Study on Temperature Field of Asphalt Pavement in Tongliao, Inner Mongolia

Yiluo Zhang, Xuechao Dong, Jiawei Wang, Ning Li

1Key Laboratory of Highway Engineering in Special Region of Ministry of Education, Chang’an University, Xi’an, China
2CHINA DESIGN GROUP CO., LTD., Nanjing, China

Abstract—In view of the special geographical landform, complex climate and serious influence of climate on roads in Inner Mongolia Autonomous Region, by studying the temperature field of asphalt pavement in Tongliao, Inner Mongolia, the respective characteristics and differences of the temperature distribution of asphalt pavement structure are obtained in this paper. The results show that the road surface temperature of the asphalt pavement in Tongliao, Inner Mongolia has a correlation with the atmospheric temperature, especially in spring and autumn. With the increase of the depth of pavement structure, the correlation between temperature and atmospheric temperature gradually becomes weaken, and it is basically out of the variation regularities of temperature at the pavement base.

1. INTRODUCTION

For highway engineering construction, climate factors affect the whole life cycle of the road. The study of temperature field is the most important part of studying the effect of climatic factors on the pavement structure. It reflects the correlation between the atmospheric temperature and the temperature of the pavement structure layer, thereby guiding the design of the pavement structure. Since the 1950s and 1960s, foreign scholars have studied the temperature field. In 1957, Barber assumed that the road structure was a semi-infinite body, affected by two major factors, atmospheric temperature and radiation, and used a formula to calculate the highest pavement surface temperature. The prediction formula of the pavement temperature field was obtained through related calculations which found that due to the parameters, the derived formula is only suitable for high temperature prediction, not low temperature prediction [1]. In 1988, the US SHRP plan pointed out that at high temperatures, the pavement surface temperature is mainly affected by atmospheric temperature, but also includes factors such as solar radiation and heat exchange. After many calculations and verifications, the relationship between latitude and the temperature of each structural layer of pavement is finally obtained. At the same time, in 1994, the prediction model derived by Huber was adopted [2][3]. In 1982, Yan Zuoren summed up the shortcomings of previous studies on the temperature field. Taking the difference of heat conduction capacity of different base materials as the breakthrough point, the solution of temperature field under various boundary conditions was systematically and completely studied by using heat conduction equation and theoretical calculation method. [4]. In 1992, Wu Ganchang analyzed the shortcomings of the statistical analysis method and the theoretical method. He believed that the...
temperature field should be regarded as two-dimensional, and the influence of various boundary conditions should be considered in the model calculation. The calculation model was derived through a series of formulas, and the engineering example was selected for testing [5]. By 2016, Liang Xuewen conducted a temperature measurement study on a representative road section of a city, and regressed the relationship between temperature and structural layer temperature in different temperature change stages after sunrise and sunset by least square method, and verified the accuracy of the prediction model [6].

The Inner Mongolia Autonomous Region is located in the northernmost part of China, with an area of 1.183 million square kilometers, accounting for one third of the national area. However, it is not concentrated in one area, but distributed in a narrow semi arc form from northeast to southwest, with a straight line distance of more than 2400 km from east to west, spanning northeast, North and Northwest China. In recent years, there has been an increasing number of engineering constructions in this area, and serious road damage has occurred in the early stage of the project, but the research in this area is scarce. In this paper, by studying the temperature field of the asphalt pavement, the regression model of the temperature field is predicted, and the characteristics and differences of the temperature distribution of the asphalt pavement structure in the eastern part of Inner Mongolia are truly and objectively understood and studied.

