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Temperature Prediction Model for Asphalt surface Layer

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Abstract. In order to explore the distribution law of asphalt pavement temperature, based on the Nanjing to Yancheng(Ning-yan) Expressway in Jiangsu Province, and obtain the meteorological environment data of the expressway, temperature sensors are buried at different depths of the asphalt pavement to continuously track the temperature at different depths of the asphalt pavement and the atmospheric temperature. The relationship between pavement temperature and meteorology at different depths was analyzed. According to the pavement depth, a temperature prediction model suitable for asphalt surface layer was established, and the model predicted temperature was compared with the measured temperature.The results show that the temperature-time distribution of asphalt pavement surface has a significant periodicity, which is an approximate sine function curve. In the error range of ± 1 ℃, the accuracy of the asphalt surface temperature prediction model is 64.1 %.

Keywords: Pavement temperature; Pavement temperature prediction model; Pavement surface

1. Introduction

Asphalt paving is exposed to the external environment and suffers from various natural cycles [1], which leads to various defects. Temperature cracks are a serious defect of asphalt paving in China [2]. Under different temperature conditions, the asphalt mixture exhibits different performances, and the failure modes are also very different. The high temperature in summer causes fluidity of the mixture, and combined with the impact of driving loads, leads to rutting of the road. The temperature in the winter plummets, and the temperature rises and falls alternately on a daily cycle, causing temperature cracks in asphalt pavements [3-5]. In view of the close relationship between strength, stability, failure mode and temperature of an asphalt mixture, it is of great significance to explore the prediction of temperature distribution in asphalt paving.

Since the Arlington pavement temperature collection in the United States, researchers have been studying the temperature of pavement structures, mainly using theoretical analysis and mathematical statistical analysis as research methods [6-7]. Based on BELLS and BELLS2, long-term pavement performance(LTPP) testing model proposed the BELLS3 temperature prediction model, which solved the problem that BELLS overestimated the lower temperature and underestimated the higher temperature of a pavement. However, the predicted model is not widely applicable because the temperature data is based on the United States and Canada[8-9].Sun Lijun et al established a temperature prediction model based on three representative regions of Tangshan, Urumqi and Shanghai, and revised the prediction results according to different climatic conditions [8,10-11].

Although a great deal of research into pavement temperature has been carried out at home and abroad, and temperature prediction models have been established, they do not have universal applicability.[12-14]. As the thickness of the surface layer of an expressway in China is generally about 20cm, the inconsistency of the thickness causes a difference of the internal temperature distribution in the asphalt paving. At the same time, the internal temperature change law in asphalt paving with different structures is also different.

The temperature field data is collected form a test section of the Ning-yan Expressway in Jiangsu Province in this paper. The temperature variation of asphalt surface under different weather conditions is discussed in this study. Thus, a temperature prediction model for Jiangsu Province is established to determine the temperature change trends in asphalt paving and guide future pavement design.

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2. Analysis of pavement temperature field

2.1 Pavement temperature field data acquisition devices and methods

The research relies on the Jiangsu Ning-yan Expressway, which connects the Huanghai Sea Economic Belt with other economic hinterlands. The typical pavement structure used in this road section is shown in Figure 1.

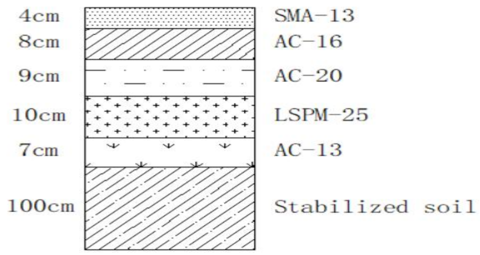

Figure 1. Pavement structure of the test section.

