Field evaluation of the effects of air convection in energy harvesting asphalt pavements

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Abstract

In this article, the performance of a convection-powered air flow through an asphalt prototype pavement is investigated in a field test. An asphalt prototype pavement with pipes buried in its aggregate layer was connected to a constant temperature heat source and installed at the University of Nottingham, UK. In the experimental configuration chosen, air at 15 °C was free to flow through the prototype pavement by natural convection and exit through a vertical chimney. The natural convection flow was meant to cool down or heat up the pavement based on the temperature gradient between the pavement surface and the air in the pipes. The experimental setup included a weather station and aimed to analyse the effect of the heat fluxes from and to the air in the pipes on the development of the surface temperature.

The experimental results produced a large dataset, which was analysed based on physical and statistical principles to provide guidance for future studies in the field. The system designed was able to provide pavement heating and cooling effectively in a real life environment. The maximum extent of the heating and cooling effects was quantified as ± 5°C.

Keywords: air convection, temperature management, asphalt pavement, energy harvesting

1. Introduction

The durability and reliability of the road infrastructure is influenced by the variation of its surface temperature, as high or low values of this parameter are responsible for softening or embrittlement of the asphalt wearing course. When the surface temperature of asphalt pavements is high they become susceptible to rutting [1] and the ageing process is faster [2]. On the other hand, when the temperature is very low, the formation of ice on the pavement constitutes a hazard for vehicles [3, 4] and the risk of fatigue failure is increased [5]. In the scientific literature, many ways have been considered to fight these issues. If the surface temperature of an asphalt pavement is expected to become too high the properties of the chosen mix may be changed, e.g.,

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thermal conductivity, specific heat capacity, albedo, or emissivity (see for example [6, 7, 8]). In the case of low pavement temperatures, the focus is usually on trying to prevent ice formation, thus, chemical substances are spread on the asphalt surface [3, 4]. A less common option, though occasionally used, is to install piping systems under the pavement surface and to circulate hot fluids through them, thus, aiming at increasing the material's temperature [9, 10].

The authors have recently tried the use of convection-powered air flows to manage the temperature of pavements [11, 12, 13], both experimentally and computationally. The use of air as the operating fluid in the place of liquids comes with advantages, i.e., the independence from electric machinery for the circulation of the fluid and the safety in the case of the rupture of pipes [14]. However, air is known to have worse heat transfer properties than water or other operating fluids, thus, its effectiveness is usually lower for pavement heating and cooling [11]. Nonetheless, the authors showed that the use of convection-powered systems allows to both cool down a hot pavement [11, 12, 13, 14] and to warm up a cold pavement [12]. Based on the previous experimental results obtained, the authors used the equipment called the ground source heat simulator introduced in [12] to generate a convective air flow through an asphalt pavement in the attempt to manage its temperature with varying weather conditions. Therefore, the aims of this paper are (i) to assess the reliability and the potential of this thermal pavement evaluation equipment when installed in the environment, (ii) to verify the representativeness of the previous experimental observations through a field test, and (iii) to assess the influence of actual weather conditions on the performance of the system.

2. Methodology

2.1. Experimental setup

In this paper, the experimental setup known as the ground source heat simulator and introduced in [12] was used (see Fig. 1). Such an experimental layout is meant to simplify the shape that an air-powered energy harvesting system could have in a real-life installation. In [12], the authors hypothesised that an inlet pipe could enter the soft shoulder of an asphalt pavement at a certain depth, then rise closer to the asphalt wearing course, and, finally, exit the pavement through an updraft chimney. The chimney could be, e.g., a traffic sign post or any other component of the road infrastructure with a similar shape and position relative to the pavement.

The ground source heat simulator comprises two main parts, i.e., an energy harvesting prototype pavement and a steel cabinet. The size of the pavement prototype represented in Figs. 1 and 2 is 470 mm x 700 mm x 180 mm [12]. The pavement prototype consists of two layers, i.e., a 50 mm-thick asphalt wearing course (limestone, maximum size 11 mm) and a 130 mm-thick aggregate layer (coarse limestone gravel), where the pipes allowing the air flow are installed.

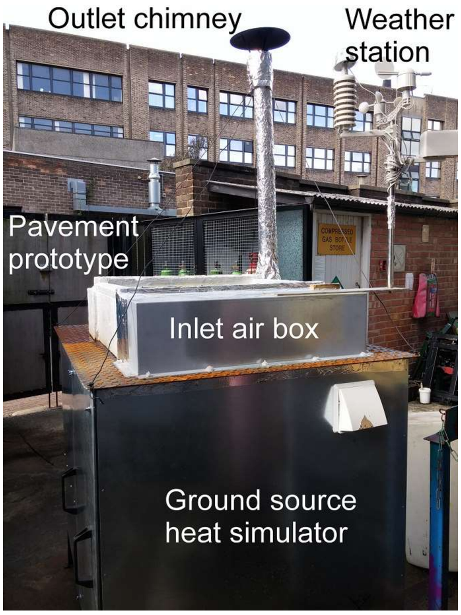

Figure 1: Photograph of the experimental setup.

