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A novel strategy of inducing solar absorption and accelerating heat release for cooling asphalt pavement

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ABSTRACT

High-temperature asphalt pavements contribute to the development of urban heat island, rutting distress and asphalt aging, etc. Implanting steel rods in the middle and bottom asphalt layers was proved to be able to construct thermal channels, but it was difficult to reduce surface and inner temperatures simultaneously. To increase solar absorption and accelerate heat release in asphalt pavement, a novel strategy of oriented heat induction was proposed according to the effect of rod-implanting mode on temperature profile. The simulation results show that the proposed structure absorbed 30.6% solar heat more than control structure. The implanting of steel rods changed the heat flow characteristics as well. The heat in the asphalt mixture in the top layer was absorbed by steel rods, which was then released to the asphalt mixture in the bottom layer after a period of fast downward heat transfer. The surface and inner temperatures reduced by maximums of 3.5 °C and 6.4 °C, respectively, compared to the control structure. The temperature reduction was verified by an indoor irradiation test. As a result, the maximum rutting depth of the proposed structure decreased by 49.2%. The proposed strategy of heat induction is expected to be used to cool asphalt pavement by inducing solar absorption and accelerating heat release.

1. Introduction

Black asphalt pavements tend to strongly absorb solar radiation, resulting in excessive accumulated heat and high pavement temperature. On the one hand, asphalt pavements cover a large percentage of urban surfaces. The high-temperature pavements release longwave radiation and convective heat to the atmosphere, intensifying urban heat island (Santamouris, 2013; Qin, 2015; Abbas et al., 2017). Many studies have shown that reducing surface temperature can contribute to mitigating urban heat island (Santamouris et al., 2012; Efthymiou et al., 2016; Anting et al., 2017). On the other hand, the high-temperature pavements easily produce plastic flows under vehicle loads (Ji et al., 2016). It has been proved that reducing inner pavement temperature is one of the promising ways to reduce rutting (Xue et al., 2013; Du et al., 2014, 2015; Du and Wang, 2015). In addition, high pavement temperature can accelerate the thermally oxidative ageing of asphalt material, which can further degrade moisture resistance, low temperature and fatigue properties of asphalt mixture (Pan et al., 2017). With the intensifying global warming problem, the above issues become more urgent to overcome.

According to the thermal balance of asphalt pavement presented in the review by M. Santamouris (Santamouris, 2013), total three kinds of thermal regulation (i.e., preventing heat absorption, absorbing heat accumulation and releasing heat accumulation) were used to decrease the heat accumulations in asphalt pavement and thereby reduce pavement temperature. First, heat-reflective (e.g., light colored pavement (Tran et al., 2009), heat-reflective coating (Rossi et al., 2016; Pisello, 2017), colored thin layer asphalt (Synnefa et al., 2011), thermochromic coating (Karlessi et al., 2009) and heat-resistant (Feng et al., 2013) materials were used to decrease the solar absorption of asphalt pavement. Tree shading was used to decrease the solar energy incident to asphalt pavement (Akbari et al., 2001). Second, phase change materials (Manning et al., 2015; He et al., 2014) and solar energy collector pavement (Bobes-Jesus et al., 2013; Pan et al., 2015) were used to absorb the heat accumulation in asphalt pavement. Third, permeable (Li et al., 2013) and water-retentive (Jiang et al., 2016) asphalt pavements were used to release the heat accumulation by moisture evaporation. These strategies cannot reach a satisfactory purpose of mitigating urban heat island and reducing rutting simultaneously. For example, the heat-resistant materials used in the top layer can increase the surface temperature of asphalt pavement (Feng et al., 2013). And then permeable pavement has a low load-carrying capacity but can only be used to in light-traffic pavements currently (Li et al., 2013; Coleri et al., 2013).

Our findings show that asphalt pavement can be cooled by

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regulating the heat transfer process, such as highly oriented heat induction (Du et al., 2014, 2015) and bidirectional heat induction (Du et al., 2015; Du and Wang, 2015). The main strategy of bidirectional heat induction is to accelerate downward heat transfer in asphalt pavement, which can be realized by using high-thermal-conductivity asphalt mixture (Du et al., 2015; Chen et al., 2016; Yang et al., 2016) or high-thermal-conductivity rods (Du and Wang, 2015). However, the previously designed structures cannot obviously absorb more solar energy, or even absorb less solar energy. Pavement surface temperature thus rises, which will intensify urban heat island and accelerate thermally oxidative ageing of asphalt. Therefore, it is necessary to explore a new heat-induced method to increase solar absorption of asphalt pavement and accelerate heat releasing to the base layer.

2. Objective

This study aims at finding a new heat-induced strategy to increase solar absorption of asphalt pavement. Meanwhile, the acceleration of heat release should also be realized to decrease heat accumulation in asphalt pavement. In such a way the surface and inner temperatures can be reduced simultaneously. For this purpose, the temperature features of total seven rod-implanting modes are studied, and a new heat-induced structure is proposed. The feasibility of this structure are confirmed by comparing the heat transfer and temperature characteristics of control structure (CS) and the structure with the same rod-implanting mode introduced in Du and Wang (2015). Finally, the rutting resistances of the three structures are compared by simulating their maximum rutting depths.

