scale prototype can be approximated equal to 30 m² (8.5 m x 3.5 m), including technical installations and sensors. Besides the HEAL system, reference sections are constructed using the same asphalt mixture and material properties without implementing heat exchange layer. The reason for constructing this section is to conduct experiments and compare output results in order to analyse the performance of the prototype with and without HEAL system. In the CyPaTs project, the asphalt pavement is placed in three layers with different thicknesses, all dense asphalt concrete (AC) mixtures with a maximum granulate size of 10 or 14 mm: top layer 3 cm, collector layer (including collector and grids) 4 cm and base layer 5 cm. Beneath the base layer, there is a 20 cm foundation layer composed of unbound materials. Pavement layer specifications and weather information during construction are summarized in Table 1.

Table 1. Specifications of pavement layers and weather data [12]

	Pavement layer information			**Average meteorological data during construction**			
	Thickness	Mixture type	Binder type	Temperature	Relative Humidity	Air Pressure	Wind Speed
	mm	-	-	°C	%	hPa	km/h
Top layer	30	AC10	50/70	22.5	22.5	1018	0-5
Collector Layer	40	AC10	50/70	19.1	19.1	1019	0-5
Base Layer	50	AC14	50/70	19.7	19.7	1017	0-5

The heat exchange system is a part of the mid-layer or collector layer, which includes a network of serpentine pipes, supporting grid and sensors. The support grid is responsible to hold the pipes in the collector layer in a preferred spacing before construction and keeps them safe during construction under the heavy loads of the asphalt machinery [23]. The reinforcing grid and tubes were sprayed with bitumen to have better adhesion with the laid asphalt. Figure 1 shows a schematic of the asphalt pavement cross-section and collector network.

[2] https://www.uantwerpen.be/en/research-groups/emib/rers/

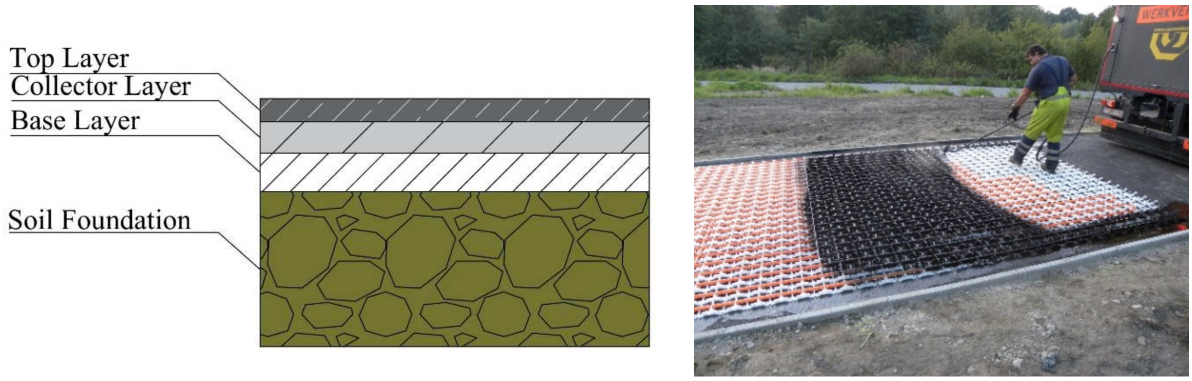

Figure 1. Pavement cross-section and collector detail with support grid

In the design phase, the pipe network is designed in such a flexible way to have multiple scenarios of HEAL. As shown in Figure 2, there are four independent sets of pipes, which enables us to study different configurations of the HEAL by switching on/off different sets. This present configuration provides us with an opportunity to investigate a fully equipped (switching on all four pipe sets) or partially equipped (switching on selective pipe sets) HEAL prototype. For example, by switching on pipe set 2 and 3, we would be able to study the effectiveness of the heated sections on the de-icing performance of asphalt pavement. In addition to selective pipe sets scenarios, in this design, it is also possible to increase the total length of circulating fluid by switching on pipe sets in series to see the effect of pipe length in the HEAL. The pipe sets include four circuits, 50 m long for each sets that result in 200 m total length of the serpentine pipe network.