In the steel cabinet, a vertical pipe called the inlet pipe was installed to connect the environment to the inlet air box (see Fig. 2). In order to simulate the presence of a geothermal source, ceramic heat emitters were pointed at the inlet pipe and connected to a thermostat to provide air at a controlled temperature of 15°C inside the inlet air box. This temperature was chosen because it is representative of a typical geothermal source [15]. It is worth pointing out that such an inlet temperature is based on the assumption that the inlet air would be at thermal equilibrium with the surrounding soil. While this is not very likely for a dynamic and convection-powered system, no data on real inlet temperatures was available for this type of energy harvesting pavement (due to its novelty) and an approximation was required. Consequently, we recommend that this aspect is addressed in the future, when data availability will be higher and more accurate hypotheses will have been formulated.

As seen in Fig. 2, the air flows from the inlet air box to the energy harvesting prototype pavement, which is placed right next to it. The energy harvesting prototype consists of an asphalt wearing course, under which a set of 13 steel pipes are installed along with limestone gravel [11]. The pipes outlet into a second mixing box, which, in turn, is connected to the environment via a 1 m long vertical chimney. At the chimney outlet a small cowl was installed to allow air to exit the system but also to prevent water infiltration.

The steel cabinet was highly insulated, so that the environmental conditions (e.g., weather, precipitation, etc.) could not influence the operation of the ceramic heat emitters. A control asphalt slab with no energy harvesting pipes was monitored along with the prototype pavement to show the effect of the experimental setup chosen.

The ground source heat simulator was installed in the University Park campus at the University of Nottingham, UK. As a result, it was exposed to varying weather conditions and day/night cycles. In particular, during the day the combined effect of the sun's radiation and thermal radiation from surrounding buildings was expected to heat up the prototype pavement, thus, causing an energy flux from the pavement to the air in the pipes (negative heat flux for the pavement). In contrast, during the night or cold periods the pavement temperature was expected to decrease and, in this case, the pavement would receive energy from the warmer air flowing through the pipes (positive heat flux for the pavement). The presence of these heat fluxes was verifiable by comparing the surface temperature of the prototype pavement to that of the control slab installed next to it.

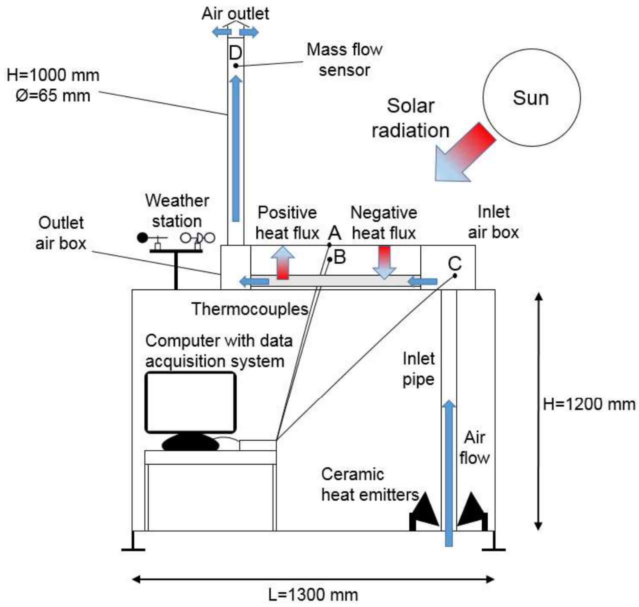

Figure 2: Scheme of the experimental setup used with position of the thermocouples and the mass flow sensor, adapted from [12].

2.2. Measuring equipment

In order to monitor the behaviour of the system a number of measuring tools were used. To begin with, K-type thermocouples (see Fig. 2) were used to record the temperature evolution on the prototype pavement surface (point A), at 50 mm from the surface (point B), in the inlet air box (point C), and on the surface of the control asphalt slab (not shown in Fig. 2). In addition, an IST FS5 thermal mass flow sensor was used to monitor the wind speed at the chimney outlet (point D in Fig. A). The sensor was connected to an electronic board to enable datalogging through an OMEGA OMB-DAQ-54 datalogger.

Finally, a datalogging PCE-FWS 20 weather station (see Figs. 1 and 2) was installed on the steel cabinet to record the evolution of the weather conditions during the experiments performed. The weather parameters monitored during the operation of the system are outdoor temperature, outdoor relative humidity, absolute pressure, wind speed, gust, wind chill corrected temperature, and mm of rain. A summary of all the logged parameters is available in Table 1. In this paper, the relative humidity

Parameter	Unit	Instrument Used
Surface temperature of the prototype pavement	°C	OMEGA OMB-DAQ-54 datalogger
Temperature at 50 mm from the surface of the prototype pavement	°C	
Temperature in the inlet air box	°C	
Surface temperature of the control slab	°C	
Outlet air speed	m/s	OMEGA OMB-DAQ-54 datalogger IST FS5 thermal mass flow sensor
Outdoor temperature	°C	PCE-FWS 20 weather station
Outdoor relative humidity	%	
Dew point	°C	
Absolute pressure	hPa	
Wind speed	m/s	
Gust	m/s	
Wind chill corrected temperature	°C	
Rainfall	mm	
Rainfall in the previous 24 h	mm	

Table 1: Parameters monitored during the experimental campaign.

is used only to provide information on the experimental conditions and is not used to describe the amount of water vapour in the air. This, instead, is done by studying the dew point, which provides a direct link with the absolute humidity. Relative humidity is the ratio between the absolute humidity and the maximum amount of water that can be stored in air at a given temperature and in a chosen volume. Thus, relative humidity does not take into account that the maximum amount of water that can be stored in air changes as a function of the air temperature and, therefore, is not a suitable means of describing the long-term variation in other physical parameters [16].