3. Materials and model establishment

3.1. Materials

Only a Sup-13 asphalt mixture was used for simplify. Its asphalt content was 5.0% and aggregate gradation is shown in Table 1. Steel rod was referred to as a representative of high-thermal-conductivity rod. The thermal physical parameters of asphalt mixture and steel rod are shown in Table 2. The elastic and creep parameters of mixtures in asphalt pavement can be found in reference (Li and Li, 2012). The elastic modulus of steel rod was 200 GPa.

3.2. Model establishment

3.2.1. Heat-transfer model

The heat transfer model used in this paper is shown in Fig. 1. A type of 8-node quadrilateral heat conduction element (DC2D8) was used. The element size was 5 × 2 cm in asphalt layers, 5 × 5 cm in base and sub-base layers, 5 × 10 cm in subgrade and 0.6 × 2 cm in steel rods. There were four basic hypotheses: (1) the boundary conditions remained constant within 7 days; (2) the left, right and bottom boundaries of the model were thermally insulated; (3) there was no heat resistance between different materials; (4) thermal properties of all materials did not change with temperature. Steel rods (diameter of 6 mm and spacing of 10 cm) were implanted in different modes.

According to the heat transfer theory, the second boundary condition refers to heat flux values, which is calculated according to Eq. (1) in this model. And the third boundary condition refers to heat convection coefficient and near-surface air temperature. The heat convection coefficient is shown in Table 3 and the air temperature is calculated according to Eq. (2) in this model. The calculation equations of solar radiation (Eq. (1)) and air temperature (Eq. (2)) are consistent with the results reported in the reference (Yan, 1984). A combination of the second and third boundary conditions was used in the upper boundary condition. Some parameters used for temperature field calculation are shown in Table 3.

Table 1
Aggregate gradation for Sup-13 mixture.

Sieve sizes (mm)	16.0	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing ratio (wt.%)	100	94.6	69.0	43.8	29.7	20.3	14.3	9.1	7.5	6.0

Table 2
Thermal physical parameters of asphalt mixture and steel rod.

Material	Density (kg/m^3)	Thermal conductivity (J/(m·h·°C))	Heat capacity (J/(kg·°C))
Asphalt mixture	2450	3822.5	1485.5
Steel rod	7830	182520	469

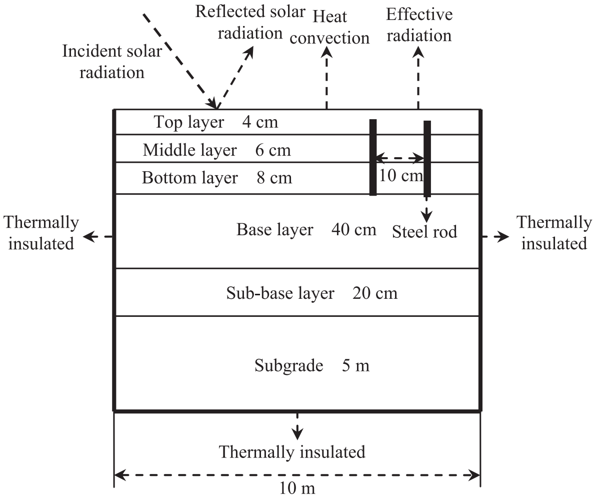

Fig. 1. Diagram of heat-transfer model.

Table 3
Parameters for temperature field simulation.

Solar radiation absorptivity	0.9
Convection coefficient W/(m^2·°C)	20
Initial temperature °C	25
Maximum air temperature T_{max} °C	35
Minimum air temperature T_{min} °C	20

$$q(t) = \begin{cases} 0 & 0 \leqslant t < 12-\frac{c}{2} \\ q_0 \cos mw(t-12) & 12-\frac{c}{2} \leqslant t \leqslant 12+\frac{c}{2} \\ 0 & 12+\frac{c}{2} < t \leqslant 24 \end{cases} \tag{1}$$

where q_0 = maximum radiation in a day (J/m^2), $q_0 = 0.131mQ$, $m = 12/c$; Q = total amount of solar radiation (J/m^2), $Q = 20.1 \times 10^6$ J/m^2; c = effective number of hours of solar radiation (h), $c = 10$ h; ω = angular frequency (rad), ω = 2π/24 rad.

$$T_a = T_1 + T_2[0.9\sin(\omega(t-t_0)) + 0.14\sin(2\omega(t_{t_0}))] \tag{2}$$

where T_1 = daily mean air temperature (°C), $T_1 = (T_{max} + T_{min})/2$; T_2 = daily air temperature amplitude (°C), $T_2 = (T_{max} - T_{min})/2$; t_0 = initial phase (h), $t_0 = 9$ h; ω = angular frequency (rad), ω = 2π/24 rad.

The heat conduction in asphalt pavement was calculated for 7 days by using the finite element software ABAQUS. The data on the 7th day, such as heat flux and temperature, were extracted to analyze the specific heat transfer characteristics of different structures.