The road section is in the hot summer and cold winter zone. With the frequent changing of the internal temperature of the asphalt pavement, the pavement defects are more serious under the combined action of vehicle load and temperature stress. To study the internal temperature change with the asphalt pavement structure, this paper uses various methods to collect data from the test section, including a bottom thermocouple temperature sensing line, surface temperature sensor and infrared thermometer. The temperature acquisition equipment and the burying methods are as follows:

1） The bottom layer uses a waterproof thermocouple temperature sensor with an accuracy of ±1 °C (K-type Longyuxin DS18b2). It can be connected to the data collector to collect the temperature values of the pavement at different times and depths. The thermocouple temperature line used in this study is buried in the bottom layer of the pavement, and the branch temperature probes are upwardly placed at 1cm and 2cm, respectively, and downwardly placed at 2cm, 3cm and 4cm to accurately obtain the temperature of the different structural layers. To ensure the safe placement of the temperature sensor and the subsequent construction work, the metal strips are first placed in the position to be buried, then the bottom layer temperature sensor is placed in the grooves which are rolled on the steal and the asphalt concrete is used as the gasket. Finally, the asphalt concrete is covered and buried.

2）The sensor used for the temperature collection of the pavement surface layer is consistent with that described above. After determining the buried position of the surface thermocouple, it is ensured that the holes’ depth is consistent with the buried depth of the sensor when drilling the hole. After the hole is cleaned, it is ensured that the thermocouple is in close contact with the bottom of the hole when the thermocouple is buried in the hole with backfill materials. Finally, the hole is sealed with glass glue to prevent moisture from penetrating. The sensor is buried as shown in Figure 3.

3）The temperature of the surface layer is collected by optris's mini plus infrared temperature gun, which has a range of -32° C to 530° C and its precision is within ±1° C. Studies have shown that atmospheric temperature, heat exchange and radiation are the main factors affecting road surface temperature [15]. Therefore, a meteorological acquisition system is used to collect atmospheric temperature and radiation conditions. The MEP pavement temperature acquisition system is used to collect the ambient temperature at a resolution of 0.1s with a response time of 0.5s. After collecting the temperature, the system distinguishes the points and storage data. The MEP pavement temperature acquisition system is shown in Figure 3.

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The temperature is collected throughout the whole year. Data including the air temperature, the temperature of the road surface and the temperature of different depths of the pavement are used to analyze the temperature of the asphalt pavement and establish the temperature prediction model of the highway in Jiangsu Province according to the temperature distribution characteristics.

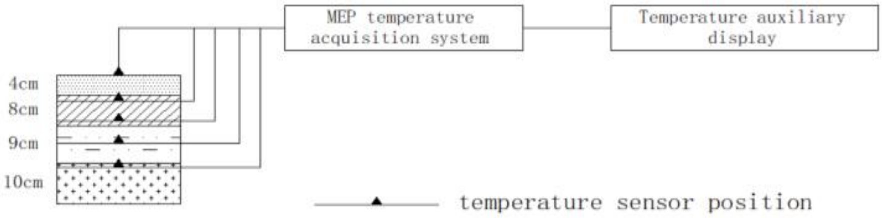

Figure 3. Data acquisition and temperature sensors.

2.2 Pavement surface temperature field data acquisition

According to the measured temperature field data of the asphalt pavement of Jiangsu Ning-yan Expressway, the temperature changes in the surface layer under different weather conditions are plotted, as shown in Figure 4.

From Figure 4, it can be concluded that the temperature change of the pavement surface is similar to the air temperature change trend, showing a slight lag, and the pavement surface temperature is higher than the atmospheric temperature.

Figure 4(a) shows the temperature variation of the pavement at different depths on a sunny day. The internal temperature of the asphalt pavement structure begins to heat up due to radiation. After the radiation is weakened in the afternoon, the temperature of the asphalt pavement begins to decrease. When comparing the internal temperature change of the asphalt pavement layer at a depth of 10cm, 16cm and 22cm, it can be seen that the closer to the pavement surface, the more sensitively the internal temperature of the pavement is affected by radiation. Due to the drop in atmospheric temperature, the internal temperature of the pavement drops significantly, and the temperature at the depth of 16cm is lower than the air temperature. Thereafter, the temperature of the Large Stone Porous asphalt Mixture(LSPM) flexible base layer is higher than the temperature of the pavement layer until the next temperature change cycle.Figure 4(b) shows the temperature change of the asphalt pavement at different depths on a cloudy day. The temperature of the pavement is greatly reduced compared with the sunny day. The temperature fluctuation of the asphalt pavement is not large and the temperature differences at the various depths are small. The temperature change of the asphalt pavement after rainwater is shown in Figure 4(c).