The installation recorded data during the period September 2015-January 2016 at a logging frequency of 15 minutes, obtaining a total of about 7500 data points for each of the parameters under investigation. The measuring equipment was off for routine maintenance and data analysis for about 1 week every month.

2.3. Theoretical background

In the experimental setup chosen, heat can flow from air to the pavement and vice-versa, as mentioned in Section 2.1. As a result, one must expect that the pavement will receive or release heat based on the temperature differences that exist.

In this paper, a simplification is made to allow the calculation of the energy flows in the pavement, i.e., the asphalt prototype pavement and the control slab are considered as if they were identical. It is clear that this is an approximation, because the asphalt mixtures might slightly differ and the presence of pipes in the prototype pavement (even if blocked to air flow) can be expected to make some difference. It is, however, an acceptable approximation, as the thermal mass (product of mass and specific heat capacity) does not vary significantly between the asphalt slabs under analysis and the weather conditions are the same. The thermal mass, which is the product of mass and specific heat capacity, is similar because the presence of air in the asphalt will have a very little influence due to its very low values for both parameters and due to the fact that it occupies a small portion (less than 2%) of the overall volume.

Therefore, since the surface temperature of both the prototype pavement and the control slab are known, a further simplification can be made. The slabs can be considered as if they had a constant temperature throughout their bodies. Let us point out that this highly simplified approach is equivalent to considering the slabs as points with given mass, temperature, and other average physical properties based on the presence of both asphalt and gravel.

Furthermore, under the hypothesis that both slabs are at thermal equilibrium with the environment at any measurement step, the energy flux existing as a consequence of the piping system and the convective air flow, Φ, may be calculated as:

$$\Phi = m_{slab} \cdot c_p \cdot (T_A - T_{control}) \quad (1)$$

where m_{slab} is the mass of the pavement Section, c_p is the specific heat capacity, T_A is the surface temperature of the prototype pavement, and $T_{control}$ is the surface temperature of the control slab. The values of the parameters used are $m_{slab} = 121$ kg and $c_p = 0.93$ kJ/(kg K) and the specific heat capacity is a mass weighted value including both layers of the prototype. Such values were calculated based on the data seen in [17] for asphalt and on the average properties of the aggregates used in the energy harvesting setup.

The calculation performed in Eq. 1 means that to take a given pavement at thermal equilibrium with the environment from the temperature $T_{control}$ to the temperature T_A the heat flux Φ, which can be positive or negative, is needed. Therefore, an approximation of the heat flux caused by the presence of the energy harvesting system and the ground source heat simulator is obtained. A positive heat flux for the pavement means that it is receiving energy from the flowing air ($T_A > T_{control}$), while a negative value means that energy is being harvested from the sun to the air travelling through the pipes buried in the pavement ($T_A < T_{control}$).

2.4. Statistical methods

Since the number of data points gathered was very high, statistical methods were used to interpret the experimental results. In particular, a correlation analysis was performed by the means of the Pearson's correlation coefficient, r, using a 2-tailed significance test. Values of the coefficient between 0.7 and 1 or -0.7 and -1 were considered as a sign of a strong relationship between the data, while values between 0.4 and 0.7 or -0.4 and -0.7 were considered as a sign of a moderate relationship. The difference in the Pearson's coefficient ranges between the present paper and an earlier one [12] is motivated by the fact that in that paper more strict conditions had to be set due to the much smaller size of the dataset under investigation.

3. Results and Discussion

3.1. Experimental conditions and weather

To begin with, it is important to discuss the effectiveness of the experimental setup chosen. For the data to be valid the inlet temperature needs to be reasonably close to the set inlet temperature. In Fig. 3, a histogram of the inlet temperature is shown.

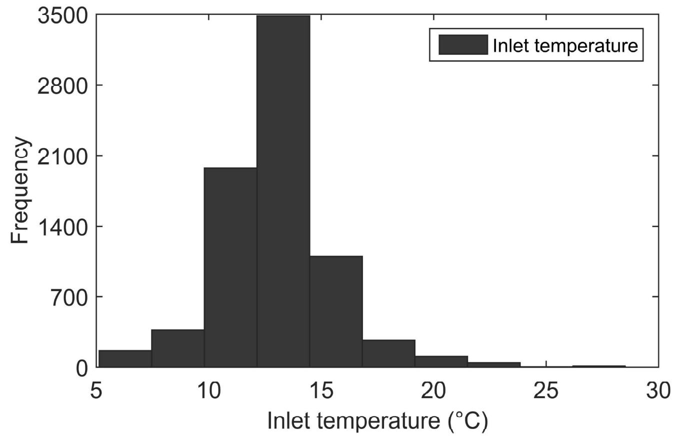

Figure 3: Histogram of the inlet temperature in the ground source heat simulator.

The observation of the histogram confirms the effectiveness of the main working mechanism experimental setup, i.e., the simulation of ground source heat at a given temperature. The most frequent temperature was between 14°C and 15°C, although, temperatures between 10°C and about 13°C were also rather frequent. The reason for this is that even if the inlet air box was highly insulated, it was still exposed to environmental conditions (see Figs. 1 and 2), thus, its temperature could not be kept perfectly constant. Nonetheless, a slight variation in the inlet temperature is even more representative of a real scenario, thus, it is not a cause of concern for the present investigation. In addition, such variation has to be accepted due to the very high difference between the maximum and minimum ambient air temperatures recorded during the experimental trial, i.e., about 19 °C and -2 °C, respectively. The highest temperature was recorded at the beginning of the experiments during September 2015, while the lowest one corresponds to a particularly cold week during November 2016. The maximum temperature was slightly higher and the minimum temperature was rather lower than the averages reported for the climate period 1981-2010 by the Met Office [18], however, this is in line with the values reported for the period of the investigation for Nottingham, UK [19]. These temperatures are not the maximum and minimum temperatures of the asphalt slabs considered in this study, as further physical phenomena such as surface convection and heat accumulation heavily influenced their temperature development.

