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Proportion and Road Performance of High-Durability Asphalt Pavement Materials Under Extreme Climates

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Abstract: This paper studies the mix proportion optimization and road performance of high-durability asphalt pavement materials based on the road performance control objectives under extreme climates, incorporating real-world project cases. According to the actual requirements of the project, a mix proportion optimization plan for high-durability asphalt pavement materials is formulated, and its road performance is verified through tests such as freeze-thaw resistance, low-temperature crack resistance, high-temperature stability, and aging resistance. Practical applications indicate that the determined mix proportion optimization plan for high-durability asphalt pavement materials is suitable under extreme climatic conditions and aligns with the design expectations of this research, providing a reference for subsequent similar projects.

Keywords: Extreme climate; High durability; Asphalt pavement materials; Mix proportion plan; Road performance

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1. Introduction

Regions in China that experience cold winters and hot summers are subject to extreme low and high temperatures, with freeze-thaw spalling, low-temperature cracking, and high-temperature rutting being common diseases of asphalt pavements. These issues not only increase the maintenance and repair costs of asphalt pavements but also shorten their service life. To address these challenges, engineering units should reasonably optimize the mix design of high-durability asphalt pavement materials according to actual project conditions to ensure their road performance and create favorable conditions for enhancing pavement durability and operational economy.

2. Project overview

A certain ring-road highway pavement renovation project has a total length of 28.6 km, featuring a dual four-lane configuration with a design speed of 100 km/h. The project area is located in a cold temperate continental monsoon climate zone, with winter minimum temperatures reaching -31°C and a maximum freeze depth of 1.8 m, experiencing an average of 12 freeze-thaw cycles annually. In summer, the maximum temperature can reach 35°C, with surface temperatures of the pavement reaching up to 65°C, and high temperatures persist for over 90 days. The original pavement, composed of AC-20C asphalt mixture, has been in continuous operation for 5 years and suffers from severe pavement diseases. Field investigations reveal that the freeze-thaw spalling area of the asphalt pavement materials accounts for up to 28%, with an average density of 8 transverse cracks per kilometer caused by low temperatures, and a maximum rut depth of 12 mm formed under high-temperature conditions, rendering it unable to maintain normal traffic flow. According to the requirements for pavement reconstruction in this project, asphalt pavement materials should have stronger tolerance to extreme temperature changes and a service life exceeding 15 years. Based on these requirements, engineering units need to optimize the mix ratio of high-durability asphalt pavement materials. This paper primarily focuses on the study of its mix ratio optimization and road performance.

3. Optimization plan for the mix ratio of high-durability asphalt pavement materials under extreme climatic conditions

3.1. Determination of optimization objectives and weights

Based on the extreme climatic conditions of the area where the project is located and the practical application requirements for pavement, the engineering unit has identified the following four optimization objectives:

(1) Freeze-thaw resistance stability;
(2) Low-temperature crack resistance;
(3) High-temperature stability;
(4) Aging resistance.

Based on these four optimization objectives, weights were determined using the Analytic Hierarchy Process (AHP). Five experts in the field of road engineering were invited to establish the judgment matrix, and after passing the consistency check, the weight results were determined as follows:

(1) The weight for freeze-thaw resistance stability is 0.35;
(2) The weight for low-temperature crack resistance performance is 0.25;
(3) The weight for high-temperature stability is 0.25;
(4) The weight for aging resistance performance is 0.15. When allocating weights, the engineering units prioritized the stability of asphalt pavement materials under winter freeze-thaw conditions, while also considering application performance under extreme temperature conditions in both winter and summer to align with the actual climatic characteristics of the project area [1].

3.2. Orthogonal experimental design and parameter screening

In this project, the engineering unit selected 70# Grade A road petroleum asphalt as the asphalt raw material, basalt with a 12.5% crushing value and a 16.8% Los Angeles abrasion loss value as the coarse aggregate, angular limestone with a 28s angularity as the fine aggregate, finely ground limestone powder with a 0.8 hydrophilic coefficient as the mineral filler material, and a composite material of I-D type SBS modifier and nano-SiO2 antifreeze agent as the additive. Combining existing experience in asphalt pavement material mix ratios, the SBS content, antifreeze agent content, aggregate gradation, and optimal asphalt-aggregate ratio were identified as key influencing factors for the orthogonal experiment. Each influencing factor was set with three parameter levels, as detailed in **Table 1**.

