Geothermics 68 (2017) 9–19

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Pavement temperature mitigation by the means of geothermally and solar heated air

A. Chiarelli*, A.R. Dawson, A. García

Nottingham Transportation Engineering Centre (NTEC), Faculty of Engineering, The University of Nottingham, University Park, Nottingham, NG7 2RD, United Kingdom

ARTICLE INFO

Article history:
Received 26 October 2015
Received in revised form 29 January 2017
Accepted 2 February 2017

Keywords:
Air convection
Temperature mitigation
Geothermal
Asphalt pavement
Environment

ABSTRACT

In this article, a novel method to mitigate pavement temperatures by the means of air convection is presented. The technique introduced here is based on a new type of experimental setup called a ground source heat simulator, which is able to feed air at a controlled temperature to a set of pipes embedded under a test pavement surface. The air at the chosen temperature can flow through the designed system by natural convection. The air heated by the simulated geothermal source can mitigate the pavement temperature in winter and summer conditions in order to avoid freezing and overheating of paving surfaces in an urban environment. In particular, during winter the geothermal air warms up the pavement, while during summer the pavement is cooled down. Laboratory tests of the ground source heat simulator allowed the collection of a high amount of data, which is here analysed statistically and computationally. This article shows that the use of geothermal energy to preheat the inlet air in pavements where an array of pipes is installed can provide a measurable contribution for the mitigation of pavement temperatures in both winter and summer conditions. Furthermore, the experimental data gathered successfully proved the effectiveness of computational simulations for the study of buoyancy powered air flow through channels buried under pavements and increased the understanding of the physical phenomena happening in the system under analysis. Finally, preliminary testing in the environment showed that the concept is effective and works as expected.

1. Introduction

In the past few years, the relationship between pavement temperatures and the built environment has been studied by a number of researchers. Pavement temperatures are mostly determined by the ambient temperature, which is variable across the year for all the areas in the so-called temperate zone (Lohmann et al., 1993). During cold periods, when the temperature is low for a long period of time and snow is present on the pavement surface, it is common to observe the formation of ice. The presence of ice on roads creates hazards for people and vehicles (Wang et al., 2008; Dai et al., 2012), and thus it often leads to traffic blocks and subsequent loss of functional availability of the road infrastructure. The presence of ice or snow is also an issue for airports, where it can have a serious impact on the safety of take-off and landing operations (Dai et al., 2012; Lai et al., 2014). Furthermore, in some situations, the presence of snow alone may be enough to make local authorities forbid vehicle circulation due to the fear of traffic accidents.

On the other hand, during hot periods, high pavement temperatures are known to allow the development of rutting and structural damage (Bobes-Jesus et al., 2013). In addition, high pavement temperatures increase the urban heat island (UHI) effect, thus, causing further issues related to a high consumption of energy by air conditioning systems in cities during summer (Golden and Kaloush, 2006). Therefore, high pavement temperatures during summer can lead to hazards in the transport infrastructure, reducing its reliability, and also contribute to additional stress on the energy distribution network.

Since in the current economy the availability of the road network for the delivery of goods is essential, methods for de-icing or snow melting during winter and for the reduction of surface temperatures during summer are of increasing importance. In the case of winter, two main solutions exist for these purposes, i.e., the use of chemical substances (Wang et al., 2008; Dai et al., 2012)

* Corresponding author.
E-mail addresses: chiarelli.andrea@gmail.com (A. Chiarelli), andrew.dawson@nottingham.ac.uk (A.R. Dawson), alvaro.garcia@nottingham.ac.uk (A. García).

http://dx.doi.org/10.1016/j.geothermics.2017.02.002

and the use of pipes where a hot fluid (typically water with an antifreeze additive) is circulated after being heated geothermally (Lund, 2000; Lund et al., 2011). The first method has been used for a long time now and it is regarded as a very effective method, however it has recently been raising concerns about its effect on the environment (Dai et al., 2012; Cunningham et al., 2008). On the other hand, the use of piping systems still has to be explored extensively and few examples exist in Argentina, Iceland, Japan, Switzerland, and U.S.A. (Lund et al., 2011). In addition, piping systems buried below the wearing course of a pavement are known to cause serious durability problems in the case of a water leakage (Chiarelli et al., 2015a,b), which also requires the remediation of non-aqueous phase liquids (NAPLs) in the subsurface when an antifreeze additive is used (McCaulou et al., 2015). In the case of summer conditions, more methods to mitigate the pavement temperatures have been studied, e.g., the use of energy harvesting pavements (Chiarelli et al., 2015a,b, 2017; Pascual-Muñoz et al., 2013; García and Partl, 2014) or changes in the materials properties such as thermal conductivity, specific heat capacity, albedo, or emissivity (Golden and Kaloush, 2006; Pomerantz et al., 1997; Akbari et al., 1999, 2015; Gui et al., 2007; Sarat and Eusuf, 2012; Santamouris, 2013; Guntor et al., 2014; Carnielo and Zinzi, 2013; Synnefa et al., 2011).

