Responsible Design and Delivery of the Constructed Project
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CONSTRUCTABILITY STUDY OF ASPHALT PAVEMENTS INCORPORATING SHALLOW GEOTHERMAL ENERGY

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The incorporation of geothermal energy in heating and electricity production has rapidly increased during the last three decades. This paper focuses on the use of shallow geothermal energy in asphalt pavement, herein called Ground Coupled Hydronic Asphalt Pavement (GCHAP) system. GCHAP consists of a series of pipes embedded within the asphalt layer coupled with another network of pipes embedded in the soil. A circulating fluid acts to exchange the heat energy between the soil and the asphalt layer. The system can be used for cooling the pavement, which results in decreasing permanent deformation in the summer. This paper presents a study on the constructability and performance of such systems on a large-scale section. Numerical analyses and a pilot study were conducted to select the system design components. A 9.6 x 4 meter GCHAP section was constructed on a municipal road in addition to another control section. The secondary network of pipes was placed three meters below the ground. Sensors were embedded within the GCHAP system to record and compare the temperature of the pavement to that of the control section. The results showed that GCHAP section can decrease the pavement temperature leading to an increase in resistance to permanent deformation. Moreover, the constructability study showed the importance of performing a pilot study before constructing the system to ensure the resilience of the pipes.

Keywords: Hydronic asphalt pavement, Permanent deformation, PPR pipes, Constructability, GCHAP, Heat energy, Large-scale section.

1 INTRODUCTION

Most roadways around the world are surfaced with asphalt concrete. The condition of these roads highly affects the Gross Domestic Product (GDP), as roads provide the ability to transport goods and services. However, with the increase in transportation activities these roads suffer from various distresses. The two main distresses are permanent deformation and fatigue. The former occurs due to binder softening at elevated temperature under loading conditions, while the latter manifests itself in the form of cracking at the bottom of the asphalt layer due to the repetitive loading and propagates towards the surface. These distresses lead to safety issues, lower the serviceability of roads, and increase the rehabilitation costs. Incorporating long-term strategies to improve the pavement performance is necessary to keep roadways safe and functional. A Ground Coupled Hydronic Asphalt Pavement (GCHAP) presents an alternative pavement system that is both more durable and more sustainable. A GCHAP system consists of a series of pipes embedded in the asphalt layer connected to another series of pipes embedded in the soil. A fluid circulates in this system and transfers the heat from the asphalt layer to the soil during summer, leading to a decrease in rutting. The system also creates an eco-friendlier environment by mitigating the Urban Heat Island (UHI) effect, a phenomenon that cause urban areas to be several degrees warmer than the surrounding regions.

The use of geothermal energy for heating/cooling purposes has been attempted in different applications. In the context of HAP, geothermal application has been implemented in Switzerland (Eugster and Shatzmann 2002) and Japan (Morita and Tago 2005) for pavement deicing and snow melting. Studies have been conducted on the effect of various parameters of HAP on thermal performance. Pan *et al.* (2015) concluded that pipes with larger diameters, closer spacing, and lower depth improve the efficiency of the system. Adl-Zarrabi *et al.* (2016) showed that the effect of pipes spacing on the HAP system is larger than that of pipes depth. Another study revealed that the effect of pipe diameter is more significant than the effect of flow rate in such systems (Mallick *et al.* 2012). Despite the numerous studies, there still remains a need to conduct a comprehensive assessment of, and comparison between, all the parameters of HAP; in addition to investing the performance of HAP coupled to the ground – GCHAP. Moreover, details on constructing the system, issues faced during implementation, and the long-term performance of such systems have not been discussed thoroughly in the literature.

2 OBJECTIVE

The main objective of this study is to evaluate the performance of Hydronic Asphalt Pavements coupled with shallow geothermal energy and present details on the design and construction process of such systems. Moreover, lessons learned behind the construction of such systems are presented as a guide for future GCHAP applications.

3 METHODOLOGY

To determine the optimal parameters of the system, and to make sure that the system is feasible and practical to construct, a numerical study and a pilot study were carried out.