2. Temperature Field Measurement

2.1. Selecting an observation location

Three temperature sensors were selected as observation points in Tongliao City in the east to observe and record representative pavement surface temperature in summer and winter. The specific location is a total of 6 sets at K201+200, K201+300, K201+500, K201+600, K201+800, K201+900 downstream of the G2511 Tonglu Expressway. Among them, K201+100~K201+700 in the downward section of G2511 Tonglu Expressway are the ATB flexible pavement test section. The test section is paved with two structural combinations. K201+100~K201+400 are structural combination one, and K201+400~K201+700 is the second structure. The pavement structure combination of the two test sections and other common sections can be seen in Table 1.

| TABLE I. PAVEMENT STRUCTURE COMBINATION OF OBSERVATION LOCATIONS |
|-----------------|-----------------|-----------------|
|                 | Normal section  | Experimental section I | Experimental section II |
| surface layer   |                 |                 |                             |
| 4cmAC-13C       | 4cmAC-13C       | 4cmAC-13C       |
| 5cmAC-16C       | 7cmAC-25        | 5cmAC-16C       |
| 7cmAC-25        |                 |                 |
| base layer      |                 |                 |
| 20cm cement stabilized macadam | 24cmATB-25 | 20cmATB-25 |
| subbase layer   |                 |                 |
| 32cm cement stabilized macadam | 32cm cement stabilized macadam | 38cm cement stabilized macadam |
| total thickness | 68cm            | 67cm            | 67cm                        |

2.2. Observation period

The initial time for burying the temperature sensor is from November 2017 to November 2018, a total of 1 year. During this time, the staff will go to the observation location to read the data and check the integrity of the instrument every 3 months. The frequency of recording temperature data is once every 1 hour.

2.3. Observation horizon

Since the pavement structure surface layer of the observation location is mostly a combination of 4cm+5cm+7cm, the buried layers of the sensor probe are 0cm, 4cm, 9cm and 24cm respectively. Temperature data includes atmospheric temperature, surface temperature and base temperature.
3. ANALYSIS OF TEMPERATURE FIELD VARIATION REGULARITIES OF ASPHALT PAVEMENT IN INNER MONGOLIA

3.1. Analysis of the relationship between temperature and pavement surface temperature in each season

Due to the difference in the length of day and night in different seasons, the solar elevation angle gradually increases from winter to summer, and then gradually decreases. Therefore, solar radiation also has seasonal variability. The relationship between temperature and pavement surface temperature in different seasons can be seen. Now the relationship between the four seasons temperature and the pavement surface temperature at Tongliao observation location is analyzed as an example, shown in Figure 1.

![Temperature of pavement structure at different depths](image-url)
It can be seen from Figure 1 that the pavement surface temperature and the atmospheric temperature change have a great similarity. The temperature trend of the spring and autumn seasons is relatively close to that of the pavement surface temperature, and the temperature is almost the same. The temperature is generally between 0~25℃, and the temperature in spring is slightly higher than the autumn temperature, reaching about 20℃, and the highest temperature in autumn is about 15℃. Observing the temperature changes in winter and summer, it can be seen that the pavement surface temperature is higher than the atmospheric temperature, the temperature difference in winter is 5-8℃, and the temperature difference in summer is 10-15℃. The reason for the analysis is that the specific heat of the pavement material is relatively small, and the temperature rises faster than the atmosphere under the action of solar radiation.

In order to understand the specific low temperature characteristics of the winter observation period, the daily minimum temperature statistics of the observation locations in January are summarized. The specific characteristics are shown in Figure 2.

![Figure 2. Variation trend of minimum temperature and road surface temperature in January.](image)

It can be seen from Figure 2 that during the observation period of January, the temperature at each observation point is generally higher at the beginning of the month, lower in the middle and late sections, and gradually rises at the end of the month. As the pavement structure diseases that have been in a low temperature environment for a long time, the most common manifestation is temperature shrinkage cracks. When the temperature stress is greater than the ultimate tensile strength of the material, cracks will appear. Therefore, when studying the low temperature characteristics of the temperature field, it is of high reference value to select the observation data of the lowest temperature occurrence day in the observation period as the representative. When analyzing the variation regularity of pavement temperature field in low temperature period in winter, January 24 at the observation location of Tongliao was the lowest temperature day in January.

### 3.2. Low temperature variation regularity of each structural layer

The internal temperature of the pavement is mainly affected by changes in the upper air temperature, but due to the different density, specific heat and thermal conductivity of different paving materials, the temperature regularity will be different. The observation data of Tongliao on January 24 were selected for statistical summary to study the variation law of low temperature temperature data of different structural layers, as shown in Figure 3.
Figure 3. Temperature of pavement structure at different depths.