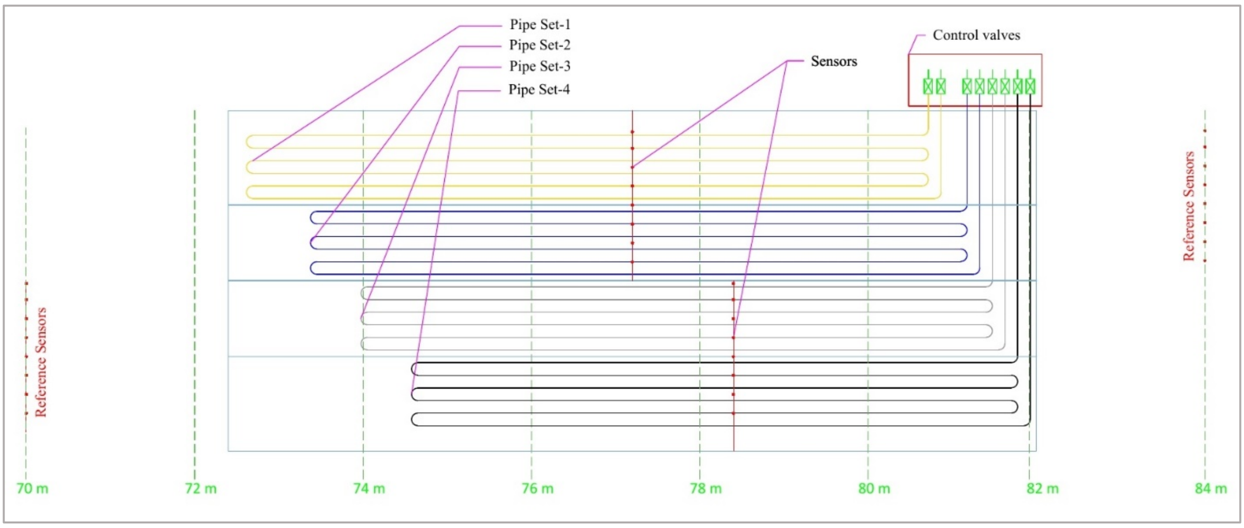

Figure 2. The geometrical configuration of pipe sets in the pipe network

Several measurement devices are installed in the HEAL system. A local stand-alone weather station will be used to record weather parameters of the site location. The weather station measures air temperature, humidity, wind speed and direction, solar radiation and barometric pressure and stores the accumulated data using a data acquisition system. The weather station has two main units: sensor units including an anemometer, pyranometer, temperature/humidity and barometric sensor, and a power supply unit that contains a solar panel, battery charger and battery. Besides, there is a shield/blower combination to minimize the direct solar influence on the ambient temperature and humidity of the surrounding air which sits over the temperature and humidity sensor. Finally, a data acquisition system is installed at the bottom of the weather station to gather all the data from available sensors [24]. Details of the weather station components and their measurement aim are summarized in Table 2.

Table 2. Overview of the components of the weather station

Component	Measurement/ Function	Device Model	Measurement range (unit)
Temperature and Humidity Probe	Relative humidity	Young Platinum temperature probe - MODEL 41342VC/VF	0 – 100 (%)
	Ambient temperature		(-50) – (+50) (°C)
Pyranometer	Solar radiation	Hukseflux SR11	0 – 2000 (W/m²)
Anemometer	Wind speed	Young ultrasonic anemometer - model 85000	0 – 70 (m/s)
	Wind direction		0 – 360 (°)
Barometer	Barometric Pressure	Young - model 61202	600 – 1100 (hPa)
Solar Panel	Power supply	Phaesun SPR-S30	0 – 30 (Wp)
Data Logger	Data acquisition	Campbell Scientific - model CR1000	-

Figure 3 shows the weather station together with its measurement components, and Figure 4 summarizes the connection of the components in a diagram, taken from [24].