3.1 Simulations

A 3D numerical model was developed in MATLAB to study the sensitivity of the six main parameters of a Hydronic Asphalt Pavement – flow rate, pipe spacing, diameter, depth, pipe conductivity, and pavement conductivity, in order to design the components of the system. On the surface, the pavement receives heat from solar irradiation and exchanges heat by long-wave radiation (with the sky) and convection (with the ambient). The heat is then transferred through the pavement medium by diffusion. The fluid in the pipes transports (advection) and diffuses the heat received from the pavement medium. The model assumes zero-flux boundaries everywhere except the top boundary, in addition to neglecting turbulent flow and viscous dissipation. The initial conditions were calibrated by running an analogous 1D model until steady state conditions were met. Lastly, the model was validated with data found in the literature (Dakessian *et al.* 2016). Figure 1 shows the simulation results.

A set of representative parameters for the pavement were chosen and then individually varied to see the effect in terms of the change in surface temperature of the pavement after 12 hours of simulation. The analysis reveals that that pavement conductivity is the most critical since its corresponding curve exhibits the steepest slope. The spacing and depth of the pipes are mildly sensitive, with pipe diameter and flow rate showing the least sensitivity as shown Figure 1a. The effect of pipe conductivity was investigated separately due to its wide range. Figure 2b shows that the effect of pipe conductivity is limited by the pavement conductivity. The surface temperature decreases steeply as a function of pipe conductivity – until reaching a certain value where the curve begins to approach an asymptote. This value resembles the approximate value of the pavement conductivity. This fact implies that there is no need to invest in highly expensive pipes which have high conductivities, since their effect is limited by the conductivity of the pavement. The analysis done on the influence of pipes spacing on the surface temperature indicated that spacing should be between 17.5 and 25 cm. In this study, a 20 cm pipes spacing was used.

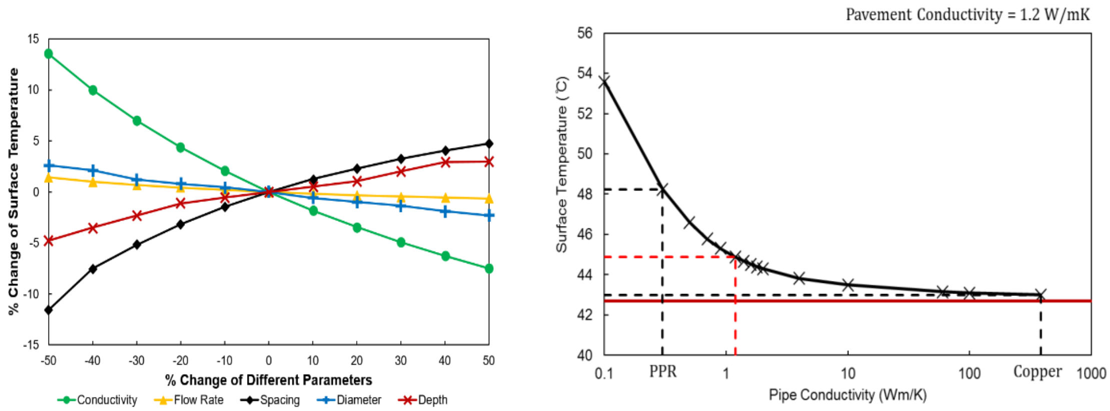

Figure 1. Simulation Results: (a) all design parameters; and (b) pipe conductivity analysis.

3.2 Pipe Material

Copper pipes cost 10 USD/m, while polypropylene (PPR) pipes cost 4 USD/m, according to a local supplier. Class 2 PPR pipes were considered in this study due to financial constraints. The main concern behind using this material is the low conductivity of PPR pipes (0.3 W/mk*) compared to that of copper pipes (385 W/mk); however, pipe materials simulations as discussed earlier showed that the limiting factor to heat transfer is the asphalt – not pipe – conductivity **(**Watts per meter-Kelvin).

3.3 Pilot Study

During construction, the PPR pipes are subjected to heavy loads under a vibratory steel drum while covered with the hot asphalt mix, which risks their structural integrity. This risk increases when the pipes are closer to the surface. In order to ensure that this problem is avoided during the construction of the large scale GCHAP pavement, a 2mx2m asphalt section with pipes embedded within was constructed (Figure 2). The section involved different types of pipe material (steel, PPR class 2, PPR class 5, PPR with aluminum, and copper), different pipe diameters (20, 25, and 32 mm), different depths from the surface (2 cm and 4 cm), and different paving techniques (laying pipes on un-compacted asphalt layer, laying pipes in subgrade, and using spacers).

