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Contribution of Pavements to decreasing the Urban Heat Island effect

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Abstract

The raising of temperatures nowadays has become a critical issue, especially in urban areas due to the phenomenon of the Urban Heat Island effect (UHI). Asphalt pavement temperatures increase due to the solar radiation, which contributes towards this effect. The concept of cooling the pavement surface is possible by means of a temperature controlled asphalt pavement. This concept will lead to a reduction of the surface temperature and subsequently a decrease of the temperatures in the surrounding urban areas during warm seasons. Thus, it will relieve the Urban Heat Island effect. For this paper the concept of temperature controlled asphalt pavement has been proposed. Theoretical consideration has been made and a numerical modelling is presented.

Keywords: temperature controlled; asphalt; thermal properties; urban heat island effect.

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1. Nomenclature

λ_a	Thermal conductivity asphalt pavement
q_s	Solar irradiance
α	absorption coefficient asphalt pavement
h	heat transfer coefficient
ε	Emissivity asphalt pavement
σ	Stefan-Boltzmann coefficient
T_a	Temperature asphalt pavement
T_{amb}	Temperature ambient
$T_{a,s}$	Temperature asphalt surface
T_{sur}	Temperature surroundings
∇	Gradient
λ_w	Thermal conductivity water
T_w	Water temperature
C_w	Heat capacity water
ρ_w	Water density
u_w	Water velocity
T_{wi}	Water temperature initial condition

2. Introduction

During summer asphalt pavement surfaces can reach up to 70°C as a consequence of the solar irradiation and pavement heat absorption capacity (Pascual-Muñoz et al., 2013). Due to its absorption capacity, the pavement absorbs the radiation and stores it in the form of heat; therefore, its surfaces emit that stored heat, which leads to higher temperatures in the air as well as in the neighbouring buildings, which both contributes to the urban island heat effect (UHI) (Wong & Chen, 2009).

A well-studied measure to reduce this phenomenon is bright pavements, which due to their lighter surface, the albedo and the thermal properties increase, whilst the surface temperature decreases, which is achieved by an appropriate selection of aggregates. Bright pavements are cheaper in comparison with other countermeasures; however, the used aggregates lead to certain disadvantages given that bright aggregates usually have poor adhesion with bitumen.

Other studies focused on the concept of a temperature controlled pavement, which relies on the premise of extracting energy from pavements during warm period in order to cool the surface, remove the heat and thus, help with the reduction of the UHI (Hess et al., 2013).

There have been few studies on the development of efficient techniques for temperature controlled asphalt; the majority of them focus on a structure of asphalt pavement with a network of embedded pipes where a fluid is transported to collect energy in summer, so that the surface is cooled. (figure. 1) (Jansen, 2014). Another technique has also been investigated, where, instead of a network of pipes, a porous layer is placed in the middle, which will lead the fluid to cool the surface (Munk, 2012).

Due to the above, the aim of this paper is to present a concept of asphalt pavement structure that allows reducing the heat from the asphalt pavement, where the temperature of the asphalt pavement can be reduced by a appropriate fluid flowing through a pipe system that will gather the heat and thus, minimize the urban island heat effect.

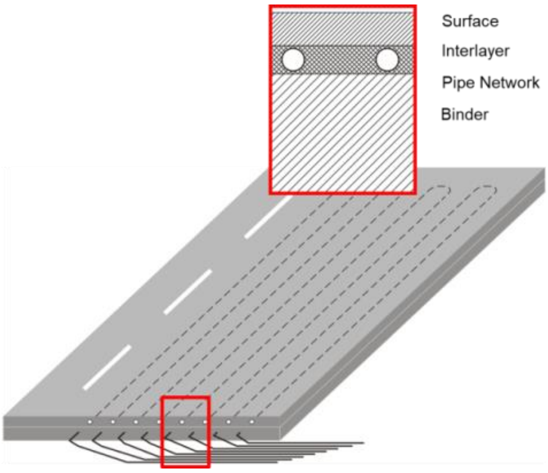

Fig. 1 Temperature Controlled Pavement with pipe network (Hess et al. 2011)

3. Methodology

3.1. Modelling heat exchange

The approach for the work presented is to study and describe the different modes of heat transfer on the asphalt pavement (figure 2) and the heat transfer between the water system and the asphalt pavement structure as well, through a finite elements analysis.