Since the use of piping systems buried under the pavement surface has been considered for both cold and warm periods, in this paper, the use of an energy harvesting pavement powered by air convection is considered for the mitigation of extreme temperature effects during the whole year. This could potentially deliver similar benefits as a water based system, but without the durability and leakage concerns. Nonetheless, it must be noted that the use of air may cause some concerns, as this fluid performs worse than water in terms of heat transfer due to its poorer thermodynamic properties. In addition, since the air flow through buried pipes is influenced by a variable heat gradient (due to varying external temperatures), its control may prove difficult. Thus, the practical design of the system could become complex.

The experimental layout used in the present work is based on a convection powered energy harvesting pavement, which consists of a set of pipes buried under the asphalt wearing course (Chiarelli et al., 2017, 2015a,b). The use of a simulated geothermal heat source is considered in this paper to control the inlet temperature for the above-mentioned energy harvesting prototype. For this purpose, a novel experimental setup called a ground source heat simulator was built at the Nottingham Transportation Engineering Centre (NTEC) and used to reach a number of temperatures meant to simulate the soil temperatures at a range of depths. The ground source heat simulator is here meant to generate a representative mass of air at thermal equilibrium with the soil.

1.1. Research objectives

The main aims of the present study are (i) to assess if it is possible to control (increase or decrease) effectively the surface temperature of a pavement through the use of air warmed up by geothermal resources, and (ii) to quantify the increase or decrease in the pavement temperature through the use of natural convection powered by geothermal or solar heat sources.

These objectives were pursued by running a number of experiments based on the use of a ground source heat simulator (see Fig. 1). The experimental results were also used to develop a modelling approach for the study of the design of buoyancy powered flow in pavements where an array of pipes or channels is installed. Furthermore, preliminary testing in the environment was carried out at the University of Nottingham, UK campus in order to verify the validity of the approach in a more realistic scenario.

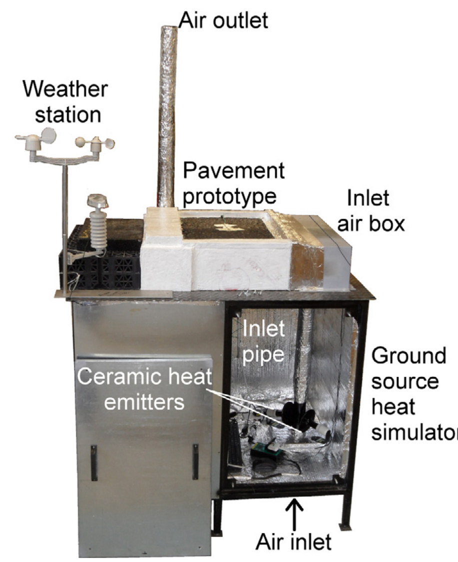

Fig. 1. Ground source heat simulator built at the Nottingham Transportation Engineering Centre (NTEC).

2. Methodology

2.1. Concept of a ground source heat simulator

In this paper, a ground source heat simulator is described for the analysis of the temperature control potential in pavements where an array of pipes is installed. A possible real apparatus for the exploitation of geothermal heat for the purposes mentioned in the Introduction is shown in Fig. 2(a). The figure shows that an air inlet could be allowed, e.g., in the soft shoulder of a pavement. Such an inlet would consist of a pipe installed beneath the pavement at a certain depth, which would act as a heat exchanger transferring heat from the ground (geothermal heat) to the air. The pipe would then rise closer to the pavement wearing course, where it would exchange heat with the asphalt surface. Finally, the air would flow through a chimney and return to the environment. The significance of this concept lies in the fact that geothermal heat alone cannot influence strongly the pavement surface due to its low temperature and depth. However, the above-mentioned layout exploits air to carry geothermal heat to the surface and potentially mitigate or solve the engineering issues related to the maintenance of paved surfaces and mentioned in the Introduction.

The ground source heat simulator is meant to show how geothermal heat can affect the pavement temperature during the whole year, when the external environment may be either cold or warm. During cold periods, geothermal heat would power the air flow by heating up the air in the pipes and, thus, decreasing its density. Geothermal heat would drive a convective air flow from the inlet to the pavement surface, where the air would lose some thermal energy and release it to the paving materials. On the other hand, during warm periods, the air flow (and ensuing heat transfer) would be driven by the high surface temperature of the pavement and the ground surrounding the buried inlet pipe would act as a heat accumulator (Lund, 2000). This would be helpful for the winter performance, as the accumulated heat would delay the moment when ice first starts forming on the pavement surface.

Note that this section only offers a hypothetical description of a possible real life layout of the technology. At this stage, it is not possible to deepen the discussion of engineering and practical construction matters, as the system is yet to be fully tested and analysed.