In summary, the pavement temperature has an obvious rise and fall phenomenon with large temperature fluctuation under a sunny state, and the temperature fluctuation curve is similar to the sinusoidal function curve. However, on cloudy days, rainy days , the temperature of the pavement has no obvious rise and fall, and the overall temperature of the pavement has a small fluctuation range.

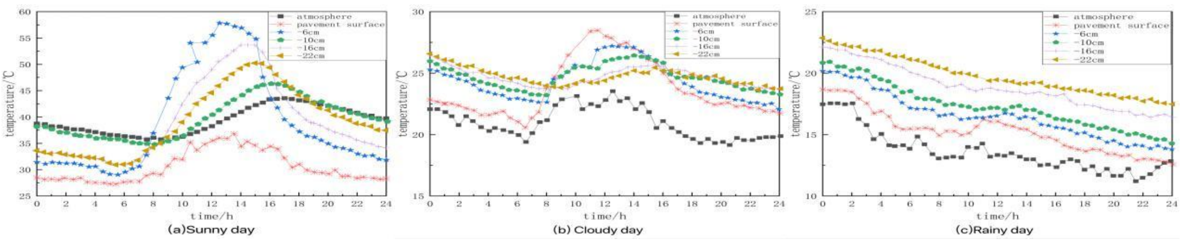

Figure 4. 24-hour pavement temperature variation curves under different weather condition

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The pavement undergoes temperature changes in a short period of time, and temperature stress of the pavement structure occurs, generating temperature fatigue cracks. It is of great significance to study the temperature variation and distribution of asphalt surface layer and to optimize the design to control temperature fatigue cracking.

3. Establishment of surface temperature prediction model

According to the above temperature field data, the temperature distribution of the middle and upper layers can be obtained, showing approximately the sinusoidal function, which is basically consistent with the related research results [26]. From the measured data, the daily temperature of different months is converted into a sine function value between 1 and -1 to establish the temperature function of asphalt paving. SPSS is used to establish the time curve function, as shown in Equation 1.

$$F(t) = \sin(-3.3252t + 7.69) \quad (1)$$

In the formula: F（t）is time function value; t=T/24, T is 24-hour time.

The temperature sine distributions of each month do not exactly match the representative time function. The sinusoidal function coefficient is introduced for correction. Considering the internal temperature differences of asphalt paving caused by the different pavement surface temperatures, atmospheric temperature and depth, other correction parameters are added to accurately estimate the pavement temperature.

$$\begin{aligned} T_d &= f(t)[2.42 + T_{air}(-0.10 + 0.002I_R + 0.243\log(d))] \\ &+ \log(d)[I_R(-1.41 + 0.002T_{air} - 0.13f(t)) + (1.01 + 1.449T_{air}) \\ &-2.012T_{air} + 2.811IR - 1.16 \end{aligned}$$

Where: Td is predicted temperature of pavement at depth d; Tair is atmospheric temperature at measuring time t; IR is surface temperature measured by Infrared gun; d is depth of predicted temperature.

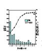
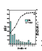
After the establishment of the surface layer temperature prediction model, this study explores the effective prediction depth of the model. The prediction results of different depths and the measured statistics are shown in Table 1. From Table 1, it can be concluded that within the 95% confidence interval, as the predicted depth increases, the prediction error also increases. The pavement surface layer temperature distribution gradually changes to the temperature distribution of LSPM base layer when the predicted depth is below 10cm. It can be concluded that the prediction model is not applicable beyond a depth of 10cm. Therefore, the established model is suitable for temperature prediction of the middle and upper layers of asphalt paving only.

Table 1. Prediction results at different depths.