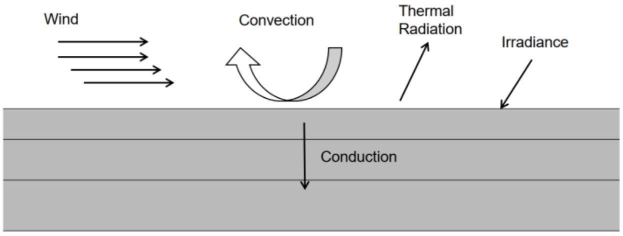

Fig. 2 Heat transfer modes in the asphalt pavement structure

The primary heat transfer modes between the asphalt pavement and surroundings are composed by the solar irradiance heat that is absorbed by the asphalt pavement surface, the convection heat flux between the pavement surface and the wind and the emitted radiation heat from the pavement surface to the environment. These heat transfer modes are analysed based on the Stefan-Boltzmann Law, where the emissivity (ε) is defined as a ratio of the heat emitted of the body to the heat emitted of a black body at the same temperature (Holman, 2010). It is a measure of a body ability to radiate or absorbed heat to the surroundings, and depends on temperature.

The emissivity for a black body is $\varepsilon = 1$, while for any other body is $\varepsilon < 1$. For the asphalt pavement surface the thermal radiation can be written as:

$$q_r = \varepsilon\sigma(T_{a,s}^4 - T_{sur}^4) \tag{1}$$

Based on the above equation it can be deduced that if the temperature of the asphalt surface is reduced in relation to the surrounding temperature the amount of heat emitted from the asphalt surface to the ambient can be reduced and therefore the urban heat island effect.

While inside the pavement, heat transfer occurs by conduction between the asphalt pavement surface and the location of the pipe network. Conduction plays an important role in reducing the temperature on the asphalt surface, as it is responsible for how heat will flow through the material and how quickly it will be diffuse.

3.2. Boundary Conditions

The energy interaction between the asphalt surface and the environment implies solar radiation gains, air convection gains or losses, the thermal radiation gains or losses and the thermal conduction to material below the surface. All these terms are present in the initial boundary condition for the pavement surface (Eq. 2). The heat transfer problem under study is shown in figure. 3.

$$-\lambda_a \nabla T_a = \alpha q_s + \varepsilon\sigma\left(T_{a,s}^4 - T_{sur}^4\right) + h(T_{amb} - T_{a,s}) \tag{2}$$

Since the energy balance equation establishes that the differences between the rates of energy enter and leaving in a control volume equals the rate of change of energy inside the control volume. The heat transfer between the asphalt pavement and the fluid can be describe as:

$$\left(-\lambda_w \nabla T_w + \rho_w C_{pw} u_w T_w\right) - (-\lambda_a \nabla T_a) = 0 \tag{3}$$

A constant temperature is assumed at the fluid inlet, for this reason the boundary conditions can be written as:

$$T_w = T_{w1} \tag{4}$$

The energy balance for the fluid outlet is given by the thermal conduction and therefore:

$$-\lambda_w \nabla T_w = 0 \tag{5}$$

Finally the boundary condition for the asphalt layer below the pipe network is:

$$(-\lambda_a \nabla T_a) = 0 \tag{6}$$

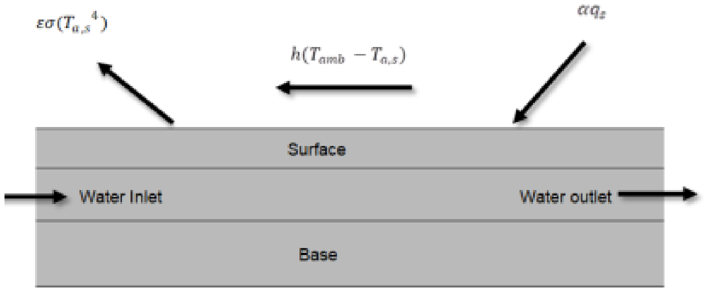

Fig. 3 Heat transfer problem

3.3. *Pavement model and properties*

The presented heat transfer analysis is under the following considerations:

- the pavement materials behave as a homogenous and isotropic material,
- a perfect contact exists between layers,
- the pavement surface behaves as a grey surface and
- the fluid is set as water.

The depth of each layer and the thermal properties of the model are presented in table. 1. According to Hess et al., 2013 the aggregate plays an important role in the heat transfer process and hence in the surface temperature. For this reason the surface is considered with an aggregate that improves the thermal conductivity of the asphalt mixture while the thermal characteristics of the remaining layers are from a common asphalt concrete base on literature.

Table 1. Thermal Properties Model.

Layer	Depth (mm)	Density ρ (kg/m^3)	Thermal Conductivity λ (W/m*K)	Specific Heat C_p (J/kg*K)
Surface	30	2380	1.5	900
Intermediate layer	40	2100	0.7	815.5
Base	50	2100	0.7	815.5

3.4. Model Consideration

A 3dimension geometry model is analysed; the pipe network is arranged in a serpentine form, with a spacing of 100mm between pipes centres. Figure 4 shows the model configurations, the width and length is set up to 1000mm.

Finite element simulations were performed to determine the temperature distribution at two points: the surface and 30 mm below the surface. The simulation was carried out in two different scenarios; first, the asphalt pavement structure was modelled under constant solar irradiation and without any system running for 6 hours; then a second simulation was carried out under the following consideration, the asphalt pavement is subjected to solar irradiation for 4 hours and after this time, the fluid will begin to flow for a two hours duration.

