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Cooling asphalt pavement by a highly oriented heat conduction structure

Du Yinfei, Wang Shengyue*, Zhang Jian

School of Transportation, Southeast University, Nanjing 210096, PR China

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ABSTRACT

In this paper, a highly oriented heat conduction structure of asphalt pavement, with a combination of low thermal conductivity layer and three-layered gradient heat conduction structure, was proposed to reduce pavement temperature and decrease nighttime heat release into the atmosphere in summer. The structure was formed by modifying contrast asphalt pavement by adding different dosages of low thermal conductivity powders to each layer. Also, it made full use of principles of thermal insulation and gradient heat conduction, and extended the scope of thermal gradient in asphalt layers. The results showed that, compared with contrast structure, the highest temperature of upper surface of bottom layer, which was used to represent the average temperature of middle and bottom layers, reduced by 2.3 °C (simulation result) and 2.4 °C (test road result). The average temperatures of middle and bottom layers reduced by 1.6 °C (at 2:30 pm) and 1.5 °C (at 6:00 pm), respectively, which were validated by test road results. Calculations of simulation result displayed that the structure released less 12.1% of heat to the atmosphere during nighttime than contrast structure. According to the results summarized above, it is concluded that the structure has a continuous cooling capacity, and is expected to reduce high temperature rutting of asphalt pavement and help to reduce high air temperature at night.

1. Introduction

Asphalt pavement has a high absorption of solar radiation, often leading to a high temperature on the surface of asphalt pavement and triggering a series of distresses such as rutting [1,2]. High temperature on road surface is one of the important reasons for forming urban heat island effect [3–5], which usually causes huge energy consumption in big cities in summer [6,7]. In addition, strong and continuous thermal radiation from road surface not only reduces the comfort level of urban residents, also easily induces diseases such as cardiovascular [8,9]. To mitigate this problem, paving cool asphalt pavements [10,11] and controlling the heat conduction in asphalt pavements [12] can be used. High temperature rutting, which can be reduced by establishing a gradient thermal conductivity in asphalt layers [13,14], can result in hydroplaning and nonuniform tire-pavement contact stresses, further aggravating pavement distresses and driving safety [15].

In the past decades, many techniques have been applied to cool asphalt pavement in summer, such as solar reflective coating [16–18], retro reflective films [19,20], colored thin layer asphalt [11], thermochromic asphalt [21,22], phase-change material [23], permeable pavement [24,25] and asphalt solar collector [26,27]. All these cooling technologies achieved ideal practical effects. For example, solar reflective coating could reduce the surface temperature by 12 °C [10]. However, the technology based on the principle of light reflection usually brings new difficulties which are hard to overcome so far. These include driver's dazzling caused by the strong reflected light [10]. In addition, because of the high roughness of asphalt pavement, the heat reflection belongs to a typical diffuse. So most of the reflected heat will be re-absorbed by the objects on both sides of road, causing secondary heat pollution [28]. For permeable pavement, its abundant pores are easy to be blocked [29]; it is also prone to raveling, which requires an excellent viscosity of asphalt [30]. For methods such as paving energy collector pavement, since the inner stress distribution of the pavement is significantly changed [31], rutting is easier to happen and expand.

Establishing a gradient heat conduction channel in asphalt pavement has proved to be an efficient strategy for cooling hot asphalt pavements in summer [13,14,32]. In general, asphalt pavements are composed of three asphalt layers. The structures in Refs. [13,14] were only composed of two layers of gradient heat conduction in middle and bottom layers, in addition to a low thermal conductivity layer in top layer. Though the structure in Ref. [32] was designed by establishing three layers of gradient heat conduction, in practice

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* Corresponding author. Tel.: +86 025 83790551.
E-mail address: sywang@seu.edu.cn (W. Shengyue).

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Fig. 1. Test specimens.

it was found that, due to a high setting of thermal conductivity of top layer, too much solar radiant heat was permitted to enter pavement, which was not only easy to cause rutting but also inclined to release more accumulated heat to the surrounding air in the night. Thus, the heat conduction structure with high thermal conductivity of top layer reported in Ref. [32] does not apply to those cities which prefer to have cool asphalt pavements at night, such as London (United Kingdom), a typical city with nighttime urban heat island effect. According to Refs. [33–36], the urban heat island intensity of London at night is 5–8 °C higher than that during the day. Obviously, more heat release will exacerbate the thermal pollution in these cities at night. To avoid too much solar radiation heat entering the pavement in the day and forming a release peak in the night, we put forward a highly oriented heat conduction structure with a combination of low thermal conductivity layer and three-layered gradient heat conduction structure. Here the highly oriented heat conduction structure was designed on the base of a three-layered contrast asphalt pavement.

2. Materials and methods

2.1. Materials

The thermal properties of asphalt mixture are mainly influenced by its void content [37]. So only a type of asphalt mixture, Superpave 13, was used to design heat conduction structures. The asphalt mixture specimens were prepared with void content of 4.0% [38]. SBS modified asphalt was used and the asphalt content was 5.2%. The coarse aggregate was basalt and the mineral filler was made of limestone. The gradation of Superpave 13 mixture is shown in Table 1.

In this paper, the thermal properties of asphalt mixture were changed by adding graphite or floating beads. As the dosage of powder can significantly affect the volume index and performances of asphalt mixture [39], the maximum dosages of floating beads and graphite were both less than 15% of asphalt volume.

2.2. Determination of thermal properties of asphalt mixture

The thermal properties of the specimens prepared by asphalt mixtures with different proportions of powders added (Fig. 1) were measured by using a thermal conductivity tester (DRM-II, made in China). In the test, three specimens were classified as one group, and the sizes of the specimens of each group were 20 × 20 × 6 cm, 20 × 20 × 2 cm and 20 × 20 × 6 cm. Before the test, the instrument heated the specimens in order to achieve a transient temperature distribution inside. Based on the principle of unsteady state, the thermal properties of the specimens were achieved automatically, as shown in Table 2.

2.3. Model establishment

A two-dimensional heat-transfer model of asphalt pavement was established by using the finite element software ABAQUS. Model parameters, including boundary conditions and thickness of each layer of the pavement, are shown in Fig. 2. The upper boundary conditions of the pavement are shown in Table 3, in

Table 1
Aggregate gradation for Superpave 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 (% by weight)	100	93.1	68.1	42.4	28.7	22.3	13.7	9.3	8.7	6.3

Table 2
Test results of thermal properties of asphalt mixture.

Filler type	Percentage by volume (%)	Density (g/cm^3)	Thermal conductivity (W/m °C)	Heat capacity (J/(kg °C))
Floating beads	0	2.45	1.0618	1485.49
	5		0.7504	1507.30
	10		0.6916	1526.54
	15		0.6529	1541.73
Graphite	0	2.45	1.0618	1485.49
	5		1.1143	1322.07
	10		1.1802	1257.30
	15		1.2207	1229.03