From Figure 3, we can clearly see the temperature variation regularity of asphalt pavement structure at different depths. Atmospheric temperature and pavement surface temperature are in direct contact with air, and the specific heat of air is quite different from that of the pavement material, so the variation range is greater than that of the internal temperature of the pavement structure. At the observation location of Tongliao, the temperature of the atmosphere and pavement surface during the day is greater than the temperature inside the pavement structure. The reason for analysis is that most of the eastern Tongliao area was sunny during the observation period, and only cloudy weather occurred on a few observation days.

At the same time, observing the internal temperature of the pavement structure, it is found that because the heat is gradually transferred from the pavement surface, the internal temperature curve is relatively smooth, and there is no sudden change point. However, due to the thickness of each layer and the time required for temperature transfer, the temperature of the lower structure layer has a significant hysteresis compared with the upper structure.
It is easy to find that after the depth reaches the base layer, the temperature change is relatively gentle, the fluctuation is small, which gradually deviates from the temperature variation law of the upper structure layer. The analysis reason is that the deeper structure layer has less influence when the temperature is transferred to this layer.

Finally, comparing the temperature laws of three different combinations of pavement structures at the Tongliao observation location, it is found that there is no significant difference in the temperature change between the semi-rigid base and the combined base at 0~5 cm, and there is no phenomenon of significant difference heat transfer due to the different materials used. However, with the increase of depth, under the same external environment, the temperature of the two combined pavement structures at 9 cm is about 3 ℃ higher than that of the semi-rigid pavement structure, and the combined pavement structure at 24 cm is higher than the semi-rigid pavement structure about 4~5 ℃. It can be found that under cold conditions, asphalt stabilized macadam material has a certain insulation effect compared with cement stabilized macadam, which can make the temperature difference within the pavement structure smaller than the semi-rigid base pavement.

| Observation locations | Maximum temperature (℃) | Minimum temperature (℃) | Temperature gap (℃) |
|-----------------------|--------------------------|--------------------------|---------------------|
| depth (cm)            | Normal | I | II | Normal | I | II | Normal | I | II |
| 0                     | -4.2   | -3.4 | -4.5 | -32.2  | -29.8 | -31.8 | 28 | 26.4 | 27.3 |
| 4                     | -15    | -14.3 | -15.1 | -25.2  | -26.1 | -22.5 | 10.2 | 11.8 | 7.4 |
| 9                     | -15.9  | -15.3 | -15.3 | -23    | -21.9 | -20.1 | 7.1 | 6.6 | 4.8 |
| 24                    | -16.1  | -16.2 | -13.9 | -19.6  | -17.6 | -15.9 | 3.5 | 1.4 | 2 |

It can be seen from Table 2 that along the depth direction, the lower the structural layer, the smaller the temperature fluctuations within a day, indicating that the internal pavement structure has a certain thermal insulation effect, and the temperature stress received by the surface layer in winter is much greater than that of the internal structural layer.

3.3. Analysis of low temperature temperature change with depth

Based on the measured data of Tongliao on January 24, the temperature curves of different depths and different times of the pavement structure are summarized, and the results are shown in Figure 4.

According to Figure 4, it can be found that the pavement surface temperature changes the most within 24 hours a day, and the temperature fluctuates between -10 ℃ and -30 ℃ in Tongliao observation area. With the increase of depth, the range of temperature change gradually decreases, and within 0-10 cm, the temperature range decreases greatly. Below 10 cm, the temperature range decreases more slowly, and basically decreases linearly. At 24 cm, the temperature change range is only 2-4 ℃.

The internal temperature of the pavement is mainly affected by changes in the upper air temperature, but due to the different density, specific heat and thermal conductivity of different paving materials, the temperature regularities will be different. The observation data of high temperature representative days at the observation points are selected for statistical summary, and the variation regularity of high temperature data of different structural layers is studied, as shown in Figure 5.