The absolute atmospheric pressure was in the range 1017-1027 hPa (average 1020 hPa), while the relative humidity was in the range 30-100% (average of 85%).

3.2. Temperatures

The data gathered in the investigation period provided satisfactory results. Generally speaking, two different scenarios were observed:

- Scenario 1: ambient temperature higher than inlet temperature during daytime (15°C)
- Scenario 2: ambient temperature lower than inlet temperature (15°C)

Scenario 1 was the first situation observed in the experiments performed, because in the month of September the ambient temperature was always higher than 15°C during the day. During the night, however, the ambient temperature dropped below the temperature of the simulated geothermal source. The temperatures of both the prototype pavement and the control slab followed this daily oscillation, however, the energy harvesting pavement was generally colder than the control slab during the peak hours of the day and warmer throughout the night. This phenomenon can be clearly seen in Fig. 4, where the surface temperatures of the two asphalt pavement sections are represented for two sample days. On the other hand, the situation observed in Scenario 2 was significantly different as the surface temperature of both pavements was always lower than 15°C. As a result, even if the pavement temperatures still followed the daily oscillation due to the change in the ambient temperature, the surface temperature of the prototype pavement was always higher than the temperature of the control slab. A graphical representation of Scenario 2 is shown in Fig. 5, where the surface temperatures measured during two sample days are represented.

The presence of two different scenarios shows that the prototype pavement designed worked in two modes, i.e., as an energy source (Scenarios 1 and 2) and as an energy harvesting system (Scenario 1). The system operation in Scenario 1 changed with the daily variation of the air temperature, however, in Scenario 2, the air in the pipes always acted as an energy source. It is expected that in a hotter climate a third scenario would exist, when the system would always be harvesting energy from the pavement. This, however, does not seem likely to be observable in the Nottingham, UK area, as the minimum temperatures in the summer months are between 10°C and 12.1°C (average for years 1981-2010 [18]). As a result, the inlet air would still be warmer than the environmental temperature at times, implying that the conditions of Scenario 1 would still apply.

The two methods of operation were characterised by different correlations with environmental conditions, as shown in Table 2. The parameters seen in Table 1 that do not appear in Table 2 do not have significant correlations with the surface temperature, thus, they are not shown.

The most interesting result shown in Table 2 is that there is no strong correlation between parameters during the energy harvesting process and only moderate correlations exist. This behaviour suggests that the energy harvesting process powered by a

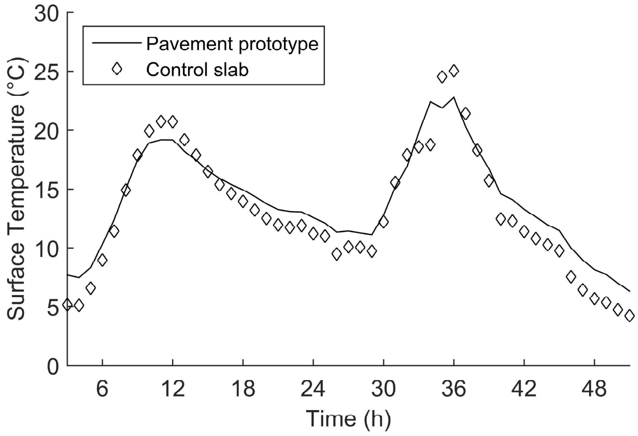

Figure 4: Surface temperature evolution of the prototype pavement and the control slab during two days in Scenario 1.

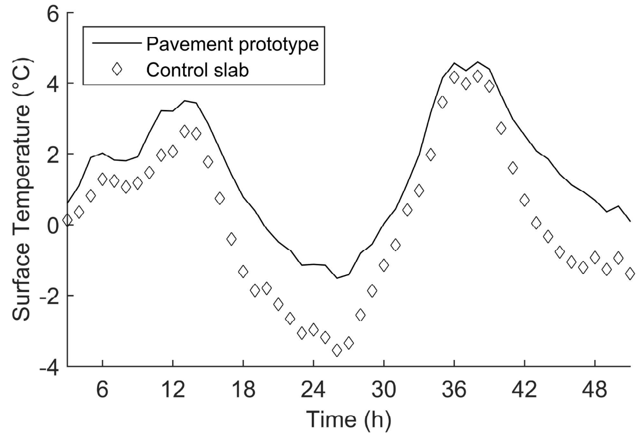

Figure 5: Surface temperature evolution of the prototype pavement and the control slab during two days in Scenario 2.

source at a constant temperature (in this case, geothermal) may be able to partially uncouple the surface temperature from the characteristics of the environmental conditions. During energy harvesting, the surface temperature of the prototype pavement is not influenced much by the outdoor temperature (see Table 2), but it is moderately influenced by wind speed (r=-0.50), gust (r=-0.52), dew point (r=+0.46), and 24 hours antecedent rainfall (r=+0.55).