Figure 2. Pilot Study Section Construction.

After constructing the 2mx2m section, pressure-testing was done to assess the performance of each pipe. All the pipe types and the laying scenarios presented previously performed well, with no leakage detected, except for the 20-mm diameter plastic pipe that was laid on the subgrade 4 cm below the surface. The reason behind this leakage might have been because the fittings were attached to the pipes by glue that couldn't resist heat.

4 GCHAP LARGE SCALE CONSTRUCTION

The system was constructed on a 9.6mx4m local road section, in addition to a control section. The excavation was carried out to a depth of 3 m, then the polypropylene pipes (PPR) were placed in a serpentine configuration. The spacing between each two consecutive pipes was set to be 20 cm, and steel bars were used to fix the pipes. A fine powder material was placed below and above the pipes to prevent large rocks from breaking the pipes as shown in Figure 3.

Figure 3. Placing fine material below and above the pipes.

After placing the pipes, a pipe connection between the bottom pipes network (3 meters below the surface) and the top pipes network (embedded in the asphalt layer) was established. Two PPR pipes 3 meters in length were welded to the two openings of the pipe network at the bottom of the excavated area. These two PPR pipes were then protected with a 10-cm diameter plastic pipe to prevent coarse material from puncturing the pipes, as shown in Figure 4. Following plastic pipes placement, sensors at three different depths in the soil were set along the pipe. These sensors are located at depths of 1, 2 and 3 meters below the surface. The excavated area was then filled with a good quality base course, and the compactor was used to compact the base course material every 1 meter. The upper piping layer was then placed in a reverse-return configuration, and sensors were placed at different location on the pipes, between the pipes, and at different depth in the asphalt layer. Asphalt was laid down using the bobcat, and mechanical combs. A small compactor was used to compact the sensors located at the surface, to prevent any sensor damage.

Figure 4. Connecting the pipe network in the asphalt layer with that in the soil.

5 RESULTS

The readings collected for the GCHAP system were affected by the shade of nearby objects at critical times of the day when the temperature reached a peak. The exact performance of the system was thus not well captured. However, inspecting the slopes of the evolution of the pavement temperatures at different depths can still give an idea of how the GCHAP system reduces the pavement temperature as depth, away from the surface, increases as shown in Figure 5. Although not as significant as the change in temperature between the surface and 2.5 cm depth, there exists a decrease in temperature as depth changes from 2.5 cm to 4.5 cm.

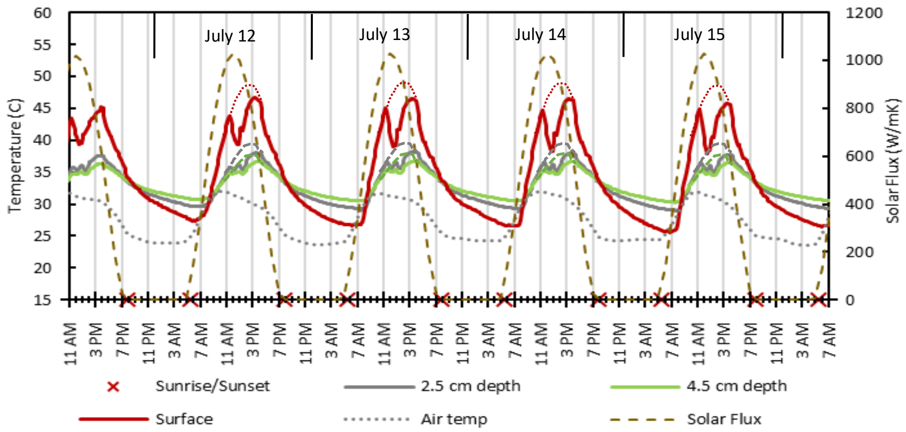

Figure 5. Temperature distribution within pavement incorporating GCHAP system.

