Experimental Research on Crack Resistance of Fiber Asphalt Mixture in Cold Area

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Abstract: The asphalt mixture’s anticracking performance is reduced to solve the problem that the asphalt pavement in the cold area is affected by the continuous and large temperature difference, and the damage features of the fiber asphalt mixture are not clear under the action of large temperature difference cycle fatigue. This article first determines the large temperature difference interval as A, B, C and uses ABAQUS to perform mechanics on the pavement structure in different large temperature difference intervals response analysis.

1. Introduction

According to my country’s cold area division[1], the cold area accounts for about 43.5% of my country’s land area. The annual climate temperature in cold regions of my country is less than 10 ℃ for no less than 7 months, and the annual average temperature does not exceed 5 ℃. Asphalt pavement materials in cold areas are comprehensively affected by many factors such as continuous low temperature, large temperature differences, and frequent freeze–thaw cycles[2][3], compared with roads in noncold areas, asphalt pavements in cold areas suffer more severe damage. The road performance drops faster.

Based on this, domestic and foreign experts and scholars have carried out much research on asphalt mixtures in cold areas as follows: Through theoretical research and practical field tests, Ai Changfa recommended the asphalt pavement structure suitable for the alpine area. Based on the finite element software ABAQUS, the mechanical response analysis of pavement under large temperature difference, temperature and load action was analyzed, and the structural design and behavior analysis method of asphalt pavement in alpine region was proposed based on different temperatures and mechanical...
However, the stress response of the pavement structure under the environment of different large temperature differences in the cold area has not been analyzed. Khan et al. proposed a road surface with lower conductivity by replacing conventional aggregates in asphalt mixtures with lightweight aggregates (LWA). The research results show that, due to the excellent thermal insulation properties of LWA asphalt mixture, it can reduce the penetration of frost into the underlying pavement layer in cold areas. However, other road performances of asphalt mixture in cold areas have not been studied yet. Porras, J. et al. used indirect tensile tests and dynamic modulus tests to evaluate the sensitivity of hot-mix asphalt mixtures to water damage after multiple freeze-thaw cycles. The research results show that it meets the 80% minimum indirect tensile strength standard after one freeze-thaw cycle; it also has higher water damage resistance after three freeze-thaw cycles. However, the number of freezing and thawing effects of the test cycle water is small, and it cannot reflect the attenuation law of road performance after multiple cycles, and the combined effect of freezing and thawing and dynamic water erosion on the water damage of the asphalt mixture is not considered. Al-Bayati, H. K. and other cold regions in Canada have passed the thermal stress constrained specimen test (TSRST) to evaluate the effect of adding steel strips to asphalt mixtures. The research results show that the incorporation of steel strips can significantly reduce the average fracture temperature, but this technology has no effect on the fracture stress of the asphalt mixture. And the effect of temperature cycling stress on fatigue damage of asphalt mixture mechanical properties has not been considered.

To sum up, the existing research mainly focuses on the research on the antifreeze–thaw performance of asphalt mixture and the resistance to water temperature cycle and considers the damage model of material road performance, but lacks consideration of asphalt mixture under the action of different large temperature difference intervals. The changing law of the material’s low-temperature antocracking efficiency and the influence of the large temperature difference cycle on the asphalt mixture’s road performance. To this end, this paper uses ABAQUS software to analyze the mechanical response of the pavement structure under different large temperature differences, explores the influence of the large temperature difference cycle on the road surface.

2. Numerical Simulation Study of Pavement Structure under Large Temperature Difference

2.1. Large Temperature Difference Range and Interval Selection
According to Wang Bo’s research on the asphalt pavement temperature field in most areas of Gansu Province, the number of days in Gansu Province where the average daily temperature difference is ≥13 °C exceeds 180 days, and the number of days with the daily extreme temperature difference ≥30°C is more than 150. The sky area is a large temperature difference area. The daily extreme temperature temperature difference ≥ 30 °C is defined as a large temperature difference, and a daily temperature drop of 30 °C is a large temperature difference, considering the fatigue effect of high and low temperature cycles with a daily extreme temperature difference ≥30 °C for 150 days on the asphalt mixture.