From Figure 5, we can clearly see the temperature variation regularity of asphalt pavement structure at different depths. Due to the large amount of solar radiation in summer, when the weather is fine, the pavement structure continuously absorbs heat during the day, which shows that the surface temperature is far higher than the temperature, and even the bottom of upper layer and middle layer near the pavement surface are higher than the atmosphere temperature.
At the same time, observing the internal temperature of the pavement structure, it is found that because the heat is gradually transferred from the pavement surface, the internal temperature curve is relatively smooth and coherent, and there is no mutation point. However, due to the thickness of each layer and the time required for temperature transfer, the temperature of the lower structure layer is obviously lagging behind that of the upper structure.

Figure 4. Temperature of pavement structure at different depths.
The observation shows that when the depth range reaches the base layer, the temperature fluctuation amplitude is relatively gentle and the fluctuation is small, which gradually deviates from the temperature variation law of the upper structure layer. The reason is that the influence of temperature transfer to this layer is small due to the deep structure layer.

Finally, comparing the temperature regularities of the three different combinations of pavement structures at the Tongliao observation location, it is found that there is not much difference in the temperature variation regularities between the semi-rigid base course and the combined base course, and there is no significant phenomenon in heat transfer due to the different materials used. The reason for the analysis is that although the specific heat and thermal conductivity of different pavement materials are different, the temperature imposed on them is only tens of degrees, so the difference in temperature conduction caused by this is also small.

**TABLE III. TEMPERATURE VARIATION RANGE OF PAVEMENT STRUCTURAL LAYER**

| Observation location | Normal | I  | II | Normal | I  | II | Normal | I  | II |
|----------------------|--------|----|----|--------|----|----|--------|----|----|
| Depth(cm)            |        |    |    |        |    |    |        |    |    |
| 0                    | 50.7   | 57.8| 51.5| 26.5   | 25.7| 25.5| 24.2   | 32.1| 26 |
| 4                    | 48.8   | 48.6| 43.9| 29.8   | 29.7| 31.9| 19     | 18.9| 12 |
| 9                    | 42.9   | 44.9| 40.8| 30.1   | 32.3| 32.5| 12.8   | 12.6| 8.3 |
| 24                   | 39.4   | 37.9| 37.1| 32.1   | 32.5| 33.1| 7.3    | 5.4 | 4  |
Figure 6. Variation trend of pavement temperature with depth.

It can be seen from Table 3 that as the road depth increases, the temperature fluctuation range of the structural layer also begins to gradually decrease. Moreover, due to the high solar radiation absorption rate of the road surface in the daytime, the surface temperature rises faster, and the pavement surface temperature difference is large.

3.4. Analysis of high temperature temperature variation with depth

Based on the measured data of Tongliao on July 30, the temperature curves of different depths and different times of the pavement structure are summarized, and the results are shown in Figure 6.

Observing Fig. 6 we can find that the pavement surface temperature changes the most in 24 hours a day, and the eastern observation area fluctuates between 20 and 60°C. With the increase of depth, the range of temperature change gradually decreases, and within 0-10 cm, the temperature range decreases greatly. Below 10 cm, the temperature range decreases more gently and basically linearly. At 24 cm, the temperature changes. The range is only 8~10°C.
4. Regression analysis of measured temperature field

4.1. The relationship between air temperature and pavement surface temperature

4.1.1. Correlation between winter temperature and pavement surface temperature

We collect and summarize the data of the minimum temperature and the minimum road surface temperature in the low temperature observation period, and draw the correlation diagram for correlation analysis. The results are shown in Figure 7.

![Figure 7](image1)

Figure 7. Relationship between temperature and pavement surface temperature in low temperature period.

Through linear regression of air temperature and pavement surface temperature at Tongliao observation location, the correlation coefficient is 0.9385. Therefore, it can be seen that the air temperature and pavement surface temperature have a good correlation, and the fitting formula can be obtained by using the following equation:

\[ T_{0(\text{min})} = 0.9175T_{a(\text{min})} + 1.0894 \]  

where \( T_{0(\text{min})} \) is pavement surface temperature; \( T_{a(\text{min})} \) is maximum temperature.