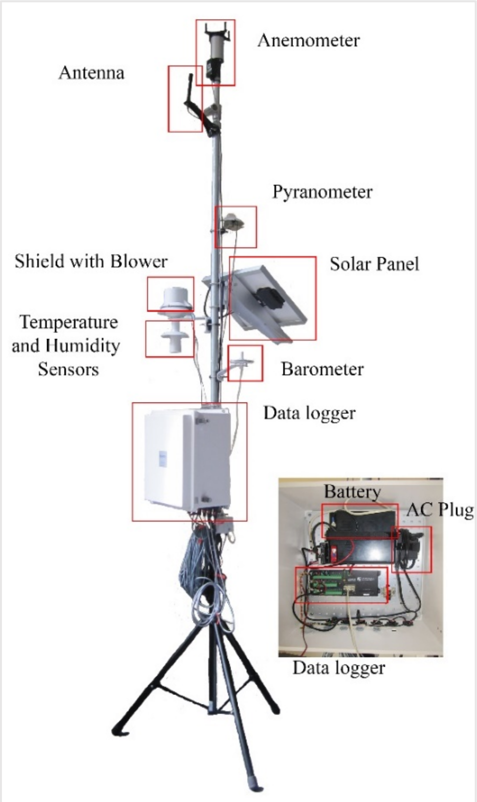

Figure 3. Weather station with different components

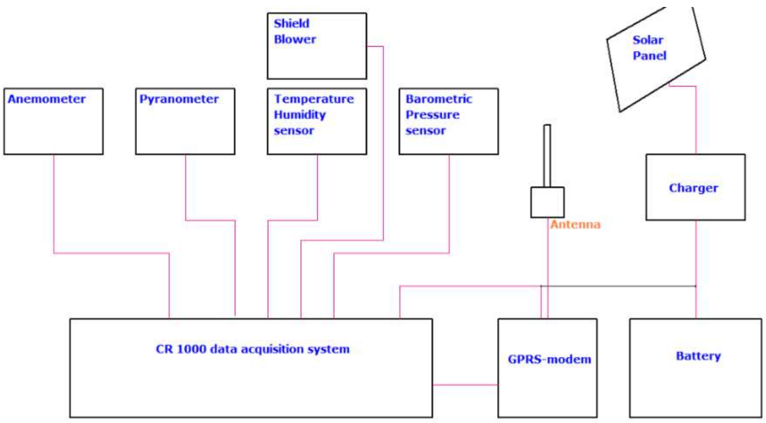

Figure 4. Diagram of the weather station [24]

Besides, to monitor and collect temperature data in the HEAL, thermocouples are installed in different locations and depths inside the asphalt pavement and HEAL pipes. These collected data will be compared to the results from asphalt surface temperature prediction and asphalt temperature profile in depth [25]. In this project, 96 sensors are placed in four different horizontal sections. Two reference lines are distinguished in 70 m and 84 m of the CyPaTs project. In addition, in the other sections sensors are placed in the middle of pipe set 2 and 4 in the HEAL, as shown with red lines in Figure 2. A schematic of the sensor plane located between 76 m and 78 m together with sensor labels is given in Figure 5. The arrangement of the sensors is different in each vertical plane. In order to collect measurement data in an identical plane, the 24 sensors are placed in the following order, 8 sensors at near-surface, 5 at top of pipes, 6 at the bottom of collector layer, 3 at a 4 cm depth from surface, and 2 at the middle of the base layer. A part of the schematic figure is enlarged in Figure 5 to show more details on the location of different sensors.

