DESIGN TEMPERATURE AND ITS PREDICTION MODEL BASED ON FATIGUE FAILURE OF ASPHALT PAVEMENTS

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ABSTRACT

As for the fatigue failure which must be controlled in asphalt pavement, the tensile strains at the bottom of the asphalt layer were taken as the index which controlled fatigue cracking of the asphalt pavement, the different-depth pavement temperatures and the strain response values at the bottom of asphalt layer of five perpetual pavement structures were measured by installing the temperature sensors and asphalt strain gages in the pavement. Based on the correlation analysis of the two values, the design temperature for the fatigue failure of asphalt pavements were determined, taking the mid-depth pavement temperature as the design temperature and the test specification for the analysis of the fatigue failure of asphalt pavements. Hourly pavement temperatures and meteorological data were measured in the Shandong Perpetual Pavement, and the distribution of mid-depth pavement temperature was studied, through calculating and analyzing the correlation between the mid-depth pavement temperatures and air temperature, the prediction model of the mid-depth pavement temperature was put forward. The results showed that the value of strain response of asphalt pavement is closely related to the pavement temperature, the maximum tensile strain increases with increasing pavement temperatures; It had a good accuracy correlation coefficient between the mid-depth pavement temperature and the tensile strain at the bottom of asphalt layer, it can better assess the ability of anti-fatigue failure by using the mid-depth pavement temperature, and provide a reliable basis for the temperature parameter to improve the accuracy of analysis of pavement structure.

KEY WORDS: road engineering, design temperature, correlation analysis, perpetual pavement, tensile strain, prediction model, fatigue failure.

Asphalt mixture is one of typical temperature-sensitive materials, its mechanical properties and pavement performance fluctuated greatly with temperature changed. Pavement temperature appears non-uniform distribution with the depth below the surface, which brings great difficulties to pavement structural analysis. Fatigue cracking is one of the common failure modes of asphalt pavements, its damage mechanism and development process are closely related to the distribution of pavement temperature field (NCHRP 1-37A, 2004). Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTJ 052—2000) makes the failure stiffness modulus as the evaluation of the design parameters of low-temperature failure, which takes 15°C as test temperature. As is known, the temperature of asphalt pavement changes with time, the use of the fixed temperature to predict fatigue life of asphalt pavement can not correctly evaluate the anti-fatigue properties of pavement structure. It will result in great differences between the predicted and measured. The Climatic-Material-Structure Model (CMS Model) developed at the university of Illinois, which simulates environmental conditions controlling temperature...

Fatigue failures caused by repetitive loading generally begin with the bottom of the asphalt mixture layer and thus to move upwards. Researches reported that the average temperature of asphalt pavement served as the representative temperature used to calculate fatigue equivalent temperature (NCHRP 1-37A, 2004), or directly adopted the bottom temperature of asphalt layer as the fatigue equivalent temperature to evaluate the anti-fatigue performance of asphalt pavement. But the above methods have lacked theoretical basis and they cannot truly reflect the actual working conditions of pavement structure. Therefore, Based on fatigue failure characteristics of asphalt pavement to determine the design temperature for reflecting the anti-fatigue performance, mid-depth pavement temperature prediction model was presented based on the measured pavement temperatures of different depth below the surface and weather station observation data, it will provide basis for the dynamic response analysis and fatigue failure of asphalt pavements.

1 METHODOLOGY

1.1 Pavement structure design

China’s Perpetual Asphalt Pavement was located in the west suburb of Binzhou city in Shandong Province, China. It was designed for 2 lanes in design direction, the total width of the pavement is 24m. The test road has total length of five kilometers and is divided into five sections, each section is designed with different material combination and thickness, Figure 1 shows the detailed layout of test sections.

![Figure 1. Pavement Structure of China’s Perpetual Pavement Test Sections](image)

1.2 Pavement sensors installation

In order to evaluate the actual strain response, Asphalt Strain Gauges (ASG-152) of NCAT were selected as the pavement strain sensors. Asphalt strain gauges were installed at the bottom of the asphalt layer before asphalt mixture paving in five sections, The layout of sensors group were shown in figure 2 (Timm et al, 2004). The embedded strain gauges were used to measure the tensile strain response under live truck loading and environmental factors. Data of pavement mechanics response under moving truck was collected at the rate of 2000 points per second. In general, tensile strain responses were collected by controlled load vehicle testing in different season in one year. Then tensile strain responses were obtained corresponding to different pavement temperatures.
Pavement temperature has a large effect on tensile strain of asphalt layer, but pavement temperature changes with depth and time. Selecting an equivalent temperature is important for analyzing and comparing mechanic response of asphalt pavement. In this experiment, temperature was measured at four depths at each section. Four temperature gauges were installed in the AC layers by drilling temperature holes and installing a bunch of temperature gauges with pre-set intervals, for example, pavement temperature gauge at surface, and 25mm, 50mm, and 58mm for S1. Temperature gauges were used to measure the pavement temperatures in different depth below pavement surface with a certain frequency, such as 30min. The depth of each thermocouple in the asphalt layer was shown in Table 1.

