Research on the characteristics of temperature field of asphalt pavement in seasonal frozen region

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Abstract. The characteristics of climate in seasonal frozen area are low temperature and a large range of temperature variation between day and night in winter. These characteristics often lead to problems of asphalt pavement, especially transverse cracks. To reduce the problems of asphalt pavement, it is necessary to examine the distribution of the temperature range of asphalt pavement. A three-dimensional finite element model was used, taking the SMA asphalt pavement as an example with solid70 and plane55 unit features of ANSYS software. It can obtain the relationship between temperature gradient and time and the relationship between temperature gradient and depth. In addition, a function relation model of stress and time was also established. It can provide a theoretical basis for the prevention and treatment of problems of asphalt pavement in seasonal frozen area. Moreover, it has an important significance for improving asphalt pavement design.

1. Introduction

Pavement materials will produce temperature stress under the effect of the change of external temperature. If the stress exceeds the threshold strength of the material, pavement will produce cracks. The two main solutions used to study temperature fields are finite difference method and finite element method. Finite difference method requires a large number of iterative calculations, but the number of iterations will make a high impact on the accuracy [1]. Finite element method can get a relatively high accuracy by using ANSYS software [2]. Northern Hebei in China is a typical seasonal frozen area, and SMA pavement is a typical pavement structure in the seasonal frozen area. The analysis can provide a theoretical basis for the prevention and treatment of problems.

2. Temperature field theory

Because of the change of external temperature, the internal structure of the pavement will generate an unstable heat flow. The heat exchange model can be expressed as follows:

\[ q = R + P \]  \hspace{1cm} (1)

According to the Newton equation, thermal convection can be expressed as follows:

\[ P = B (T_{\text{air}} - T_0) \]  \hspace{1cm} (2)

where B is the heat transfer coefficient (W/m²°C); Tair is the air temperature(°C); and T0 is the road surface temperature (°C).

Thermal radiation, including solar radiation and active radiation, can be expressed as follows:
\[ R = \alpha_s Q - F, \]  
\[ (3) \]

where \( \alpha_s \) is the radiation absorption coefficient; \( Q \) is the energy of solar radiation; and \( F \) is the efficient radiation.

Heat flow can be obtained by Fourier's law:

\[ q = -\lambda \frac{\partial T}{\partial n}, \]  
\[ (4) \]

where \( T_b \) is the road surface boundary temperature (°C).

Air temperature including the efficient radiation can be drawn by expanding the temperature amplitude method [3] :

\[ T_w = T_1 + (T_2 + C_f \cdot a_0) \left( 0.96 \sin \left( \omega \left( t - t_0 \right) \right) + 0.146 \sin(2 \omega \left( t - t_0 \right)) \right), \]  
\[ (5) \]

where \( T_1 = (T_{\text{max}} + T_{\text{min}})/2, T_2 = (T_{\text{max}} - T_{\text{min}})/2; C_f \) is the effective emissivity coefficient; \( T_{\text{max}} \) is the maximum temperature(°C); \( T_{\text{min}} \) is the minimum temperature(°C); \( t_0 \) is the initial moment, \( t_0 = 3(\text{h}); \) and \( \omega = 2\pi/24 \) (rad).

Therefore, the unsteady heat flow above the upper boundary can be expressed as follows:

\[ -\lambda \frac{\partial T}{\partial n} = B \left( T_w + \frac{\alpha Q}{B} - T_b \right). \]  
\[ (6) \]

3. Finite element model of the pavement

To efficiently distribute load stress of the base layer and protect the permafrost roadbed, the gravel cushion whose thermal conductivity is small was added. The material parameters and geometry parameters of structural layers are shown in Table 1.

| Structural layer | Elasticity modulus (Mpa) | Poisson's ratio | Density (kg/m³) | Thermal conductivity (w/m*k) | Specific heat Capacity (j/kg*k) | Temperature shrinkage coefficient (10-5/°C) | Thickness (cm) |
|------------------|--------------------------|----------------|----------------|-----------------------------|-------------------------------|---------------------------------------------|--------------|
| SMA              | 1400                     | 0.25           | 2323           | 1.2                         | 1050                          | 2                                           | 3            |
| AC               | 1200                     | 0.25           | 2334           | 1.2                         | 1050                          | 2                                           | 7            |
| base layer       | 1100                     | 0.25           | 2275           | 1.3                         | 1080                          | 1.02                                        | 20           |
| gravel cushion   | 200                      | 0.35           | 2140           | 1.8                         | 1020                          | 50                                          | 18           |
| soil base        | 50                       | 0.35           | 1800           | 1.5                         | 1040                          | 50                                          | -            |