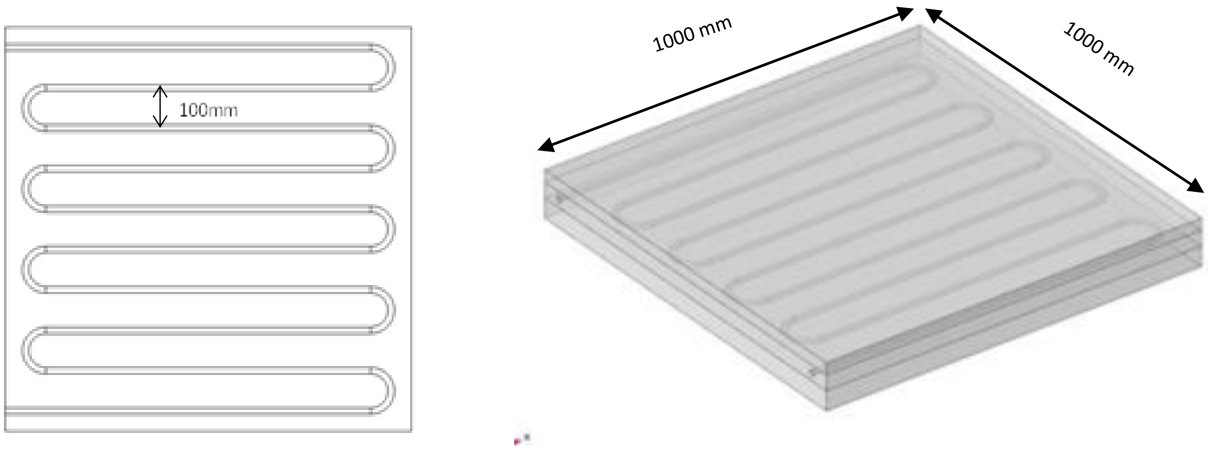

Fig. 4 Geometry and model considerations

4. Thermal Analysis

4.1. Evaluation

The premise of this analysis relies that the surface temperature of the asphalt pavement will decrease due to the flowing water below the surface through a conduction heat transfer, hence based on the Stefan-Boltzmann Law the different of temperature between the surrounding and the asphalt surface is reduced which gives a reduction of the amount of heat emitted back to the air. In order to evaluate this concept the temperature of the surface and at 30mm from surface were predicted with and without water flowing. Also with this model it will be possible to understand the heat transfer by conduction from the surface asphalt pavement to the pipe location.

Figure 5 shows the surface temperature without water flowing , it was assumed that the surface had an initial temperature of 20°C, as the solar irradiance is introduced, the temperature increase is noticeable, which reflects the fact that as the day goes by the solar irradiance increases, which means a higher temperature on the pavement surface. At e.g. 30mm from the surface (Fig. 7.) the distribution on temperature is increasing slowly in comparison with the temperature distribution of the surface, both cases no water was running.

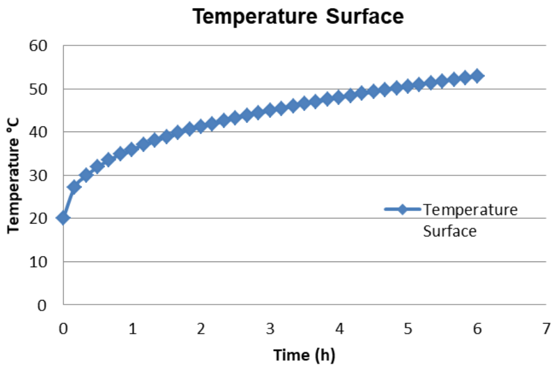

Fig. 5 Temperature in the surface no water flowing

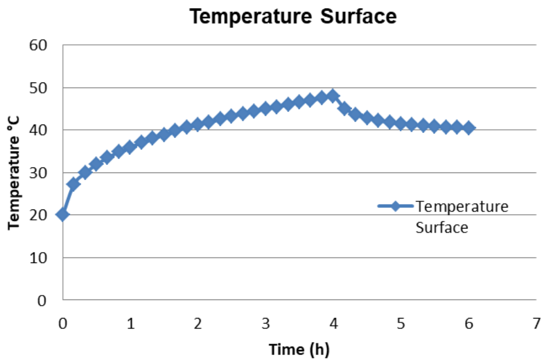

Fig. 6 Temperature in the surface water flowing

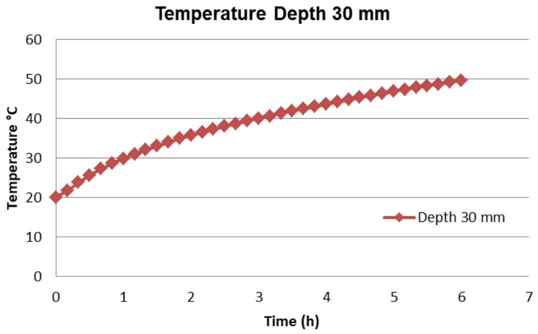

Fig. 7 Temperature 30mm below surface no water

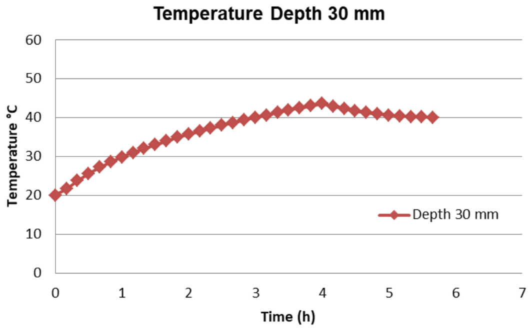

Fig. 8 Temperature 30mm below surface water flowing

Once the water starts flowing (Fig. 6 and Fig. 8) there is a drop in the temperature, this is significant since it confirmed that the temperature of the aspahalt pavement surface is reduced. The drop of temperature from the surface is more steep in the first hours of the simulation in comparison with the reduction of temperature in the pavement structure e.g. at 30 mm from the surface. It is noticeable, that as the simulation continues, the temperature between the surface and the 30mm depth becomes more similar. Due to the thermal properties of the surface, the heat is transferred more efficiently.