Table 1: Depth of each thermocouple sensors below pavement surface, cm

<table>
<thead>
<tr>
<th>Temperature gages</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>T2</td>
<td>25</td>
<td>19</td>
<td>19</td>
<td>16</td>
<td>7</td>
</tr>
<tr>
<td>T3</td>
<td>50</td>
<td>32</td>
<td>32</td>
<td>35</td>
<td>14</td>
</tr>
<tr>
<td>T4</td>
<td>58</td>
<td>40</td>
<td>40</td>
<td>45</td>
<td>22</td>
</tr>
</tbody>
</table>

Figure 2. Sections S1 to S5 high speed sensor layouts

2 DATA ACQUISITION AND ANALYSIS

2.1 Selection of a representative pavement temperature for fatigue failure

Pavement temperature has a large effect on tensile strain of asphalt layer, but pavement temperature changes with depth and time. Selecting an equivalent temperature is important for analyzing and comparing mechanic response of asphalt pavement. In this experiment, temperature was measured at four depths. The most appropriate temperature was selected as the one to correlate the best to measured strain.

The value of strain response of asphalt pavement structure and pavement temperature are closely related, but at different depths of the pavement structure, the fluctuation of temperature is different from the road surface, the deeper the measuring point is, the smaller fluctuation is (Straub et al, 1968). Selecting a representative temperature is important for analyzing and comparing mechanic response of asphalt pavement. The representative value of the pavement temperature and maximum strain values should be of a good correlation.
To compare the correlation between the maximum longitudinal strain and the pavement temperature at different depths, a truck with 540kN tridem axle load was selected as the testing truck and used to test in different pavement temperature. Figure 3 showed the correlation between different depths pavement temperature of structure S1 and maximum longitudinal strain. The results of regression analysis were shown in Table 2. Regression analysis shows that the mid-depth pavement temperature (T2) is closely related to the maximum longitudinal strain. Therefore, the mid-depth pavement temperature is defined as the representative temperature to compare and analyze the asphalt pavement structural responses.

\begin{align*}
T1 : y &= 8.4049e^{0.0353x} \\
R^2 &= 0.9235 \\
T2 : y &= 8.6608e^{0.0429x} \\
R^2 &= 0.97 \\
T3 : y &= 8.5284e^{0.0529x} \\
R^2 &= 0.955 \\
T4 : y &= 8.3658e^{0.0548x} \\
R^2 &= 0.943
\end{align*}

Figure 3. Relation of pavement temperature and strains at the bottom of asphalt layer

<table>
<thead>
<tr>
<th>Structure</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.924</td>
<td>0.97</td>
<td>0.955</td>
<td>0.943</td>
</tr>
<tr>
<td>S2</td>
<td>0.794</td>
<td>0.867</td>
<td>0.845</td>
<td>0.80</td>
</tr>
<tr>
<td>S3</td>
<td>0.789</td>
<td>0.851</td>
<td>0.835</td>
<td>0.786</td>
</tr>
<tr>
<td>S4</td>
<td>0.708</td>
<td>0.840</td>
<td>0.701</td>
<td>0.654</td>
</tr>
<tr>
<td>S5</td>
<td>0.882</td>
<td>0.872</td>
<td>0.869</td>
<td>0.861</td>
</tr>
</tbody>
</table>

2.2 Distribution of mid-depth pavement temperature

According to the measured hourly pavement temperature and meteorological data on June 25, 2008, daily-hour changing curve of asphalt pavement temperature and air temperature was obtained, shown in Figure 4. As can be seen from Figure 4, mid-depth pavement temperature showed the similar trend with air temperature, due to heat conduction from surface to bottom will take some time, as the depth increases, the impact will gradually weakened, daily changing differences become smaller and smaller, and hysteretic characteristic increased gradually, pavement temperature distribution curves of different depth and different layers have a phase difference, 1 hour for air temperature, 3–5 hours for temperature at the bottom of the pavement, and 2~4 hours for the mid-depth of the asphalt layer.
Pavement temperature changing cycle is usually adopted one year, the distribution of pavement temperature was analyzed by hourly temperature, and frequency distribution of hourly pavement temperature in test road was shown in Figure 5. We can make certain of the distribution of air temperature and the pavement temperature in the mid-depth pavement temperature, and the proportion of a certain temperature range in one year. On the basis of the distribution of hourly pavement temperature, cumulative damage method can be used to analyze the required PG grade of asphalt for different functional structural layer of pavement structure; it can also be used to calculate permanent deflection or fatigue failure of asphalt pavement, so as to establish new pavement design method.