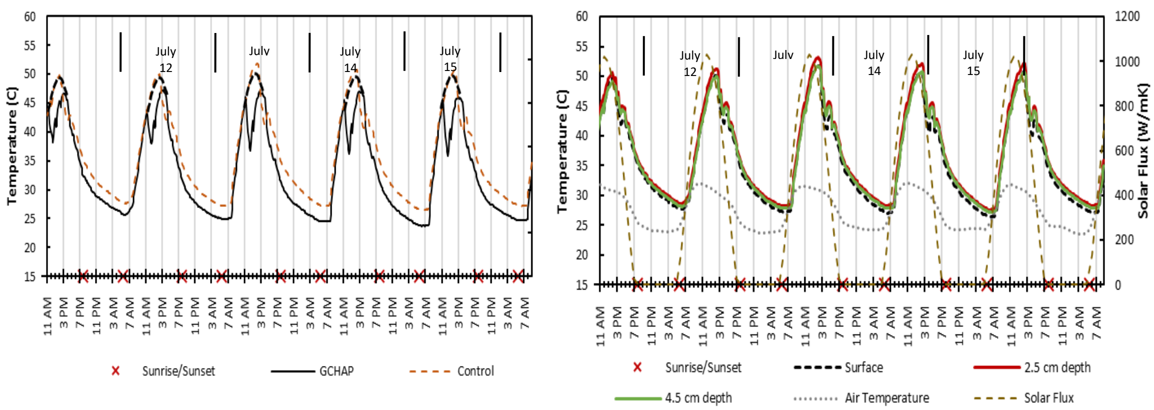

Figure 6. (a) Effect of GCHAP system on surface temperature; and (b) temperature distribution within control section.

Figure 6a shows that the GCHAP system had little impact on decreasing the peak surface temperature (according to an educated extrapolation of the curves) compared to the control section. However, at 2.5 cm and 4.5 cm depth, the GCHAP was able to decrease the temperature by at least 10 °C (Figure 5 and Figure 6b). The ability of the system to decrease the temperature is a function of the location of interest relative to the location of the pipes. Since the surface is the farthest from the pipe, it is the least affected. The direct solar radiation arriving at the surface also plays a major role in counteracting the effects of the system. At 2.5 cm and 4.5 cm depth, the decrease in temperature is more pronounced since they are closer to the pipe but approximately at the same radial distance which explain the smaller difference in temperature between the two. In terms of the cooling curve, the lower temperature of the Soil in the GCHAP system might have played a role in increasing the rate at which the pavement cools and the extent to which it cools as shown in Figure 6(a).

6 LESSONS LEARNED AND CONCLUSIONS

This section points out lessons learned in constructing this unconventional pavement system:

- If unconventional pipes are to be used within the asphalt layer (e.g. use of PPR in this study), it is essential to study the heat and chemical resistance of these pipes against asphalt.
- Covering and protecting both ends of the pipe to prevent obstruction due to contaminants is essential for a more effective operation, in addition to protecting the pipe network embedded in the soil with a layer of fine material before filling and compaction.
- Cool water should be circulated through the pipe network while spreading the asphalt. The pipe network should be pressurized during compaction to better protect the pipes.
- For future research purposes, care should be taken in accounting for the effect of shade, as this would affect the sensors that measure the surface temperature, yielding to temperature values less than the real surface temperature.
- If the test section is conducted on a small section of a minor road, the contractor might not be able to control the asphalt layer thickness. If the thickness of the asphalt layer within which the pipes are embedded is altered, the pipes would be influencing a greater or smaller area and the sensors would be reading temperatures at levels different than what they were meant to.
- In this study, three months after construction and under traffic loading, the pavement started showing a slight deformation, specifically in areas between the pipes. It is possible that the initial deformation the pavement undergoes in its early life was mitigated by the presence of pipes as a support. However, this differential settlement could introduce undesirable shear stresses, thus for future research on GCHAP, more attention should be given to this issue.

As a conclusion, the findings of this research are as follows: (1) The use of PPR in GCHAP is a feasible and practical option, (2) the limiting factor to heat transfer is the asphalt conductivity and not the pipe conductivity, thus it is more economical to invest in increasing the asphalt conductivity rather than in highly conductive pipes such as copper, and (3) GCHAP system decreases the pavement temperature which could lead to a decrease in rutting.

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