4.2. Interpretation

The reduction of the asphalt surface temperature shown in the prediction model (fig. 6) proves that the amount of heat emitted back from pavemenet surface back to the neighboring air can be reduced, which also means a reduction in the reflectance of the asphalt pavement surface.The emitted heat is one of the contributors to the urban heat island effect, therefore a reduction of this effect can be achieved.

One of the main factors affecting the temperature distributions of the asphalt pavement is solar irradiance. If the latter increases, also the surface temperature does. For this reason, it is necessary to understand the role of thermal properties of asphalt mix materials. As can be seen in Figures 6 and 8, the surface temperature is higher than the temperature at 30 mm from the surface, but as soon as the water begins to flow over time the temperatures become similar due to the ability of the surface to conduct heat more effectively.

It is worth mentioning that the surface was considered with a higher thermal conductivity in comparison to the common asphalt concrete.

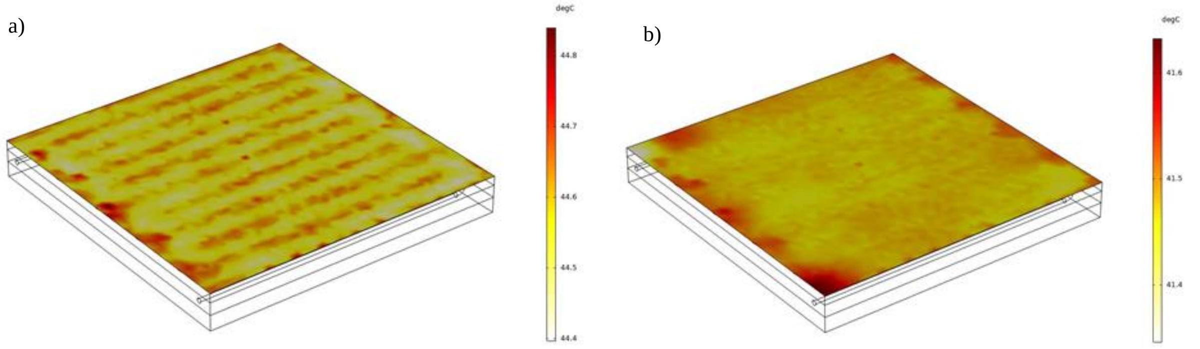

Fig. 9 Temperature distribution in asphalt surface a)15 min water flowing b) 1h after water flowing

Figure 9(a) and 9(b) presents the temperature distribution in the first minutes and hour of the system working resp. after the water started flowing. As it can be seen due to the pipe arrangement the temperature is not completely uniform. Hence more simulation need to be performed at different flow rates as well as different pipe spacing and diameter, in order to investigate a distribution that will lead to reduce the emitted heat more evenly.

5. Conclusions and Outlook

The numerical analysis proves that the concept of a temperature-controlled asphalt pavement decreasing the surface temperature by a flowing fluid is feasible and will contribute to diminishing the effect of urban heat island (UHI) in urban areas.

It is possible to model the temperature distribution of the asphalt pavement through an analysis of finite elements and at the same time, convection, radiation, conduction heat transfer problems.

The future work of this project will be focused on improving the heat transfer between the different layers from the thermal properties of the material, determine the influence of the flow rate, spacing arrangement and depth of the pipes. A comprehensive study under different boundary conditions (radiation-convection) in order to determinate the parameter having a greater impact in the performance of the system so that the concept is adaptable in different urban locations and weather parameter.

Acknowledgements

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