The presence of wind caused the surface temperature to decrease (r=-0.50 for wind speed, r=-0.52 for gust). This is in accordance with previous literature on pavement thermodynamics [20] and is motivated by the fact that stronger wind (or wind blasts, in the case of gust) increase the heat exchange between the warm surface temperature and the air, thus, removing energy from the pavement. It is relevant to report that even if this natural temperature reduction effect is beneficial for the pavement, less energy is available for harvesting. As a result, if that further aim were to be chosen for the pavement, the presence of wind is a drawback, as the air in the pipes can absorb a lower amount of heat.

The correlation coefficient between the dew point and the surface temperature is

	T_A Energy harvesting	T_A Energy release
Outdoor Temperature	+0.28	+0.88*
Wind Speed	-0.50**	+0.03
Gust	-0.52**	+0.04
Dew Point	+0.46**	+0.63**
Wind chill corrected temperature	+0.33	+0.87*
24 Hour antecedent Rainfall	+0.55**	-0.25

Table 2: Pearson's correlation, r, between weather conditions and surface temperature of the prototype pavement (T_A). *=strong correlation, **=moderate correlation.

mostly related to meteorology, because higher values of the dew point are associated with higher atmospheric air temperatures, while lower values of the dew point are normally recorded during cold periods. The Pearson's correlation coefficient between temperature of the atmospheric air and dew point was calculated as r=+0.72 for the whole dataset, which in turn means that the surface temperature of the prototype pavement should be affected by the temperature of the atmospheric air to some extent. The outdoor temperature, however, was not able to strongly influence the pavement temperature during energy harvesting because the air in the pipes acted as a damper, thus, mitigating the potential temperature increase due to solar radiation and thermal radiation and absorbing part of the extra heat that would have affected the daily surface temperature evolution.

Finally, the 24h antecedent rainfall during energy harvesting was found to have a moderate positive linear correlation with the surface temperature of the prototype pavement. This phenomenon is unusual, because, generally speaking, the presence of water on a warm or hot surface is known to reduce its temperature due to evaporation, which absorbs the energy that drives the phase change from liquid to vapour [21, 17]. Such temperature reduction usually continues until the water on the pavement is completely evaporated. In this case, however, the increase of the thermal mass of the material as a whole due to rainwater (asphalt+water instead of asphalt+air in the pores) probably exceeded the enthalpy of evaporation. The reason for this is that the pavement temperature never reached high peaks and did not stay warm or hot for long periods of time, thus, the evaporation rate during the energy harvesting process was rather low and was overcome by the increase in the thermal mass. Water has much better thermal properties than the air it replaced in the pores or on the surface, thus, the pavement obtained a higher thermal inertia, i.e., it was able to retain its temperature for a longer time based on the first law of thermodynamics [22], where the thermal inertia of materials is described by the volumetric heat capacity (product of specific heat capacity and density). Furthermore, due to the very high values of humidity found in the experiments, water evaporation was hard because the air was almost always close to vapour saturation.

On the other hand, in the case of an energy flux from the air in the pipes to the pavement, the situation was quite different. The surface temperature of the pavement was mostly influenced by the outdoor temperature (r=+0.88) and the wind chill corrected temperature (r=+0.87). The correlation between the surface temperature of the pavement and the dew point was discussed above and the same ideas apply also in the case of energy release from the pavement.

The correlation between pavement temperature and both outdoor temperature and wind chill corrected temperature is similar because these two parameters are related to each other. The wind chill corrected temperature is defined as the decrease in the air temperature felt by the human body due to air flow [23] and it is fairly similar to the air temperature when the wind speed is not high. In the experiments described in this paper, the wind speed recorded was rather low for the majority of the data points (see Fig. 6), thus, such similarity is justified. The strong dependency of the surface temperature on the temperature of the atmospheric air comes from the fact that, unlike in the case of energy harvesting, in Scenario 2 the air in the pipes could not provide damping against the environmental conditions. This is because in the conditions of Scenario 2 the air temperature never went above the inlet temperature of the ground source heat simulator, and thus, the pavement stayed cold at all times. Therefore, the warmed-up air was not able to balance the cooling effect caused (and maintained) by the environment and only provided a constant heat source that was not strong enough to uncouple the pavement from the changes in atmospheric conditions. Furthermore the almost linear relationship between temperature of the atmospheric air and pavement surface temperature (r=+0.88) is in agreement with the previous literature [24].

It is also interesting to notice how the wind speed and gust did not influence the surface temperature when air in the pipes was releasing heat to the pavement. The reason for this is that in Scenario 2 the temperature gradient was from the air in the pipes to the pavement surface (the pavement temperature is lower than the air temperature), thus, there was a very little amount of heat available to remove by wind through thermal convection. In addition, due to the stratification of air related to density, the coldest share of the atmospheric air was in contact with the pavement at all times, which only contributed to keeping the pavement temperature low.

Finally, it is important to comment on the sign of the Pearson's correlation coefficient between the surface temperature of the pavement and the 24h antecedent rainfall during heat release from the air in the pipes (r=-0.25). This coefficient is not relevant for the analysis due to its low value, however, it interesting to look into the reason that caused an inversion of the sign in the correlation compared to the energy harvesting condition. During winter or cold periods (part of Scenario 1 and Scenario 2), air was drier than in hot periods, thus, if water was present on the pavement due to rainfall it was likely to start evaporating. As mentioned above, the evaporation process requires energy (i.e., heat), therefore, the water subtracted it from the pavement. As a result, with a higher amount of rainfall a lower surface temperature of the pavement was observed [16].

