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Research Paper

Cooling permafrost embankment by enhancing oriented heat conduction in asphalt pavement

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HIGHLIGHTS

- Solar radiation heat was prevented from entering the embankment in summer.
- The downward heat transfer efficiency in asphalt pavement and embankment reduced.
- The net heat accumulation in the embankment decreased.

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ABSTRACT

In this paper, a new method was proposed to decrease the heat accumulation in permafrost embankment by controlling an oriented heat transfer in asphalt pavement. Two highly oriented heat-induced structures, named G-OHIS (only gradient thermal conductivity) and G+R-OHIS (combined gradient thermal conductivity and heat reflective layer), were designed by using two indexes of summertime daily heat absorption and annual net heat accumulation on the top of embankment. The results showed that the heat absorptions on the top of embankments of the G-OHIS and G+R-OHIS in summer decreased by 9.9% and 23.2% respectively. The annual net heat accumulation on the top of embankment decreased by 6.2% for the G-OHIS and 37.9% for the G+R-OHIS. Moreover, the summertime mean daily temperatures on the top of embankments of the G-OHIS and G+R-OHIS reduced by 0.74 °C and 1.66 °C respectively. The annual temperature difference on the top of embankment reduced by 1.07 °C for the G-OHIS and 1.96 °C for the G+R-OHIS. The effectiveness of the G-OHIS in reducing pavement temperature was validated by an indoor irradiation test. It is expected to reduce permafrost thawing and other pavement distresses caused by permafrost thawing by controlling an oriented heat transfer in asphalt pavement.

1. Introduction

In permafrost regions, black asphalt pavement strongly absorbs solar radiation and prevents the evaporation of embankment [1]. The coupling effect breaks the original energy balance on the surface of permafrost and becomes one of the two main reasons for permafrost thawing [2,3]. Statistical investigations on Qinghai–Tibet highway showed that approximately 85% of embankment destructions were caused by permafrost thawing [4], which then brought hazards to human infrastructures [5] and thermal disturbances to its surrounding areas [6]. Therefore, this work is devoted to exploring a solution for decreasing the heat accumulation in the embankment and then reducing permafrost thawing and other pavement distresses caused by permafrost thawing.

Before this paper, many technologies, such as crushed-rock revetment [7], ventilated duct [8], crushed rock interlayer [9], thermal insulation [10], and other combined technologies [11], have been proposed to protect permafrost embankment. Gradient heat conduction structure of asphalt pavement (GHCS) could also be used to achieve the above goal [12,13]. In literature [13], the temperature distribution in the GHCS was measured, but the impacts of the GHCS on the heat and temperature distributions in permafrost embankment were not provided. Besides, high-thermal-conductivity graphite was added in the top layer, which would allow this structure to absorb external heat more easily.

In this paper, a new method for decreasing the heat accumulation in permafrost embankment and further reducing permafrost temperature was proposed by controlling an oriented heat transfer in asphalt pavement [14]. According to the structure and

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environment characteristics of newly planned Qinghai–Tibet expressway, a heat transfer model was established by using the infinite element software ANSYS in Section 2. In Section 3 two highly oriented heat-induced structure of asphalt pavement, named G-OHIS (only gradient thermal conductivity) and G+R-OHIS (combined gradient thermal conductivity and heat reflective layer), were designed by using two indexes of summertime daily heat absorption and annual net heat absorption on the top of embankment. The heat transfer characteristics of asphalt pavement and embankment were analyzed to evaluate the effects of the structures on permafrost protection in Section 4, and in Section 5 the effectiveness of the G-OHIS in reducing pavement temperature was validated by an indoor irradiation test.

2. Test materials and numerical model

2.1. Proportion of asphalt mixture

The thermal properties of asphalt mixture are mainly influenced by its void content [15]. Besides, asphalt mixtures in the top layer, bottom layer and flexible base layer have small differences in designed void content. As a result, only a type of Superpave-13 asphalt mixture was used in numerical simulation and experimental validation [14,16]. SBS modified asphalt, basalt aggregate and limestone mineral filler were used. The optimal asphalt–aggregate ratio was 5.0%. The aggregate gradation was shown in Table 1.

2.2. Measurement of thermal properties of asphalt mixture

To realize the purpose of gradient heat conduction in asphalt pavement, two kinds of powder, high-thermal-conductivity graphite (thermal conductivity of 130–140 W/m·°C) and low-thermal-conductivity floating beads (thermal conductivity of 0.08–0.10 W/m·°C), were added into asphalt mixture. A DRM-II thermal conductivity tester (Xiangtan Instruments and Meters, Hu'nan Province, China) was used to measure the thermal properties of different asphalt mixtures (Fig. 1). The instrument, based on the principle of unsteady state, could automatically calculate the thermal properties of the test specimens according to the characteristic of temperature change and thermal conduction differential equations. Three plates were taken in each group, setting sizes of 20 × 20 × 6 cm, 20 × 20 × 2 cm and 20 × 20 × 6 cm respectively. The test results of the thermal properties of asphalt mixture were shown in Table 2. The densities of different asphalt mixtures were assumed to be the same for the small influence of the addition of powder on the density of asphalt mixture.

2.3. Heat transfer model

A one dimensional heat transfer model was established by using the software ANSYS, according to the designed structure of the newly planned Qinghai–Tibet expressway, as shown in Fig. 2. The variations of thermal properties of asphalt mixture with temperature were ignored. Besides, the right and left boundary conditions were assumed to be thermally insulated, because the calculation results were extracted from the center of the cross section. The 12 m-thick embankment could be used to reduce the influence of the bottom boundary condition on the calculation result. As a result, the bottom boundary condition was set to be thermally insulated as well. In the model, two types of element, plane55 and surf151, were used. The element size was 2 × 10 cm in the top layer, 2.5 × 10 cm in the bottom layer, 3 × 10 cm in the flexible base layer, 6 × 10 cm in the semi-rigid base layer and 12 × 10 cm in the embankment.

According to the parameters such as solar radiation, convection coefficient and air temperature in Table 3, the model was calculated by using the first and third boundary conditions. The distributions of solar radiation and air temperature were approximated according to Eqs. (1) and (2), which were reported in literature [17].

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

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

$$T_a = T_1 + T_2[0.96\sin(\omega(t-t_0)) + 0.14\sin(2\omega(t-t_0))] \quad (2)$$

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), $\omega = 2\pi/24$ rad.

The initial temperature distributions in summer and winter are shown in Tables 4 and 5.

Table 1
Aggregate gradation of 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	94.6	69.0	43.8	29.7	20.3	14.3	9.1	7.5	6.0

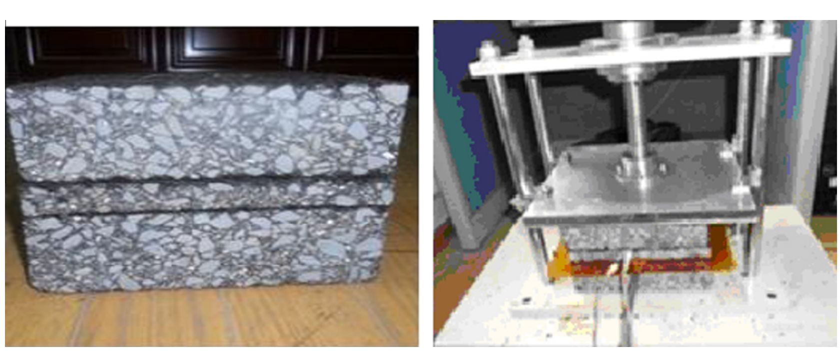

Fig. 1. Test specimen for the thermal properties of asphalt mixture.