Analysis and applicability of road temperature stress behavior in cold area under large temperature difference

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Abstract—In order to understand variation of temperature stress in pavement interior in externe or great cooling climate, the tem- perature stress behavior and structural applicability of three diff- erent base types in cold region were studied. With the help of Ab- aquas software, the temperature stress of the pavement under the environment of large temperature difference of 20℃, 30℃ and 40℃ daily is obtained, and the mechanical response of different base courses under the coupling effect of temperature and dyna- mic load is analyzed. The results show that composite base pave- ment has the best applicability in the cold region with large tem- perature difference. When the daily temperature difference incre- ases by 10℃ in winter, the variation range of road surface,asph- alt base and cement stabilized macadamite top is about 30%~35%, 15%~28% and 41%~50%, respectively. When the da- ily temperature difference increases by 10℃ in summer, the stre- ss increases by 102%~121%, 77%~80% and 18%~21%, respect- vely. The stress increase of composite base pavement is the least. Moreover, it still has advantages under the coupling effect of temperature and dynamic load. To be specific, all the mechanical indexes are small under the coupling effect of low temperature a- nd dynamic load. The shear stress of asphalt layer is better und- er the action of high temperature and dynamic load.

1. INTRODUCTION

The damage of asphalt pavement, such as ruts, low-temperature cracks and reflective cracks of base course, is related to the effect of temperature. The research on temperature stress at home and abroad has made considerable progress, but the behavior and applicability of temperature stress of different base course pavement in cold areas are still less.YanZuoRen [1] assumed that heat transfer was one-dimensional heat conduction only transmitted to the pavement depth. Considering environmental meteorology and heat conduction, the heat conduction equation of the pavement temperature was obtained, and the pavement temperature field prediction model was established. The analytical solution of the obtained temperature field could calculate the pavement temperature field more accurately. Ji- zhong liu [2] applied meteorology and the basic theory of heat transfer, and established the system of the asphalt surface shape of the heat conduction equation, with the aid of finite element computing platform, using orthogonal test method for analysis of the high altitude pavement temperature field and temperature stress of the optimal level, the optimal level combination, influence factors of primary and
secondary order get inversion structure, flexible structure compared with typical semi-rigid base structure can greatly improve the supply temperature uneven phenomenon, reduce the temperature shrinkage phenomenon and can prevent the surface layer, the stress transfer at the grass-roots level, which can prevent the generation of cracks; AI changfa \(^3\) established the plane strain model of pavement with finite element method, discussed the reasonable material thermal property parameters, model size and boundary conditions of the finite element method modeling, and analyzed the correlation between the temperature field change of pavement in alpine region and the above parameters, and obtained the fatigue life of asphalt layer with semi-rigid structure of flexible base asphalt pavement under different temperature and temperature ;Hao Peiwen \(^4\) discussed in detail the change characteristics of elastic modulus and temperature shrinkage coefficient with different temperature reduction amplitude, and established a three-dimensional finite element model of asphalt pavement at low temperature, by analyzing the influence of temperature drop, elastic modulus and temperature shrinkage coefficient on the temperature stress of asphalt pavement, the daily temperature cycle with continuous temperature change and asphalt concrete modulus and temperature shrinkage coefficient changing with temperature are adopted to calculate the temperature field and temperature stress of asphalt pavement, which is more in line with the actual stress condition of pavement structure; Huang Daqiang \(^5\) takes two typical asphalt pavement structures of semi-rigid base and flexible base as the research object, the dynamic performance of asphalt mixture, the temperature behavior of asphalt pavement and the dynamic behavior characteristics of asphalt pavement under the coupling effect of temperature and dynamic load are systematically studied. It is concluded that the stress alternation caused by temperature alternation and the temperature stress field under low temperature condition of pavement structure in alpine region need to be considered emphatically. The temperature stress of graded macadam base is close to 0, and the temperature stress field of asphalt pavement under the coupling effect of temperature and dynamic load is close to 0. It has excellent adaptability to temperature change and is the preferred base material type in alpine region.