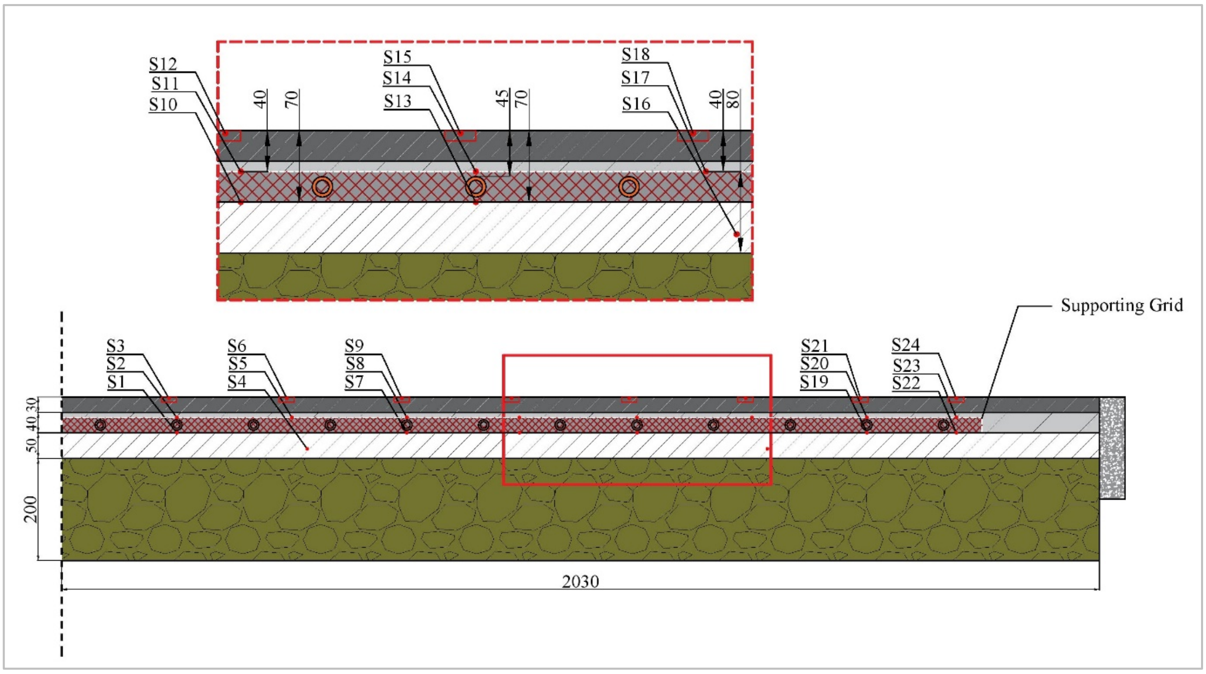

Figure 5. Location and label of sensors in asphalt layers (units in mm)

In addition to the weather station which records local weather parameters, there are several electromechanical measurement devices used in the HEAL. A schematic of electromechanical instruments used in the prototype is shown in Figure 6. Each component is responsible for a specific (measurement) reason, where all data acquisition is collected using data logger. A general categorization of electromechanical instruments could be (1) sensors and (2) regulators. Thermocouple, temperature transmitter, heat meter, and flow transmitter are in sensors group, while ball valve, three-way valve, throttle and heat exchanger pump are grouped in regulators. Using different implemented sensors, parameters of the circulating fluid flow such as temperature and flow rate are monitored continuously. In order to maintain or change these parameters to have a preferable operation, for example, an increase of flow rate in pipes, different regulators are used. According to literature, the rate of water flow through pipes has a considerable effect on the thermal performance of a HEAL [26-28]. Together with design parameters (i.e. asphalt material or pipe spacing) of a HEAL which mainly are not adjustable after construction, there are several variable control parameters that affect the thermal performance of a HEAL. In this research, control parameters include pipe arrangements, fluid flow rate, which is linked to type of flow (laminar or turbulent), inlet and circulating temperature. The inlet temperature of fluid and temperature of circulating water are two important control parameters that affect the performance of the HEAL. In the current study, different scenarios are planned such as a constant inlet temperature and an adaptive inlet temperature to achieve a steady asphalt temperature. Continuous monitoring and control circle is necessary to increase the performance of an asphalt solar collector, due to the sensitivity of collector's performance on the control parameters [7,8,10,22,29].