4.1.2. Correlation between temperature and pavement surface temperature during high temperature period

We collect and summarize the data of the highest temperature and the highest pavement surface temperature during the high temperature observation period, and draw the correlation diagram for correlation analysis. The results are shown in Figure 8.

![Figure 8](image2)

Figure 8. Relationship between temperature and pavement surface temperature in high temperature period.
Through linear regression of the temperature at the observation location and the pavement surface temperature, the correlation coefficient is 0.9319. It can be seen that the temperature at the observation location has a good correlation with the road surface temperature. The fitting formula is as follows:

\[
T_{0\text{\,(min)}} = 1.6538T_{a\text{\,(min)}} - 13.565, \tag{2}
\]

where \(T_{0\text{\,(min)}}\) is pavement surface temperature; \(T_{a\text{\,(min)}}\) is maximum temperature.

### 4.2 Correlation between air temperature and pavement surface temperature

From the analysis of the regularity of the temperature field, it can be seen that there is no obvious difference in the variation characteristics between the daily variation trend and the variation trend along the depth, and the basic trend is the same. In order to research the quantitative difference of the temperature field data of the observation location, the regression is performed to obtain the relationship between the pavement surface temperature and the air temperature, and the temperature within the structure and the pavement surface temperature, as shown in Table 4.

**TABLE IV. PREDICTION MODEL OF TEMPERATURE RELATIONSHIP IN TONGLIAO AREA**

| Pavement surface temperature - air temperature | formula | \(R^2\) |
|---------------------------------------------|---------|------|
| 4cm Temperature - road surface temperature  | \(y=-0.0058x^3-0.344x^2-4.9061x-25.384\) | 0.9895 |
| 9cm Temperature - road surface temperature  | \(y=0.0014x^3+0.0717x^2+1.2728x-11.657\) | 0.9721 |
| 24cm Temperature - road surface temperature | \(y=-0.0046x^3-0.2772x^2-5.0368x-44.411\) | 0.6083 |

| Pavement surface temperature - air temperature | formula | \(R^2\) |
|---------------------------------------------|---------|------|
| 4cm Temperature - road surface temperature  | \(y=-0.0232x^3+1.9935x^2-55.42x+527.75\) | 0.9191 |
| 9cm Temperature - road surface temperature  | \(y=-0.0486x^3+4.6126x^2-143.88x+1511.6\) | 0.8424 |
| 24cm Temperature - road surface temperature | \(y=0.0025x^3-0.2844x^2+10.912x-108.48\) | 0.5739 |

| Pavement surface temperature - air temperature | formula | \(R^2\) |
|---------------------------------------------|---------|------|
| 4cm Temperature - road surface temperature  | \(y=-0.0102x^3-0.6097x^2-9.8756x-52.675\) | 0.9626 |
| 9cm Temperature - road surface temperature  | \(y=0.0019x^3+0.0846x^2+1.3397x-11.169\) | 0.9407 |
| 24cm Temperature - road surface temperature | \(y=0.0013x^3+0.0515x^2+0.9512x-9.2242\) | 0.8689 |
| Depth        | Temperature - road surface temperature | Formula                                      | $R^2$  |
|-------------|-----------------------------------------|----------------------------------------------|--------|
| 24cm        | y=0.0052$x^3$+0.256$x^2$+4.3799$x$+10.67 | 0.5171                                       |        |
| 4cm         | y=-0.0023$x^3$+0.3667$x^2$-13.761$x$+177.13 | 0.9465                                       |        |
| 9cm         | y=-0.0014$x^3$+0.1515$x^2$-4.6929$x$+74.882 | 0.9062                                       |        |
| 24cm        | y=-0.0035$x^3$+0.3787$x^2$-13.26$x$+184   | 0.4414                                       |        |

**Tongliao experimental section I in summer**

| Pavement surface temperature - air temperature | Formula                                      | $R^2$  |
|-----------------------------------------------|----------------------------------------------|--------|
| y=-0.0023$x^3$+0.3667$x^2$-13.761$x$+177.13   | 0.9465                                       |        |
| y=0.001$x^3$-0.1373$x^2$+6.3215$x$-59.371     | 0.9081                                       |        |
| y=-0.0014$x^3$+0.1515$x^2$-4.6929$x$+74.882  | 0.9062                                       |        |
| y=-0.0035$x^3$+0.3787$x^2$-13.26$x$+184      | 0.4414                                       |        |