To sum up, many scholars only discussed the law of pavement temperature stress in different pavement structures under typical climate conditions, but ignored the change of pavement internal temperature stress under extreme or large cooling climate environment. Therefore, this paper takes the temperature characteristics of Tongliao region in Inner Mongolia as the representative climate of the cold region. Firstly, the temperature stress changes of different pavement structures under the daily temperature difference of 20 °C, 30 °C and 40 °C will be studied, and the temperature field of asphalt pavement under the condition of continuous periodic varying temperature in the cold region will be simulated by using the finite element calculation software Abaqus. Then the sequential coupling method is used to obtain the temperature stress in the structure. Finally, the temperature stress behavior and adaptability of different pavement structures with different upper base materials under the action of large temperature difference are analyzed.

2. PAVEMENT STRUCTURE AND PARAMETER DETERMINATION FOR TEMPERATURE ANALYSIS

2.1. Determination of pavement structure

In order to explore the base pavement in different temperature under the action of temperature stress and the adaptability to temperature, structure layer thickness and a trend of temperature effects, here to Inner Mongolia cold typical semi-rigid base structure (structure I) on grassroots respectively replaced by asphalt stabilized macadam and grading macadam III II composition structure and the structure, the flexible base pavement base materials for asphalt stabilized macadam and grading macadam commonly, this kind of structure has been widely used in foreign countries and better pavement performance \(^6\). The three kinds of structures have the same thickness, but the materials used in the upper base layer are different. They are respectively the representative structures of semi-rigid, inverted and composite base layer pavement. The three different types of representative structures are shown in Figure 1.
2.2. Finite element three-dimensional model for temperature analysis

Actual pavement structure temperature changes over time, so for the transient temperature field under the condition of variable temperature, and periodic changes under the change of atmospheric temperature, the effect of the cyclical changes on pavement temperature field can be described by finite element in the periodic boundary conditions, the author with the help of a FILM, DFLUX user subroutine, and consider the solar radiation, sunshine time, maximum and minimum temperature and daily average wind speed and other factors, simulation of pavement structure under the condition of periodic warming of the transient temperature field.

The calculation model size of Abaqus will have an impact on the temperature analysis results. According to the research of Wang Zhigang [5], with the increase of the length of the calculation model, the temperature stress gradually decreases and finally tends to be stable. After trial calculation, the temperature stress decreases by 0.06% for each 1m increase when the length of the calculated model reaches 7m. Calculation model based on this, the paper size is: length of 7 m, 7 m wide, depth of the subgrade is 6 m, model for temperature field analysis of cell type for DC3D20, used for thermal stress analysis of cell form for C3D20R, model of boundary conditions are as follows: the direction (the z axis) impose constraints on the z direction displacement, transverse direction (x) on the x direction displacement constraints, subgrade base for completely fixed. The calculation type is shown in Figure 2.

2.3. Finite element environmental parameters for temperature analysis

Environmental parameters related to pavement temperature field is mainly to provide the first and the second kind boundary condition of calculation model parameters (write DFLUX and FILM program), according to the meteorological data in tgo region, winter and summer. The daily temperature values in winter and summer include the daily temperature hour value and the daily average wind speed. The average daily wind speed was determined as 3.5m/s in summer and 4.0m/s in winter based on the data inquired from China Meteorological Data Network. On January 12, the lowest hourly temperature was -22.1℃ at 6 o 'clock, and the highest daily hourly temperature was -6.8℃. On July 28, the lowest daily hourly temperature was 18.8℃ at 4 o 'clock, and the highest daily hourly temperature was 31.6℃.
winter cold season, total solar radiation $Q$ is 8.57 J/m$^2$, the real effective sunshine time is 7.35 h. In the hot summer season, the total daily solar radiation $Q$ is 22.5 J/m$^2$, and the actual effective sunshine duration $C$ is 9.80 h. The average daily wind speed is 3.5 m/s. The solar radiation absorption rate is 0.90, the road emissivity is 0.81, the absolute zero value is $-273$℃, and the Stefan-Boltzmann constant is $2.041 \times 10^{-4}$.

2.4. Finite element material parameters for temperature analysis
At present, the most widely used thermal stress calculation formula is based on quasi-elastic beam, such as Formula 1.

$$\sigma(T_{t_2}) = \sum_{t_1}^{T_{t_2}} \alpha(T) E(T) \Delta T$$  (1)

Where, $T(t_1)$ and $T(t_2)$ are the temperature values at time $T_1$ and $T_2$ respectively. $\alpha(T)$ is the temperature shrinkage coefficient of asphalt mixture at temperature $T$; $E(T)$ is the stiffness modulus at temperature $T$; $\Delta T$ is the temperature difference from $t_1$ to $t_2$; $\sigma(T_{t_2})$ is the cumulative temperature stress.