According to the temperature division of asphalt pavement in Gansu Province, the average minimum temperature of the coldest month is −14.0 ~ −2 °C, and the average maximum temperature of the hottest month is 33 ~ 35 °C. Therefore, take the upper limit of the highest temperature as 35 °C, 10 °C as a step, and the large temperature difference action range is 30 °C. Set three groups of large temperature difference action intervals. The specific intervals are A [35°C ~ 5°C], B [25 °C ~ −5 °C], C [15 °C ~ −15 °C].

2.2. Thermal Stress Analysis Parameters

2.2.1. Pavement Structure
The semi-rigid base asphalt pavement, widely used in Gansu area, is used. The specific pavement structure and thickness are shown in Figure 1.
Upper layer 4 cm AC-13
Middle layer 8 cm AC-20
Lower layer 10 cm AC-25
Base 30 cm cement-stabilized crushed stone (CTB)
Subbase 20 cm lime soil (LS)
Soil foundation (SG)

Figure 1. Asphalt pavement structure

2.2.2. Material Parameters
See Table 1 for the pavement temperature field thermal property parameters, Table 2 for the mechanical parameters of the asphalt mixture, Table 3 for the mechanical parameters of the base and soil-based materials, and Table 4 for the coefficients of pavement material temperature reduction at different temperatures.

| Parameter                                      | Pavement surface | CTB     | LS     | SG     |
|------------------------------------------------|------------------|---------|--------|--------|
| Thermal conductivity k(J/(m·h·℃))              | 4695             | 5624    | 5143   | 5620   |
| Density ρ(kg/m³)                               | 2420             | 2200    | 2100   | 1800   |
| Heat capacity C(J/ kg·℃)                       | 925.7            | 912.5   | 943.1  | 1040   |
| Solar radiation absorption rate                 | 0.9              |         |        |        |
| Road emissivity ε                               | 0.81             |         |        |        |
| Absolute zero(℃)                               | -273             |         |        |        |
| Stefan-Boltzmann constant σ (J/(h·m²·K⁴))     | 2.041×10⁻⁴       |         |        |        |

| Mixture type | Temperature(℃) | Modulus of resilience (MPa) | Poisson's ratio |
|--------------|----------------|-----------------------------|-----------------|
| AC-13        | 40             | 710                         | 0.35            |
|              | 30             | 820                         | 0.35            |
|              | 20             | 1000                        | 0.3             |
|              | 10             | 1200                        | 0.3             |
|              | 0              | 1400                        | 0.3             |
|              | -10            | 4500                        | 0.25            |
|              | -20            | 9000                        | 0.25            |
|              | 40             | 632                         | 0.35            |
|              | 30             | 780                         | 0.35            |
|              | 20             | 1080                        | 0.3             |
| AC-20        | 10             | 1100                        | 0.3             |
|              | 0              | 1200                        | 0.3             |
|              | -10            | 4200                        | 0.25            |
|              | -20            | 8500                        | 0.25            |
|              | 40             | 580                         | 0.35            |
| AC-25        | 30             | 750                         | 0.35            |
Table 3. Mechanical parameters of base course and soil-based materials

| Material Type               | Compressive elastic modulus (MPa) | Poisson's ratio |
|----------------------------|-----------------------------------|-----------------|
| Cement stabilized macadam (CTB) | 1200                             | 0.2             |
| Lime soil (LS)              | 300                               | 0.3             |
| Soil foundation (SG)        | 45                                | 0.4             |

Table 4. Temperature shrinkage coefficient of pavement materials

| Material Type               | Temperature shrinkage coefficient at different temperatures \((x \times 10^{-5}/\text{°C})\) |
|----------------------------|---------------------------------------------|
|                            | 40°C 30°C 20°C 10°C 0°C -10°C -20°C         |
| AC-13                      | 4.49 3.88 3.35 2.89 2.5 2.16 1.86          |
| AC-20                      | 4.49 3.88 3.35 2.89 2.5 2.16 1.86          |
| AC-25                      | 4.49 3.88 3.35 2.89 2.5 2.16 1.86          |
| Cement stabilized macadam (CTB) | 1                               |
| Lime soil (LS)              | 15                              |
| Soil foundation (SG)        | 50                              |

2.2.3. Temperature Representative Value

For representative values of 24 h of temperature in the temperature difference intervals between A, B, and C, refer to Figure 2.
3. Temperature Field Analysis

Use ABAQUS finite element software to simulate road surface and solar radiation input, effective road surface radiation, air temperature and convective heat exchange through FILM and DFLUX user subroutines, simulate environmental effects on road surface in cold areas, and simulate road surface under the condition of periodic temperature changes. Structure temperature field. With the pavement depth $h$ (road surface $h = 0 \text{ cm}$), the temperature field of the pavement structure in each temperature difference interval is shown in Figure 3.
Figure 3. Temperature field of pavement structure in each temperature difference interval.