2.3 Pavement structural response analysis

Pavement structure bears different stress and strain state under repeated wheel loading, due to the compressive strength of asphalt pavement materials is much larger than the tensile strength, while the tensile stress at the bottom of the asphalt pavement is larger than that of surface. Thus, under repeated wheel loading, in general, asphalt pavement fatigue cracking began to occur from the bottom to top. Research and analysis showed that fatigue failure of flexible asphalt pavement is closer to the constant strain fatigue state, considering the foreign asphalt pavement design methods commonly used the tensile strain at the bottom of the pavement as a control index of fatigue failure, this paper adopted the tensile strain at the bottom of the asphalt layer as the control index to prevent fatigue cracking.
The temperature in the mid-depth pavement temperature and tensile strain at the bottom of the asphalt layer were measured separately from the five test sections, shown in Table 3.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Mid-depth pavement temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>S1</td>
<td>13.4</td>
</tr>
<tr>
<td>S2</td>
<td>25.9</td>
</tr>
<tr>
<td>S3</td>
<td>31.5</td>
</tr>
<tr>
<td>S4</td>
<td>13.3</td>
</tr>
<tr>
<td>S5</td>
<td>37.2</td>
</tr>
</tbody>
</table>

As can be seen from Table 3, tensile strain at the bottom of asphalt layer was affected by temperature greatly; tensile strain at the bottom of asphalt pavement increased with increasing pavement temperature. The higher pavement temperature is, the larger tensile strain at the bottom of the asphalt layer is. For example, when pavement representative temperature grew from 20°C to 30°C, the tensile strain of perpetual pavement structure of S1 increased 11.5 με, however, when temperature grew from 30°C to 40°C, tensile strain increased 17.8 με. According to the field data, the tensile strain of the four kinds of flexible base asphalt pavement structure was seldom greater than 70 με except semi-rigid base asphalt pavement structure of S5; at high temperature range, the maximum tensile strain was usually not more than 100 με. Semi-rigid base asphalt pavement structure of S5 has the strongest sensitivity to temperature, pavement temperature is above 30°C, the tensile strain grew faster. These results will help us correctly understand and analyze early damage of asphalt pavement in China in recent years.

2.4 Multi-layer linear elastic analysis

Asphalt mixture is a typical temperature-sensitive material, its strength and modulus varies with temperature, in the high temperature range, it shows a visco-plastic properties, but at low temperature range, it appears a behavior of elastic properties (Christison, 1972). In order to take into account the elastic properties of the pavement in low temperature areas, test section S2 is used to analyze and divided into two layers-Asphalt layer and non-asphalt layer, shown in figure 6. Asphalt layer takes dynamic modulus as parameter for response calculation. The dynamic modulus of hot mixture asphalt were measured with NCHRP 1-37A Test Method DM-1 (Standard Test Method for Dynamic Modulus of Asphalt Concrete Mixtures, 2002), Non-asphalt layer is the foundation of asphalt layer and it takes equivalent resilient modulus as parameter for strain response analysis. Equivalent resilient modulus of foundation was determined by FWD back-calculation. Equivalent resilient modulus of foundation and dynamic modulus of asphalt layer of different temperature were shown in table 4, which were taken as the input parameters for Bisar3.0. Axle load parameters were adopted Chinese standard axle load, as is shown in Table 5. Based on the linear elastic theory, strains at the bottom of the asphalt layers of S2 were calculated with Bisar3.0, shown in Figure 7. As can be seen, the strains go up as the temperature increases based on multi-layer linear elastic analysis of the pavement structure under the loading.
Figure 6. Schematic diagram of strain response analysis for structure S2

Table 4: Dynamic modulus of HMA and foundation for BISAR3.0, MPa

<table>
<thead>
<tr>
<th></th>
<th>E 0°C</th>
<th>E 5°C</th>
<th>E 10°C</th>
<th>E 15°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMA</td>
<td>41528</td>
<td>28944</td>
<td>20173</td>
<td>14060</td>
</tr>
<tr>
<td>Foundation</td>
<td>570</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Input parameters for load