In conclusion, it can be observed that the presence of a piping system, through which air is allowed to flow, is able to reduce the temperature oscillation of the pavement during different weather conditions. The experimental results and the statistical analysis of the dataset suggest that the negative effects of a high pavement temperature variation in a brief period of time can certainly be mitigated and the extent of such mitigation in the experimental setup considered in this paper is quantified in Section 3.3. The mitigation potential on a higher pavement surface, however, should be studied in a larger installation with no thermal insulation, so that more practical guidance can be developed for further developments.

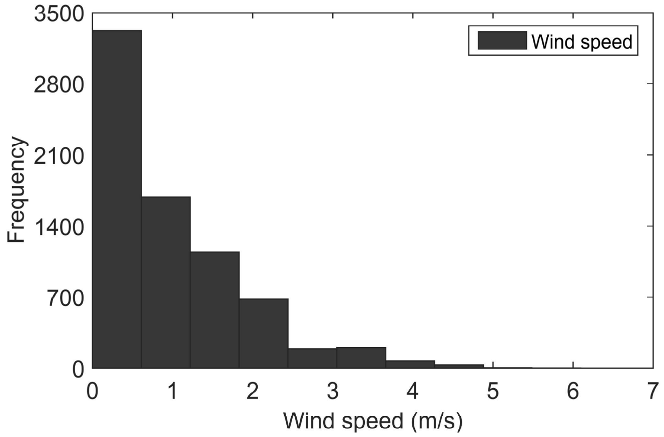

Figure 6: Histogram of the wind speed during the experimental campaign.

3.3. Energy exchanged

Considering the oscillation of the surface temperature seen in Figs. 4 and 5, it is expected that the calculation of the energy exchanged based on Eq. 1 will yield positive and negative values. In Scenario 1 the curves corresponding to the prototype pavement and the control slab intersect twice every 24h, thus, meaning that the sign (i.e., the direction) of the heat exchanged calculated with Eq. 1 will change. On the other hand, in Scenario 2, the direction of the heat flow is always towards the pavement, as the prototype pavement was warmer than the control slab. This can be clearly seen in Fig. 7, where the energy calculated with Eq. 1 is ordered by its value and plotted against the corresponding data points. To begin with, it can be observed that the negative values of energy cover a much smaller portion of the graph compared to the positive values. These values correspond to the energy harvesting process, which was limited to the first part of the investigation, when the environment was still warmer than 15°C (at least during the day).

On the other hand, positive values of the heat flux cover the largest part of Fig. 7 and represent a heat flux from the air in the pipes to the pavement. This is in agreement with the weather conditions that were measured and shows that the pavement received heat effectively.

The slope of the curve shown in Fig. 7 needs to be analysed, too. The high slope at both ends of the graph (x<500 and x>7000) means that the number of data points where the energy exchange was higher than about 220 kJ or lower than about -220 kJ was rather low. These points correspond to temperature differences between the energy harvesting pavement prototype and the control slab higher than 2 °C and up to 5 °C, which were found only in peak conditions (very high or very low ambient temperature). It is, therefore, possible to state that the most frequent temperature reduction or increase achieved by the means of air convection in the experiments performed was between -2 °C and +2 °C. Considering the small size of the prototype pavement, the temperature reduction or increase achieved is reasonably high, however, further studies must determine whether it is high enough to justify the resources needed for the installation of the system. This could be achieved by performing a life cycle assessment of the setup chosen (in the case only the increase of the pavement life by virtue of reduced rutting and extended fatigue life is considered) and/or by the means of a thermo-economic analysis (if the energy in the air flow is used for a chosen aim after releasing or absorbing heat). It could be that for Nottingham conditions such a pavement would not be justifiable whereas it could be in some other climatic conditions.

It is also interesting to notice that the maximum and minimum values of energy calculated with Eq. 1 are about ±600 kJ, which corresponds to a maximum surface temperature difference between prototype pavement and control slab of about ±5.5°C. This result is in agreement with the values previously reported by the authors [11, 12]. Finally, it is important to point out that Fig. 7 refers to the period between September 2015 and January 2016, thus, it appears unbalanced towards the energy release mode of operation. It can be expected that for a whole year the curve would be more balanced, with similar numbers of data points for the energy harvesting and the energy release parts of the figure. The scale of the vertical axis in Fig. 7, however, is expected to change based on the climate, as higher or lower environmental temperatures would certainly influence the value of the peak points on the left and right sides of the figure.

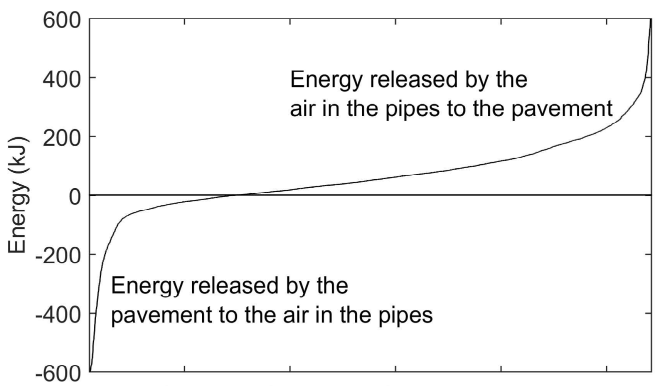

Figure 7: Energy absorbed and released by the prototype pavement according to Eq. 1.