To store the extracted energy from the HEAL during summer for wintertime, heat storage is necessary. Hence, two boreholes with 100 m depth each were proposed and constructed in January 2019. Figure 7 shows the construction stage of the storage boreholes and their location with respect to the cycling path. The energy storage boreholes were drilled and sealed with thermal grout in order to minimize heat loss between the borehole wall and the ground and to prevent contamination of various aquifers. The drilled borehole is connected to the control centre (the wooden shed in Figure 7), in which all monitoring and control of the heat flow will be performed.

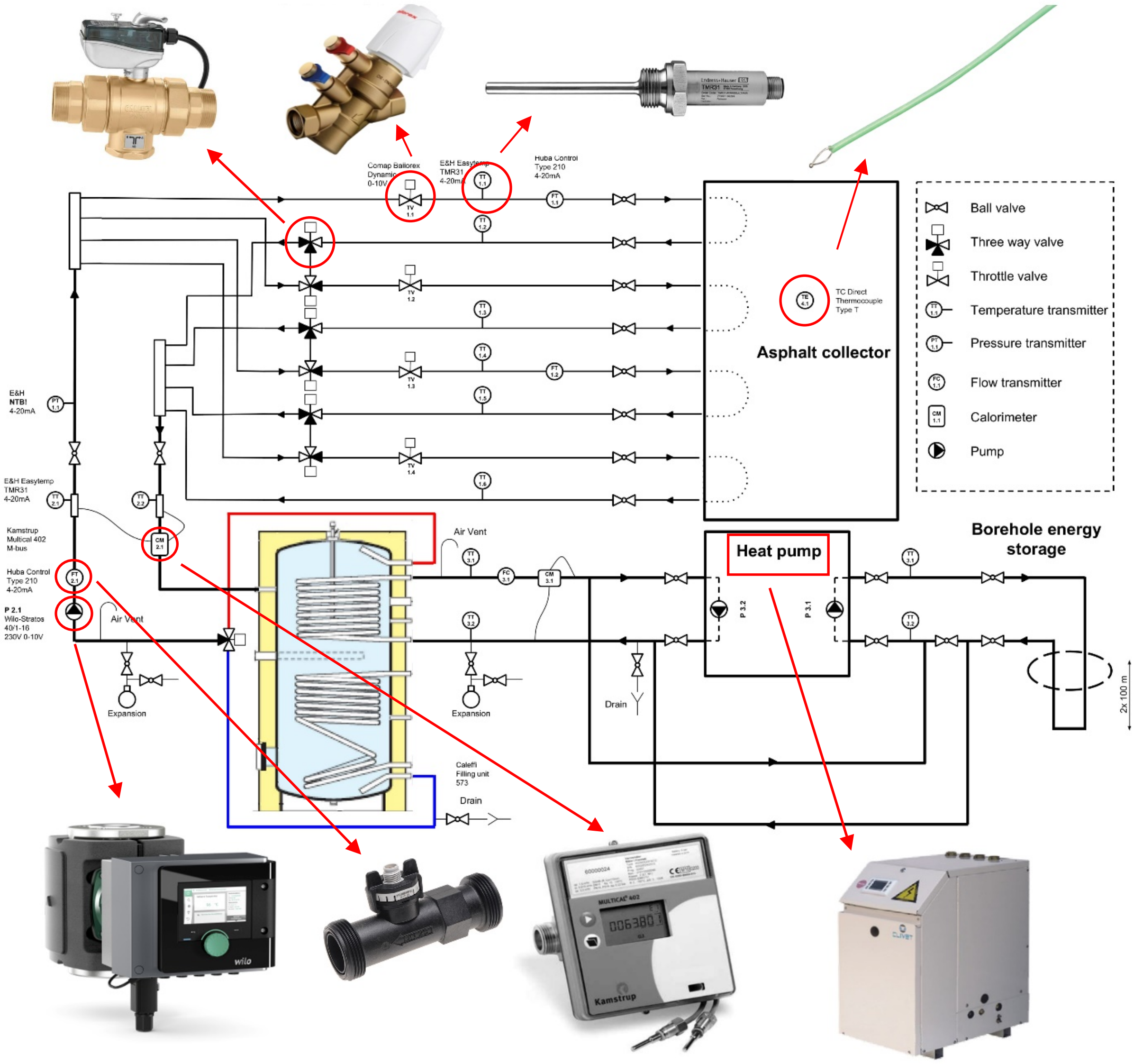

Figure 6. Overview of electromechanical instruments in the HEAL prototype

Figure 7. Borehole construction stage

3. HEAL FINITE ELEMENT MODEL

In this section, a description on the Finite Element (FE) modelling of the large-scale prototype is given. An actual-size 3D model is simulated for the HEAL project, based on an initial model, developed and validated in [7]. The FE-based HEAL model is developed for further parametric investigations to study the long term efficiency of the system as well as the predicted amount of energy extraction. For such large scale prototypes, either it is not very practical to consider different design parameters in one prototype, or not cost-effective to construct multiple large scale models to study the effect of several design parameters. Hence, using a large scale prototype in combination with a validated FE simulation model, it is convenient to extend a model to the more in-depth parametric analysis of the HEAL performance. Previous parametric studies on the design or input parameters with respect to the system performance showed that the thermal conductivity of the material, the solar absorptivity of the asphalt surface and embedment depth of pipe are the most dominant design parameters [7,29,30]. However, to improve the anti-icing performance of asphalt concrete, pipe spacing is determined to be the most significant design parameter [22].