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axle load standard</td>
<td>BZZ-100</td>
</tr>
<tr>
<td>Axle load</td>
<td>100KN</td>
</tr>
<tr>
<td>Single wheel load, P (KN)</td>
<td>25</td>
</tr>
<tr>
<td>Diameter (cm)</td>
<td>21.3</td>
</tr>
<tr>
<td>Tire pressure, p (MPa)</td>
<td>0.7</td>
</tr>
<tr>
<td>Distance between center point</td>
<td>31.95</td>
</tr>
<tr>
<td>of the equivalent circle (cm)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7. Calculated strain responses

3 PREDICTION MODEL FOR MID-DEPTH PAVEMENT TEMPERATURE

The FHWA integrated model (Lytton et al, 1990) integrates three previously developed models, with some modifications, to investigate the environmental effects on the pavement. SHRP developed the maximum surface pavement temperature model that use parameters of latitude and air temperature. In this paper, mid-depth pavement temperature prediction model is based on the factors of depth and air temperature.

Based on the 8760-hour temperatures of the mid-depth pavement temperature and meteorological data on test section in 2008~2009, regression analysis showed that the pavement temperature in the mid-depth pavement temperature and air temperature agree with a good linear relationship, correlation coefficient $R^2$ was 0.902. If we used quadratic polynomial regression, correlation coefficient $R^2$ was 0.8964, as shown in Figure 8. The above analysis showed that the prediction model was of a square correlation coefficient.
As for periodical changes in pavement surface temperature and heat exchange within the
pavement, the pavement temperature along the depth is very complicated (KAGN et al, 2007). Figure 4 showed the typical pavement temperature distribution in one day, the points in Figure 9 showed that temperature changed with the depth of the pavement. Using polynomial regression for pavement temperature distribution along the depth, the results showed in Figure 9, as shown in solid line. Clearly, pavement depth \((H)\) of the cubic polynomial had the most accurate simulation of the pavement temperature field.

With the increase in pavement depth, the pavement temperatures were affected gradually
weakened by air temperature, so we introduced the products of air temperature and
pavement \((T_aH)\) depth into the prediction model to reflect the influence degree of
environment factors. Based on the above considerations and application of the
convenience, mid-depth pavement temperature \((T_{mp})\) can be expressed as air temperature
\((T_a)\) and the depth \((H)\) function, that is

\[
T_{mp} = a_1 + a_2T_a + a_3T_aH + (a_4H + a_5H^2 + a_6H^3) \quad (1)
\]

Where, \(T_{mp}\) is mid-depth pavement temperature, \(\circ C\); \(T_a\) is air temperature, \(\circ C\); \(H\) is the
depth from the surface, cm; \(a_1\sim a_6\) is the undetermined regression coefficient.

Multiple regression analysis for mid-depth pavement temperature \((T_{mp})\) and air temperature
\((T_a)\), and depth \((H)\), derived a empirical formula for mid-depth pavement temperature
based on air temperature and depth using least square method, such as the formula (2),
Table 6 is the regression results for prediction model. The regression coefficients have
reached a higher level; the prediction model has a higher accuracy.

\[
T_{mp} = 1.576 + 1.138T_a - 0.007T_aH + (0.06H + 0.0000383H^2) \quad (2)
\]
Table 6: Results of regression analysis

<table>
<thead>
<tr>
<th>$R$</th>
<th>$R^2$</th>
<th>$R_{adj}^2$</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.946</td>
<td>0.896</td>
<td>0.896</td>
<td>3.505</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS

(1) To take tensile strain at the bottom of the asphalt layer as the design indexes of controlling fatigue cracking of asphalt pavement. The maximum tensile strains at the bottom of the asphalt layer were measured under different pavement temperatures on test pavement sections. The tensile strains at the bottom of the asphalt layer were affected by temperature greatly, it showed the same change characteristic, and in general, it increased with increasing the pavement temperature. The tensile strain at the bottom of the asphalt layer showed strong temperature sensitivity, the higher the temperature is, the faster it is.

(2) The mid-depth pavement temperature was closely related to the maximum longitudinal strain, so taking the mid-depth pavement temperature of the asphalt layer as the design temperature for fatigue failure of pavement structure.

(3) Based on the measured pavement temperature field and local meteorological data, the correlation analysis was conducted on the influencing factors, and developed a temperature prediction model for mid-depth pavement temperature.

(4) Because of the limitations due to geographical position and statistical analysis technique, when the prediction model was applied into other areas, it should be calibrated or revised according to the local data.

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