A three-dimensional pavement model was established with the unit solid70 and plane55 of ANSYS software, which are suitable for the transient thermal analysis. It can calculate the temperature range, and then take it as a temperature load for the stress analysis. The pavement model's size is 6 m * 6 m * 6 m. In the division of grid generation of pavement, the surface layer and the base layer are refined. Contact conditions between layers are completely continuous. The surface boundary condition can be obtained by Equation (1-6), and the lower boundary is soil base temperature. Other boundaries are adiabatic state. A constraint is that the driving direction and the direction of road width have the constraints of respective management and the bottom of the pavement is fully constrained.

The most adverse weather condition in Chengde was chosen for the study of temperature field. The soil base temperature is 13.6°C, and the maximum and minimum air temperatures are -3°C and -20°C.
respectively. Surface boundary condition of temperature is shown in Figure 1. The time of initial temperature field is 20:00, and the distribution of the initial temperature field is shown in Figure 2.

4. Finite Element Analysis

4.1 Analysis of temperature field

The distribution of temperature field affects the stress of the pavement. By comparing the temperatures of road surface and the bottom of upper surface layer, it was found that the time of appearance of the minimum and maximum temperatures gradually goes backwards with the increase of depth.

Figure 4 shows that the temperature fluctuation amplitude with the increase of depth gradually decreases, which indicates that the external environmental impact on pavement is reduced. Therefore, the thickness of the surface layer or the base layer is important to decrease the temperature fluctuation amplitude.

4.2 Analysis of temperature gradient

The value of the temperature gradient in the depth direction can roughly reflect tensile stress, which can lead to transverse cracks. Figure 5 shows that the change of the temperature gradient is substantially consistent with the temperature. As can be seen in Figure 6, with the depth increasing, the magnitude of temperature gradient change of the surface layer is reduced. Meanwhile, it is almost a constant in the base layer and the cushion layer.
4.3 Analysis of temperature stress

The distribution of pavement flexural stress is shown in Figure 7 and Figure 8. The surface layer was subjected to compressive stress under the positive temperature gradient and subjected to tensile stress under the negative temperature gradient, while the base layer has been in a state of tensile stress.

Figure 9 shows that pavement stress will change with time and the state of stress of the surface layer is alternated. Figure 10 shows that the surface layer is in tension for half of the time, it is prone to fatigue damage and cracking. In addition, the base layer is in tension for most of the time so that its relaxation properties will drop at low temperature, which makes the base layer cracks occur easily.

The change trend between temperature stress and time of the surface layer is a sinusoidal relationship. Then, the sinusoidal model about the temperature stress and time was established to describe or predict...
stress value and stress state of the pavement interior structure. The model is as follows:

\[
\sigma = \sigma_1 + \sigma_2 \sin \left( \alpha t + t_0 \right)
\]

where \( \sigma_1 = (\sigma_{\text{max}} + \sigma_{\text{min}})/2 \), \( \sigma_2 = (\sigma_{\text{max}} - \sigma_{\text{min}})/2 \); \( \sigma_{\text{max}} \) is the maximum temperature stress (Mpa); \( \sigma_{\text{min}} \) is the minimum temperature stress (Mpa); \( \omega = 2\pi/24 \); \( t_0 \) means the average moment of the maximum tensile stress and the maximum compressive stress corresponding bit.

The following equations can be obtained by bringing the stress data into Equation (7).

1. The relationship between stress and time of the bottom of the upper surface layer is as follows:

\[
\sigma = 0.022 + 0.395 \sin \left( \frac{\pi}{12} (t - 10) \right)
\]

2. The relationship between stress and time of the bottom of the surface layer is as follows:

\[
\sigma = 0.052 + 0.138 \sin \left( \frac{\pi}{12} (t - 12) \right)
\]

5. Summary

Through the analysis of the characteristics of pavement temperature range in seasonal frozen region, it was obtained that stress of the surface layer alternately change with time, and the sinusoidal function design about the stress and time was obtained at the same time. The surface layer is in tension for half the time so that the surface layer is prone to fatigue damage and cracking. The base layer is in tension for most of the time in winter, thus its relaxation properties will drop at low temperature, which makes the base layer cracks occur easily. Therefore, the external temperature affects the stress state of the pavement greatly, and pavement design should take full account of the temperature stress.

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