In this study, a recently developed FE modelling framework is extended to simulate the large-scale HEAL prototype. The modelling framework was validated with experimental results and showed a very good agreement with regards to both outlet temperature of circulating fluid and pavement temperature [7,30]. There are several parameter categories in a HEAL model: geometrical parameters of design, weather parameters, material specifications, flow parameters etc. Weather parameters are necessary to calculate parameter-dependent variables such as incident solar radiation, dry-bulb air temperature, hypothetical sky temperature and the heat transfer coefficient regarding convection. These weather parameters are monitored and collected using a local weather station in order to have more precise weather data. Additional weather data (e.g. for other locations) can be added into the FE-Model from the Meteonorm software[3]. Apart from using a validated modelling framework, in this study, the HEAL model was improved by decreasing the number of mesh elements and further extended in terms of simulation components.

In this developed simulation, the HEAL is coupled with two 100 m boreholes in order to store extracted energy in the summer days. To bridge the gap in the simulation of extracted heat into the storage, this model is using the previously validated FE modelling framework [7] and models both the asphalt collector and boreholes to be compared with the experimental results from the HEAL project. As a first improvement, using numerical simplification techniques, the generated mesh around the semi-circle pipe network is neglected, which resulted in a dramatic decrease in the number of elements (Figure 8). The number of elements has been decreased by 58%, from 628000 to 260000 by this simplification, which reduces calculation time drastically.
Although the entire prototype is modelled in 3D, to have simple and regular mesh generation, the used supporting grids are not taken into account in the (thermal) simulation. The HEAL FE-Model is simulated using the heat transfer in solids and fluid flow module in the COMSOL Multiphysics software[4]. Depending on the flow velocity, both steady-state and laminar flow solver will be used. For more details on the finite element modelling of the asphalt collector, see [7,30]. A 3D FE model of pipe set-1 is shown in Figure 9.