It can be seen from Formula 1 that stiffness modulus is very important for the calculation of temperature stress. According to the current research situation of temperature stress [5][7][8][9], there are few studies on the stiffness modulus of asphalt mixture, so it is difficult to accurately obtain the modulus value of asphalt mixture at different temperatures. There are also few test results or prediction models for the temperature shrinkage coefficient of materials, and asphalt mixture is usually not differentiated in calculation. In addition, it is difficult to determine the initial conditions of temperature stress calculation, that is, it is difficult to determine the reference temperature when the temperature stress in the material is 0. Therefore, there is still a certain gap between the calculated results of pavement temperature stress and the real value, so it is more suitable for law analysis. Based on the above, which is also convenient for the study of the coupling effect of road temperature and dynamic load, the author chooses dynamic modulus to calculate the road surface temperature stress considering the most unfavorable situation, that is, it assumes that the road surface is subjected to the long-term effects of vehicle load and temperature in use. In this paper, the relative values of the temperature stress of each structure are analyzed, and the absolute values are not discussed in detail.

3. TEMPERATURE STRESS OF PAVEMENT UNDER LARGE TEMPERATURE DIFFERENCE
Large temperature difference is a significant climate characteristic in cold regions. According to the investigation and interview results, there will be some days with temperature difference greater than 20℃ or even close to 40℃ in a long cold winter. Therefore, this section will carry out the analysis of the temperature stress changes of different pavement structures under the daily temperature difference of 20℃, 30℃ and 40℃.

3.1. Temperature stress of low temperature pavement
In this paper, the realization of the large temperature difference by controlling the tallest temperature constant temperature difference will, in turn, is set to 20 ℃ and 30 ℃, 40 ℃, and by using the Abaqus simulation pavement temperature stress at this time, because of the cement stabilized gravel layer upon layer bottom temperature stress to compressive stress, this section is no longer extract the layer temperature stress, tables, the road asphalt layer bottom and the top layer of the cement stable macadam mixture, time history curve drawing calculation results as shown in Figure 3.
Figure 3. Time history curve of temperature stress of low temperature pavement under large temperature difference

It can be seen from Fig. 3 that the variation of daily temperature difference has little influence on the temperature stress of road surface with different structure types. The increase of daily temperature difference will increase the tensile stress of asphalt bottom and cement stabilized macadam top, but the increment rate and increment rate of stress are different for different structure types. The maximum temperature stress under different daily temperature difference of each structure is summarized in Table I–III.

TABLE I. MAXIMUM TENSILE STRESS AT LOW TEMPERATURE (kPa) AT STRUCTURE I WITH DIFFERENT TEMPERATURE DIFFERENCES

| HORIZON NUMBER | Structure I |
|----------------|-------------|
|                | 20°C        | 30°C        | 40°C        |
| 1              | 2200.43     | 2929.1      | 3776.82     |
| 2              | 1685.49     | 2336.81     | 2647.07     |
| 3              | 396.28      | 611.96      | 834.51      |

TABLE II. MAXIMUM TENSILE STRESS AT LOW TEMPERATURE (kPa) AT STRUCTURE II WITH DIFFERENT TEMPERATURE DIFFERENCES

| HORIZON NUMBER | Structure II |
|----------------|--------------|
|                | 20°C         | 30°C         | 40°C         |
|                |              |              |              |
TABLE III.  MAXIMUM TENSILE STRESS AT LOW TEMPERATURE (KPa) AT STRUCTURE III WITH DIFFERENT TEMPERATURE DIFFERENCES

| HORIZON NUMBER | Structure III |
|----------------|---------------|
|                | 20°C | 30°C | 40°C |
| 1              | 2210.76 | 2963.38 | 3832.89 |
| 2              | 1873.21 | 2588.08 | 2928.91 |
| 3              | 64.06   | 101.92  | 141.11  |

(Note: The layer number 1 represents the road table, 2 represents the asphalt bottom, and 3 represents the top of the cement stabilized macadam layer.)