**Tongliao experimental section II in winter**

| Pavement surface temperature - air temperature | Formula                                      | $R^2$  |
|-----------------------------------------------|----------------------------------------------|--------|
| y=-0.0066$x^3$-0.3945$x^2$-6.0235$x$-34.757  | 0.9599                                       |        |
| y=0.0008$x^3$+0.0341$x^2$+0.5138$x$-14.753   | 0.9362                                       |        |
| y=-0.0042$x^3$-0.2376$x^2$-3.8587$x$-33.849  | 0.8841                                       |        |
| y=0.0121$x^3$+0.5664$x^2$+8.9314$x$+32.994   | 0.4364                                       |        |

It can be seen intuitively from the above table that although the regularities of the previous analysis are roughly similar, there are still great differences in the regression formula of the measured data. From the perspective of the correlation coefficient, there is a good correlation between the pavement surface temperature and the atmospheric temperature, and the 4cm structural layer temperature and the pavement surface temperature have good correlation. As the depth increases, the regularity gradually weakens. When reached the cement stabilized macadam base layer, the data has completely lost the corresponding relationship, which further proves the difference in temperature changes between different material layers.
5. CONCLUSION

- There is a great similarity between the pavement surface temperature and the atmospheric temperature in the four seasons in Inner Mongolia. In the spring and autumn seasons, the temperature and the pavement surface temperature trend are closer, and the temperature is almost equal.
- In cold conditions, asphalt stabilized macadam has a certain thermal insulation effect compared with cement stabilized macadam, which can make the temperature difference inside the pavement structure less than that of semi-rigid base pavement.
- During the low temperature period, as the depth increases, the range of temperature change gradually decreases, and within 0-10 cm, the range of temperature change decreases greatly. Below 10cm, the decrease trend of temperature amplitude is relatively gentle, basically linearly decreasing. When the depth range reaches the base layer, the temperature fluctuation range is relatively gentle, the fluctuation is small, and it gradually deviates from the temperature variation regularity of the superstructure layer.
- During the high temperature period, the eastern observation area fluctuates between 20 and 60°C. As the depth increases, the temperature variation range gradually decreases, and within 0-10 cm, the temperature variation change decreases greatly. Below 10 cm, the temperature range decreases more slowly, and basically decreases linearly. At 24 cm, the temperature variation range is only 8-10°C.
- During periods of high temperature and low temperature, the air temperature has a good correlation with the pavement surface temperature, and the fitting formulas are as follows:
  \[ T_{0\text{min}} = 0.9175T_{a\text{min}} + 1.0894 \]
  \[ T_{0\text{min}} = 1.6538T_{a\text{min}} - 13.565 \]

ACKNOWLEDGMENT

We gratefully acknowledge the valuable cooperation of Xuechao Dong and Jiawei Wang in preparing this Application note.

REFERENCES

[1] Huber, G.A. Weather Database for the SUPERPAVE Mix Design System[C Strategic Highway Research Program, SHRP-A-648A, National Research Council, Washington DC, 1994.
[2] Kennedy, T.W., etal. Superior Performing Asphalt Pavements(Superpave):The Product of the SHRP Asphalt Research Program. Strategic Highway Research Program, SHRP-A-410, National Research Council, Washington DC, 1994.
[3] Huber, G. A. Weather Database for the SUPERPAVE Mix Design System. Strategic Highway Research program [R], SHRP-A-648A, National Research Council, Washington, 1994.
[4] Zuoren Yan. Temperature field analysis of layered pavement system [J]. Journal of Tongji University, 1984(03): 76-85.
[5] Ganchang Wu. Analytical theory of the temperature field of the semi-rigid base asphalt pavement[J]. Applied Mathematics and Mechanics, 1997(02):169-176.
[6] Liang Xuewen. Regression analysis of temperature field distribution of asphalt pavement[J]. Transportation World, 2016(12): 38-39.