3.4. Outlet air speed

The values of air speed measured by the thermal mass flow sensor ranged between 0 m/s and about 0.3 m/s. Based on the statistical analysis of the whole dataset, it appears that only a weak link exists between the outlet air speed and the surface temperature of the prototype pavement, as the Pearson's correlation coefficient between these parameter is r=0.4.

However, if the same hypotheses made in Section 3.2 are considered, it can be observed that the dataset actually shows two different behaviours based on the mode of operation. When the system is harvesting energy (daytime in Scenario 1), the Pearson's correlation coefficient between the surface temperature and the air speed is r=0.73, which indicates a strong and positive relationship with high linearity between the two parameters. In addition, during energy harvesting, the outlet air speed showed a moderate negative correlation with the wind speed (r=-0.53), which is in agreement with the fact that, in this mode of operation, the surface temperature was reduced in the presence of wind (see Section 3.2). As a consequence of a lower pavement temperature, a lower amount of energy could be absorbed by the air in the pipes and used to increase its outlet velocity, which is a function of air density.

On the other hand, during part of Scenario 1 and Scenario 2, the air speed was in the range 0-0.08 m/s, i.e., the air flow was due to natural convection caused by the residual heat left in the operating fluid after transmitting energy to the pavement.

As mentioned in Sections 3.2 and 3.3, most of the data points correspond to Scenario 2, thus, most of the measured values of outlet speed are very low.

The effect of the roof installed over the chimney to avoid water infiltration (see Figs. 1 and 2) is not studied in this paper, however, it is expected that this aspect could be somewhat optimised.

4. Perspectives for simplified modelling of the system

If the surface temperature of the control slab is represented versus the temperature difference with the prototype pavement and sorted in ascending order, it can be observed that these parameters are not linearly related (see Fig. 8). Plotting data as shown in Fig. 8 can be useful if information on the pavement temperature in a chosen location is available, because it could be used to predict what would happen if energy harvesting pipes coupled with a heat source (e.g., a geothermal source) were installed. Such a prediction, however, is not simple, because of the non-linear behaviour seen in Fig. 8.

In order to solve this issue it is possible to use a fitting equation, which, in the case under analysis, is a fifth order polynomial ($R^2 = 0.9975$) with coefficients $p1 = 5.725e{-6}$, $p2 = -0.0004303$, $p3 = 0.01153$, $p4 = -0.1333$, $p5 = 0.8229$, and $p6 = -2.245$. The use of this fitting polynomial yields the results seen in Fig. 9, where it can be observed that the curves representing real and predicted temperatures are reasonably close to each other and that the error rarely exceeds ±2°C. In the case of peaks, a higher error up to ±5°C can be observed. This means that using a fitting equation to try and predict the effects of air flow under an asphalt pavement is acceptable only at an early design stage. Furthermore, the fitting equation is specific to the location considered, thus, the curve seen in Fig. 8 is very unlikely to be applicable in other locations. Finally, it is necessary to keep in mind that the curve might differ if other geometric configurations of the pipes or different inlet temperatures were considered. Therefore, a possible solution could be creating families of curves similar to the one in Fig. 8 corresponding to different designs of the system. This, however, is highly impractical, especially considering that convection-powered energy harvesting is not mature at the moment. Another obstacle to this approach is that databases of pavement temperatures are not common, thus, models should be used to predict the pavement temperature based on the weather conditions (see, e.g., [25], [26], or [27]). The predicted temperature could, then, be used as an input for the above-mentioned fitting equation to try and evaluate the temperature mitigation effect caused by the air flowing under the pavement. Future investigations could focus on the approach described in this section, however, it is relevant to point out that more realistic computational fluid-dynamic simulations of convection-powered energy harvesting were successfully carried out in [12] and [13], thus, this pathway is also viable (even though it is theoretically more complex).

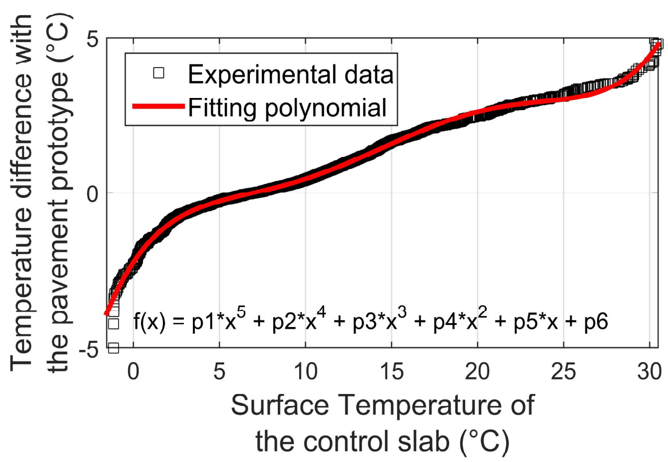

Figure 8: Surface temperature of the control slab vs. Temperature difference with the prototype pavement.