Analysis Table I–III, three road table structure temperature stress difference is not big, temperature increase 10 °C, the temperature stress path table is increased by 30% ~ 35%, but overall present structure III>structure I> structure II, this is because the structure of asphalt layer II base for asphalt stabilized macadam thicker, heat capacity is higher, and the asphalt mixture pavement performance as heat preservation performance is good, road table temperature decreases, and the structure III although asphalt layer thickness and structure the same as section analysis of graded crushed stone because of heat capacity and smaller modulus increase tensile stress in the route table.

The tensile stress of asphalt bottom and cement stabilized macadam top varies greatly among the three structures. The variation range of temperature stress of each structure with a daily temperature increase of 10°C is shown in Table IV

TABLE IV.  MAXIMUM TENSILE STRESS AT LOW TEMPERATURE (KPa) AT STRUCTURE III WITH DIFFERENT TEMPERATURE DIFFERENCES

| STRUCTURE TYPE | Structure I | Structure II | Structure III |
|----------------|-------------|--------------|---------------|
| Horizon number | 2           | 3            | 2             | 3             | 2     | 3     |
| 20°C~30°C      | 38.64       | 54.43        | 27.99         | 49.79         | 38.16 | 59.10 |
| 30°C~40°C      | 18.41       | 56.16        | 15.42         | 40.64         | 18.19 | 61.18 |

Table IV Variation amplitude of low-temperature tensile stress at each layer of three structures with different temperature differences (%)II combined base structure (structure) of asphalt layer bottom and the roof of the cement stable macadam mixture, temperature stress on the change in the minimum; I semi-rigid base structure (structure) and flip chip type structure (structure III) than at the grassroots level in the asphalt layer bottom, structure III change is small, and at the top of the cement stabilized gravel layer structure I changes small. It shows that the composite base course has the best adaptability to the low temperature under the condition of large temperature difference, while the semi-rigid base course and the inverted base course have the advantages of each other.

3.2. High temperature pavement temperature stress

Under different daily temperature differences, the time-history curve of temperature stress of pavement in high temperature season is basically the same as that of low temperature. Therefore, only the maximum tensile stress of each layer of the three structures is extracted here, as shown in Table V–VII. In particular, since the temperature stress of cement-stabilized macadamia is compressive, this is no longer counted.
TABLE V. MAXIMUM TENSILE STRESS AT HIGH TEMPERATURE (KPA) AT EACH LAYER OF STRUCTURE WITH DIFFERENT TEMPERATURE DIFFERENCES

| HORIZON NUMBER | Structure I | 20°C | 30°C | 40°C |
|----------------|-------------|------|------|------|
| 1              |             | 741.48 | 1645.8 | 3325.19 |
| 2              |             | 476.93 | 867.12 | 1663.61 |
| 3              |             | 472.27 | 578.3 | 686.41 |

TABLE VI. MAXIMUM TENSILE STRESS AT HIGH TEMPERATURE (KPA) AT EACH LAYER OF STRUCTURE II WITH DIFFERENT TEMPERATURE DIFFERENCES

| HORIZON NUMBER | Structure II | 20°C | 30°C | 40°C |
|----------------|--------------|------|------|------|
| 1              |             | 739.29 | 1645.8 | 3325.19 |
| 2              |             | 16.28 | 28.79 | 51.68 |
| 3              |             | 13.69 | 16.58 | 19.63 |

TABLE VII. MAXIMUM TENSILE STRESS AT HIGH TEMPERATURE (KPA) AT EACH LAYER OF STRUCTURE III WITH DIFFERENT TEMPERATURE DIFFERENCES

| HORIZON NUMBER | Structure III | 20°C | 30°C | 40°C |
|----------------|--------------|------|------|------|
| 1              |             | 754.55 | 1645.85 | 3321.43 |
| 2              |             | 523.89 | 876.73 | 1704.03 |
| 3              |             | 84.56 | 101.93 | 150.69 |

(Note: The layer number 1 represents the road table, 2 represents the asphalt bottom, and 3 represents the top of the cement stabilized macadam layer.)

As can be seen from Table V–VII., the three structures of road surface tensile stress with the same daily temperature difference under high temperature are basically the same as those under low temperature environment. As the daily temperature difference increases by 10°C, the surface tensile stress increases by 102%~121%, which is higher than the low temperature environment, indicating that sudden cooling in summer in cold region of Inner Mongolia may also cause cracking of asphalt surface layer.