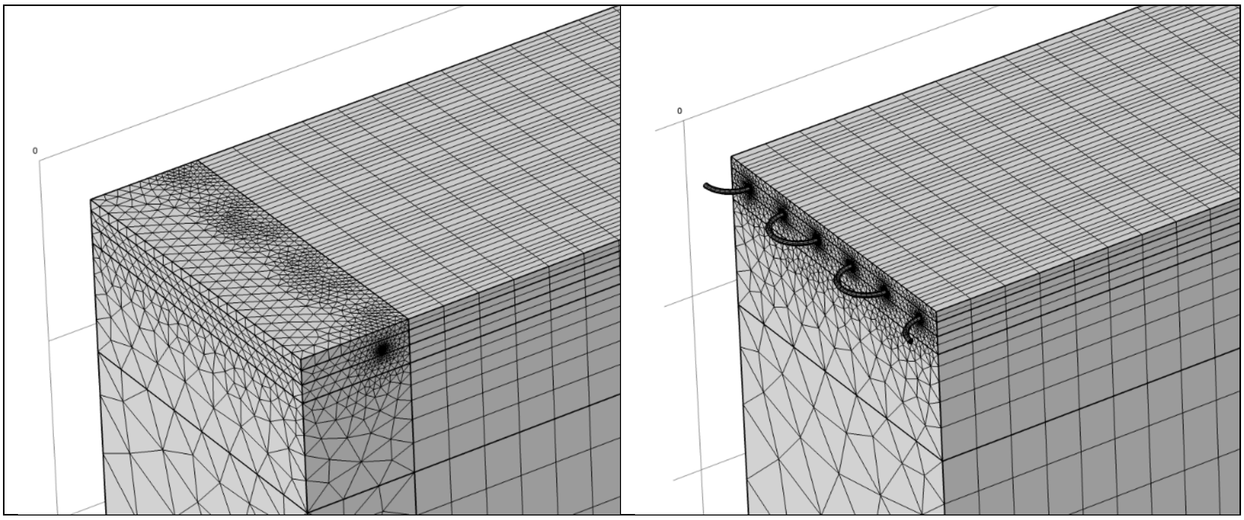

Figure 8. Different generated mesh for HEAL

[3] https://meteonorm.com/en/
[4] https://www.comsol.com/

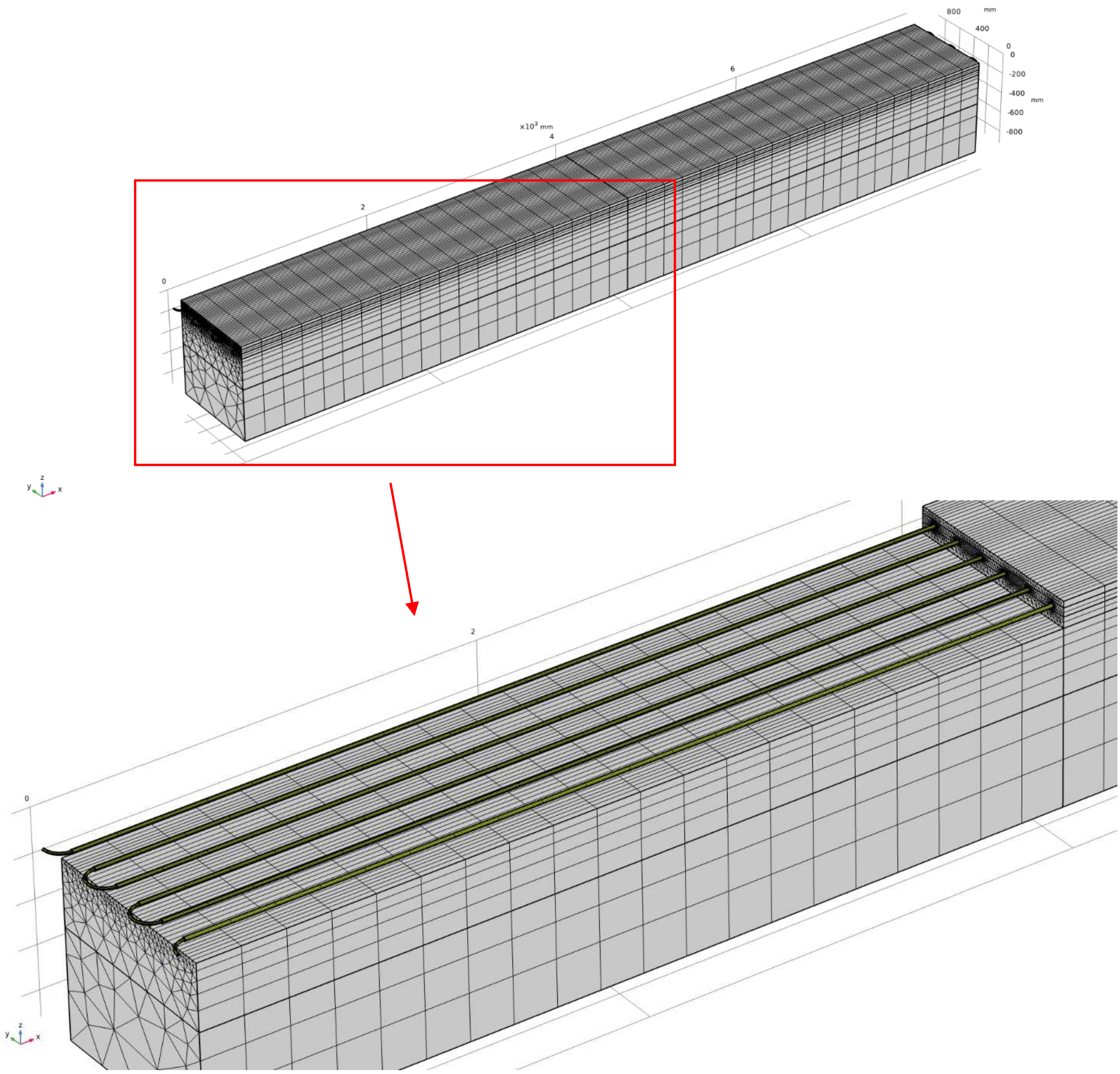

Figure 9. Details of mesh for the FE model

For the validation of the improved and extended FE simulation model with experimental outputs, we expect that results will be available during the conference presentation.

4. Conclusions

In this paper, a large-scale prototype of a heat exchanging asphalt layer is described which will be used to study the actual thermal performance of this system. In the first phase, the prototype is designed with flexible geometrical options to investigate the effect of geometrical arrangement parameters. Second, different components of the HEAL system are introduced with a description of various installed devices for the sake of measurement and control. Thirdly, the following has been accomplished so far:

- a large-scale prototype is successfully installed at the Campus Groenenborger of the University of Antwerp, with possibilities to measure and control many parameters that influence thermal behaviour of a HEAL, such as weather parameters, asphalt surface temperature, asphalt temperature distribution profile and fluid flow;
- two 100 m boreholes have been drilled recently to store the extracted heat from asphalt surface;
- extensive electromechanical devices are installed to reuse the extracted heat during winter and improve the overall thermal performance by adding a heat pump;

- a previously developed FE model framework is adapted to simulate the thermal performance of the complete HEAL system and boreholes, in order to show the (1) potential of long-term energy extraction and reusing this energy (2) efficiency of the system in providing low-grade energy (3) decreasing pavement, distresses potential by regulating asphalt the temperature distribution profile;
- finally, the developed FE model will be validated by the experimental results on the large-scale prototype by controlling the different input parameters in the system while measuring the weather parameters simultaneously.

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