It can be seen from Figure 3 that the change law of the asphalt pavement structure temperature field is consistent with the 24 h temperature change law in Figure 2, and the change of outside air temperature has the most significant impact on the road surface temperature; as the depth increases, the temperature change rate of the pavement structure layer decreases. The greater the temperature difference in the pavement structure, the greater the temperature stress generated, which affects the
structure’s crack resistance stability. During the change of the temperature of the pavement structure in Zone A with time, the temperature of the road surface (h = 0 cm) has reached the maximum value of 55.6°C at 16 h, while the temperature of the top surface of the middle layer (h = 4 cm) has not reached the maximum value. The temperature difference between the top surface and the middle surface layer is 10.1°C; the temperature difference between the upper layer and the middle surface layer of the B zone is 10.4°C at 16 h, and the temperature difference between the upper layer and the middle surface layer of the C zone and the B zone is 12.1°C at 16 h.

4. Thermal Stress Analysis
A finite element model of the pavement structure is established to determine the temperature stress in the pavement structure, as shown in Figure 4. They were considering that the temperature stress changes in the depth of the upper layer road surface, the upper layer surface and the middle layer surface are taken into account the temperature stress analysis of the large temperature difference interval. The temperature stress response of the pavement structure is shown in Figure 5.

![Figure 4. Thermal stress analysis finite element model](image)

(a) Change of temperature stress of pavement structure in section A with time
Figure 5 shows that the change in the law on the temperature stress of the asphalt pavement structure is consistent with the 24-h law on the change in air temperature in Figure 2. The change of outside air temperature has the greatest impact on the temperature stress at the top surface (h = 0 cm) of the upper layer. As the depth increases, the temperature stress of the structural layer is reduced accordingly.

It can be seen from Figure 5(a) that as the ambient temperature drops at 0 h, the temperature of each structural layer decreases, but the tensile stress inside the structure continues to increase until it receives the maximum tensile stress at 6 h; the ambient temperature starts at 6 h. When it rises, the road structure changes from tension to compression at 8 h until it receives the maximum compressive stress at 16 h. After 16 h, the temperature stress of the road surface gradually decreases as the temperature drops. The maximum tensile stress and compressive stress of the upper surface of each section (h = 0 cm) are, respectively, 0.46MPa and 0.09MPa for the A section; 0.28MPa and 1.02MPa for the B section; 0.73MPa and 2.01MPa for the C section; calculate the road surface in each section. The temperature stress variation range at h = 0 cm shows that the A, B, and C intervals are 0.55MPa, 1.3MPa, and 2.74MPa. It can be seen that the pavement structure in the C interval suffers the greatest temperature stress, and the temperature stress varies the most, indicating the C interval. The large temperature difference of 15°C ~ −15°C also has the greatest impact on the crack resistance of asphalt pavement. The temperature stress caused by this interval should be considered to improve the crack resistance of asphalt pavement in cold areas.
5. Conclusion
(1) Compared with the general temperature difference interval, the large temperature difference has the most significant impact on the maximum temperature difference generated by the different layers of the pavement structure, so it has a more significant impact on the uneven temperature stress; the pavement h = 0 cm in the large temperature difference intervals A, B, and C. The temperature stress changes are 0.55, 1.3, and 2.74 MPa, respectively. The pavement structure in section C suffers the largest temperature stress change.

(2) Compared with roads in noncold areas, the large temperature difference in section C will significantly increase the probability of pavement cracks due to the temperature fatigue stress of the pavement, and the rate of damage after cracking is also faster. Therefore, the design of pavement structures in cold areas should be considered. For example, the temperature stress caused by the alternation of high and low temperatures in the C section can improve the asphalt pavement’s anticracking performance with large temperature differences in cold areas.

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