5. Recommendations for future design

Based on the experimental results obtained, it is possible to devise some possible improvements for the design of this kind of systems. The effects of weather conditions on thermal performance obviously cannot be avoided if pipes or air channels are installed under an asphalt pavement in the environment. Therefore, the only feasible improvements will be in the structure of the pavement and they need to be related

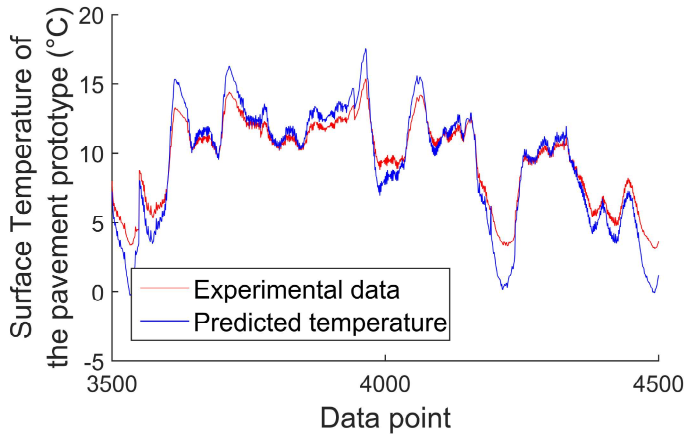

Figure 9: Prediction of the surface temperature of the prototype pavement.

to the way the warmed-up air interacts with the materials of which the pavement is made and with its temperature evolution.

To begin with, it was found that during summer the presence of an internal air flow was able to make the pavement somehow independent of the temperature of the atmospheric air. This was a consequence of the energy harvesting process and is a function of the temperature difference between the pavement surface and the air in the buried pipes. As a result, it is expected that a colder air flow could absorb a higher amount of energy and, therefore, further distance the evolution of the surface temperature of the pavement from that of the atmospheric air. Such a solution, however, might cause issues in the case of cold weather, when a warmer heat flux would be beneficial. In practice, increasing the inlet temperature (i.e., the temperature of a hypothetical geothermal source) from 15°C might be not financially feasible, as such high temperatures are found at increasingly high depths or would require energy storage arrangements (e.g., from summer solar energy or summer building cooling activities). Therefore, an optimal temperature should be found by the means of computational simulations or by trial-and-error in the location where the system would be installed. This decision should be based not only on current weather conditions but also on the predicted trends for the future, as the buried pipes would be installed in a pavement, which is expected to have a rather long lifetime.

Due to the high humidity of the climate in the experimental location, it was found that the 24h antecedent rainfall did not influence the results negatively. This, however, would not be valid in a less humid area, where the evaporation of rainwater would be greater, absorbing more heat from the pavement, thus, cooling it down. This effect would be stronger with hot weather, when the air temperature is higher, however, it may affect the system operation in cold periods, too. The most problematic issues would arise with cold weather, when the pavement temperature should be kept at the highest possible value and, then, water evaporation might render the positive influence of the heating system useless by subtracting energy from asphalt. A possible, and probably partial, solution for this is the use of a very dense asphalt

wearing course, so that water infiltration would be minimised.
Finally, it is expected that the system outlet could be optimised to achieve a better air speed for the circumstances when this is relevant for the use, if any, of the exhaust air. The optimisation could be approached computationally or experimentally by finding a design that works for both cold and hot weather, when the outlet air is colder than 15°C or warmer than 15°C, respectively. The temperature of the outlet air should be carefully considered for this optimisation because the air speed is a function of the density difference between the outlet of the prototype and the environment.

6. Conclusions

In this paper, an experimental study on the performance of an energy harvesting pavement coupled with a simulated geothermal source was presented. Base on the experimental data gathered and on its analysis, it can be concluded that:

- The experimental setup chosen functions correctly in the environment in all weather conditions and is able to maintain an inlet temperature of about 15°C.
- The air flowing in the pipes buried under the prototype pavement is able to heat up and cool down the pavement by up to ±5°C.
- During warm weather, the pavement temperature mostly depends on moisture and on the presence of rainwater on the surface, while there is no strong link with the temperature of the atmospheric air. Moreover, the presence of wind has a negative correlation with the pavement temperature, thus, meaning that if wind is present the pavement will be colder and there will be less energy available for harvesting.
- During cold weather, the pavement temperature depends on the temperature of the atmospheric air and on its humidity.
- The study of the energy exchange in the pavement shows that average values are in the range between -200 kJ and 200 kJ, which correspond to an average temperature difference of ±2°C.
- The air speed at the chimney outlet had rather low values, from 0 m/s to 0.3 m/s and values above 0.08 m/s were found only during energy harvesting. Very low values related to the natural movement of air due to convection were found during energy release from the air in the pipes to the prototype pavement.
- It is possible to predict the surface temperature of the prototype pavement with a reasonable accuracy, however, the results obtained are not precise enough for a final design stage. In addition, the approach used might not be applicable to pavements with different sizes or pipe arrangements.

- The results presented in this paper refer to a specific time of the year and, thus, are unbalanced towards the energy release mode of operation. It is expected that the energy fluxes during a whole year would be balanced in terms of data points for each mode of operation, but they would have different maximum and minimum peaks depending on the specific climate that is considered.

For the purposes of future work, further studies should be performed to assess if the benefits resulting from the temperature mitigation effects obtained with the system under analysis are high enough to justify the investments required for its installation. Furthermore, a comparison should be pursued to find out how the use of air convection compares to changes in the physical properties of the asphalt mixture in terms of sustainability, life cycle cost, and economic cost. Finally, an analysis of the different approaches to model the system performance in the environment is required to find out whether they can be accurate enough for the development of final designs or not.

Acknowledgements

The authors thank the University of Nottingham for the financial support provided for the Ph.D. of Andrea Chiarelli.

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