Prediction depth(cm)	95% Confidence interval	Decision coefficient, R2
2	±2.0	0.96
4	±3.0	0.94
6	±3.0	0.94
8	±3.5	0.92
10	±4.0	0.89
12	±4.5	0.86

To verify the accuracy of the established prediction model, taking the temperature data collected as an example, the BELLS3 proposed by LTPP is used. The BELLS3 estimation model is shown in Equation 3:

$$\begin{aligned} T_d &= 0.95 + 0.892 \times I_R + [\log(d) - 1.05] \times [-0.448 \times I_R + 0.621 \times (1 - D) \\ &+ 1.83 \times \sin(h_{18} - 15.5)] + 0.042 \times IR \times \sin(h_{18} - 13.5) \end{aligned}$$

=T/24*18，（T is 24-hour time，if T is 13:30，=13.5/24*18=10.125）

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The conversion of time parameters is based on the calculated method summarized in a previous paper [17]. The temperature error analysis of the pavement predicted by BELLS3 is shown in Figure 7. Compared with the prediction model established in this paper, the prediction points of the error in the range of 0° C significantly reduce, the prediction points of the error in the range of 0~1° C and 1~2° C are basically the same, and the prediction points of the error in the range of 2~3° C have increased obviously, which shows that the applicability of the model established for this region in this study is stronger than BELLS3. The reason is that the model established by BELLS3 adopts parameters from foreign climatic condition; the BELLS3 model is not targeted at temperature prediction of paving in Jiangsu Province. Therefore, based on the climate, radiation and heat exchange conditions in Jiangsu, the predicted results of the temperature prediction model established in this study are closer to the measured results.

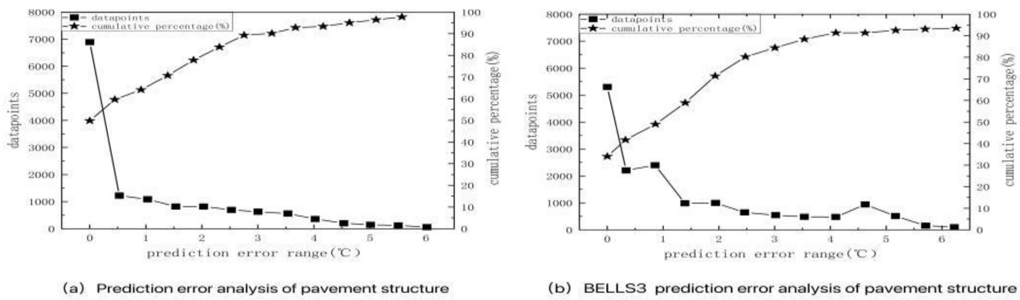

Figure 7. prediction error analysis of pavement structure.

The parameter settings are the same as for the pavement surface temperature prediction model, including road surface temperature, atmospheric temperature, time function, and predicted position depth. The temperature prediction model for the LSPM flexible base is shown in Equation 4.

$$T_d = -0.259T_{air} + 0.470T_{air}\log(d) + 0.057I_RT_{air} - 0.023I_RT_{air}\log(d) + 0.0741I_R\log(d)$$
$$+I_R(-2.54\times10^{-8}t^6 + 2.11\times10^{-5}t^4 - 0.004t^2 - 0.008t)$$

The error analysis of the prediction model is plotted in Figure 10. The statistical results show that within the range of ±4° C in the 95% confidence interval, the error in the range of 0° C is 59.1%, the error in the range of 0° C ~1° C accounts for 12%, the error in the range of 1 to 2° C accounts for 14%, and data with an error of 2 to 3° C accounts for 7.9%. It can be found that the data within ±2° C error can reach 85.1%. Therefore, it is considered that the model can accurately predict the internal temperature of the asphalt flexible base layer.

4. Conclusion

1. The asphalt pavement temperature and atmospheric temperature change almost synchronously and periodically, but the road surface temperature change lags slightly. The change rule of surface temperature is approximate to sine time function curve.

2. In this paper, the time parameter function is determined according to the surface temperature distribution law, and the surface temperature prediction model is established. The predicted depth range of the surface temperature prediction model is within 10 cm below the surface of the asphalt pavement, suitable for medium and upper layers with high sensitivity

3.The temperature prediction model established in this paper is only applicable to sunny days and rainy days. The next step will be to study the prediction model of rainy days and winter cold weather, and provide guidance for asphalt pavement disease analysis.

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