TABLE VIII. VARIATION AMPLITUDE OF HIGH TEMPERATURE TENSILE STRESS AT EACH LAYER OF THREE STRUCTURES WITH DIFFERENT TEMPERATURE DIFFERENCES (%)

| STRUCTURE TYPE | Structure I | Structure II | Structure III |
|----------------|-------------|--------------|---------------|
| Horizon number |             | 2            | 3             | 2             | 3             | 2             | 3             |
| 20°C~30°C      | 81.81       | 22.45        | 76.84         | 21.11         | 67.35         | 20.54         |
| 30°C~40°C      | 91.85       | 18.69        | 79.51         | 18.40         | 94.36         | 47.84         |

By the tables I ~VII, with the increase of temperature difference of three kinds of structure temperature stress has increased, the structure of II increase minimum amplitude, structure I and III each other to have good and the gap is not big.
4. COMPARISON OF MECHANICAL RESPONSE UNDER COMBINED ACTION OF TEMPERATURE AND DYNAMIC LOAD

In order to understand the mechanical response state of pavement more comprehensively and truly, it is necessary to carry out the mechanical analysis of pavement structure under the coupling action of temperature and load. The mechanical responses of three kinds of pavement structures under the combined action of temperature and dynamic load are studied. Due to the large gap between the length of time-varying nodes of temperature field and temperature stress field and dynamic load stress field, the time-varying nodes of temperature field and temperature stress field are much larger than the dynamic load stress field. Based on the consideration of temperature effect and the most unfavorable combination of dynamic loading conditions, namely, we assume that the temperature stress of the continuous time domain dynamic load effect, in a sequential coupling method (load transfer method) to II I structure, structure, structure III thermal analysis is done first, and then the thermal analysis results as the load added to the dynamic load calculation, finite element structure model, the temperature field and temperature stress field affect the mechanical response of dynamic load, thus finish temperature and mechanical response of pavement under dynamic load coupling simulation. For this reason, this paper constructed the coupling action analysis model of temperature and dynamic load, in which the dynamic load adopted the sinusoidal load model proposed by Imad L. al-qadi, the maximum strength of the load was set at 0.7mpa and the speed was set at 100km/h.

4.1. Comparative analysis of coupling effect between low temperature and dynamic load

In this section, 6 o'clock in a typical winter climate is selected as the most unfavorable situation for the effect of low temperature on the pavement. With the help of the Abaqus analysis platform, the time history curves of the mechanical indexes of the three pavement structure types are obtained, as shown in Figure 4.
Fig. 4 is analyzed, and the peak values of mechanical indexes of the combined effect of low temperature and dynamic load of each structure in winter are ranked, as shown in Table IX.

**TABLE IX.** RANKING OF MECHANICAL INDEXES OF PAVEMENT UNDER COMBINED ACTION OF LOW TEMPERATURE AND DYNAMIC LOAD

| Mechanical index                                      | Mechanical index ranking |
|-------------------------------------------------------|--------------------------|
| Tensile stress of asphalt base                         | S2>S3>S1                 |
| Shear stress of asphalt layer                          | S2>S1>S3                 |
| Asphalt bottom tensile strain                         | S2>S3>S1                 |
| Road surface tensile stress                            | S2>S3 >S1                |
| Tensile stress of cement-stabilized macadam bed        | S3>S2>S1                 |
| Pressure strain on top of subgrade                     | S3>S2>S1                 |
| Road deflection                                        | S3>S2>S1                 |

According to Figure 4 and Table IX, compared with semi-rigid base and inverted base, composite base has advantages in all mechanical indexes. For the inverted base course pavement, its overall performance under the coupling field action is poor, even weaker than the semi-rigid base course pavement, because the modulus of asphalt mixture increases at low temperature, and the modulus ratio of graded crushed stone increases, but the structural integrality of the pavement decreases.
4.2. Comparative analysis of coupling effect between high temperature and dynamic load
In this section, 14:00, a typical summer climate, was selected as the most unfavorable situation for pavement high-temperature action. With the help of Abaqus analysis platform, the time-history curve of mechanical indexes was obtained as shown in Figure 5. In particular, this section will not make statistics on the tensile stress of the asphalt layer and the tensile stress of the pavement surface layer in the high temperature period in summer, because the asphalt layer is under compression and the tensile stress of the asphalt material is generally not the object of study under high temperature.

![Figure 5](attachment:figure5.png)

**Figure 5.** Time history curve of mechanical index of road surface under dynamic load at high temperature

FIG. 5 is analyzed, and the peak values of mechanical indexes of the combined action of high temperature and dynamic load of each structure in summer are ranked, as shown in Table X.

| Mechanical index                        | Mechanical index ranking |
|-----------------------------------------|--------------------------|
| Shear stress of asphalt layer           | S2>S3>S1                 |
| Tensile stress of cement-stabilized macadam bed | S3>S1>S2                 |
| Pressure strain on top of subgrade      | S3>S1>S2                 |
| Road deflection                         | S3>S1>S2                 |
As shown in Fig. 5 and Table X, due to the decline of asphalt mixture modulus at high temperature, the overall strength of composite base course pavement structure becomes weaker. The structural strength is less than that of semi-rigid base course pavement, but still better than that of inverted base course pavement. According to the shear stress of asphalt layer and graded crushed stone layer in high temperature season, the structure of composite base pavement is small and has some advantages in resisting rut in high temperature season.

5. CONCLUSION
(1) Under the action of large temperature difference, the variation amplitude of temperature stress in each layer of the three structures at high and low temperatures is similar. In other words, for road surface temperature stress, the variation range is > of semi-rigid base pavement, > of inverted base pavement, composite base pavement. For other layer temperature stress, the change of composite base layer pavement is still the smallest, while semi-rigid base layer and inverted base layer pavement are superior to each other.
(2) Under the effect of temperature and dynamic load coupling, the low temperature combined base pavement on all mechanical indexes are smaller. Under high temperature, the strength of composite base course decreases, but the maximum difference is only 3%. According to the shear stress of asphalt layer and graded crushed stone layer in high temperature season, the structure of composite base pavement is small and has some advantages in resisting rut in high temperature season.
(3) In general, the composite base pavement is the most suitable for large temperature difference in cold areas, and still has advantages under the coupling effect of temperature and dynamic load. Therefore, in cold areas, this paper recommends that the combined base pavement should be given priority. When the pavement pays more attention to the bearing capacity, semi-rigid base pavement structure can be considered.

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REFERENCES
[1] YAN Zuoren. Temperature field analysis of layered pavement system [J]. Journal of tongji university,1984(03):76-85.
[2] LIU Jizhong. Numerical calculation and analysis of temperature field and temperature stress of asphalt pavement in high altitude area of yunnan province [D]. Chongqing jiaotong university, 2009.
[3] AI Changfa, HUANG Daqiang, YU Xiaoli , et al .Analysis of dynamic performance of asphalt pavement under thermo-load coupling based on seasonal temperature; journal of south China university of technology (natural science edition) ,2017,45(04):66-73
[4] HAO Peiwen, ZHANG Lanfeng.Temperature stress analysis of asphalt pavement based on continuous variable temperature,[J].Journal of xi'an university of architecture and technology (natural science edition)2018,50(02):176-183.
[5] HUANG Daqiang. Coupling dynamic behavior of asphalt pavement temperature and load in alpine regions [D]. Southwest Jiaotong University,2016
[6] ZHANG Hongchun. Research on comprehensive crack resistance technology of semi-rigid base asphalt pavement[D]. Chang'an university,2008.
[7] FU Guozhi, CAO dandan, ZHAO Yanqing, et al .Determination of low temperature critical cracking temperature of asphalt mixture [J/OL]. Journal of composites .
[8] ZHENG Jianlong, research on key technologies of asphalt pavement design. Hunan province, changsha university of science and technology, December 25,2010.
[9] AI Changfa. Study on behavior characteristics and design methods of asphalt pavement in alpine regions [D]. Southwest jiaotong university,2008.
[10] ZHANG Xiaoning, SUN Lijun. Inverse calculation of modulus of asphalt pavement surface and base structure [J]. Journal of tongji university (natural science edition), 2004(10): 1386-1389.

[11] WANG yuefeng, WANG Chuanpei, ZHUANG Chuanyi. Study on temperature correction of dynamic modulus of asphalt mixture [J]. China and foreign highways, 2012, 32(02): 210-214.

[12] Shang YaPeng. Temperature shrinkage test and temperature stress analysis of semi-rigid base asphalt pavement[D]. Chang'an university, 2008.