Table 1. Factors influencing orthogonal experiments and their level parameter table

No.	Factor	Level 1	Level 2	Level 3
1	A: SBS modifier content (%)	3	4	5
2	B: Antifreeze agent content (%)	0.5	1.0	1.5
3	C: Aggregate gradation (Grade)	I	II	III
4	D: Optimal asphalt-aggregate ratio (%)	4.3	4.5	4.7

Data sourced from the orthogonal experimental design plan of an engineering unit, where material dosage and mix ratios are measured by mass.

3.3. Determination of the optimal mix ratio

The optimal mix ratio was selected using a comprehensive scoring method. Based on the weight of each influencing indicator, a comprehensive score was calculated for each test group. The higher the score, the better the overall performance of the material. The calculation formula is as follows:

$$S = 0.35 \times S_{TSR} + 0.25 \times S_{DS} + 0.15 \times S_R \quad (1)$$

Where, S represents the comprehensive score; S_{TSR} represents the score for freeze-thaw stability, converted proportionally, with a full score (100 points) standard of temperature bending strain (TSR) ≥ 80%; S_{ε} represents the score for low-temperature crack resistance, converted proportionally, with a full score (100 points) standard of low-temperature microstrain (Ɛ) ≥ 2500μƐ; S_{DS} represents the score for high-temperature stability, converted proportionally, with a full score (100 points) standard of dynamic stability (DS) ≥ 300 cycles/min at the optimal asphalt-to-aggregate ratio; S_R represents the score for aging resistance, converted proportionally, with a full score (100 points) standard of ductility retention rate (R) ≥ 70% after aging.

Nine sets of orthogonal experiments were conducted based on the influencing indicators. After calculation, it was found that Group 5 had the highest comprehensive score (92 points), with a mix design of 4% SBS dosage, 1.0% antifreeze dosage, mineral aggregate gradation of AC/20CII, and an optimal asphalt-to-aggregate ratio of 4.5%. Under these mix parameters, the freeze-thaw stability of the asphalt pavement material was 88.8%, the corresponding low-temperature bending strain was 2850μƐ, the optimal asphalt-to-aggregate ratio for dynamic stability was 3650 cycles/min, and the ductility retention rate after aging was 78%. This mix ratio can be used as the optimal mix for high-durability asphalt pavement materials in this research [2]. The specific orthogonal experimental plan and comprehensive score data are shown in **Table 2**.

Table 2. Orthogonal experimental plan and comprehensive score data

No.	SBS content (%)	Antifreeze agent content (%)	Aggregate gradation (grade)	Optimal asphalt-aggregate ratio (%)	Comprehensive score
1	3 (A1)	0.5 (B1)	I (C1)	4.3 (D1)	72
2	3 (A1)	1.0 (B2)	II (C2)	4.5 (D2)	85
3	3 (A1)	1.5 (B3)	III (C3)	4.7 (D3)	78

Table 2 (Continued)

No.	SBS content (%)	Antifreeze agent content (%)	Aggregate gradation (grade)	Optimal asphalt-aggregate ratio (%)	Comprehensive score
4	4 (A2)	0.5 (B1)	II (C2)	4.7 (D3)	88
5	4 (A2)	1.0 (B2)	III (C3)	4.3 (D1)	92
6	4 (A2)	1.5 (B3)	I (C1)	4.5 (D2)	83
7	5 (A3)	0.5 (B1)	III (C3)	4.5 (D2)	75
8	5 (A3)	1.0 (B2)	I (C1)	4.7 (D3)	81
9	5 (A3)	1.5 (B3)	II (C2)	4.3 (D1)	79

Data sourced from the orthogonal experimental design plan of an engineering unit.

4. Road performance testing of high-durability asphalt pavement materials after mix ratio optimization

4.1. Freeze-thaw resistance stability test

The freeze-thaw resistance stability of the material was tested through the Marshall freeze-thaw test. The specimens were divided into two groups. The first group was placed in water at 25°C for 48 hours of heat preservation before undergoing splitting strength (R_1) testing. The second group was first frozen at -18°C for 16 hours, then placed in water at 60°C for 24 hours of heat preservation, and finally placed in water at 25°C for 4 hours of heat preservation before undergoing splitting strength (R_2) testing. The evaluation formula for freeze-thaw resistance stability is as follows:

$$TSR = \frac{R_2}{R_1} \times 100\% \quad (2)$$

The test results showed that the average splitting strength R_1 of the first group of optimized mixture materials was 1.25 MPa, and the average splitting strength R_2 of the second group was 1.11 MPa, both higher than the freeze-thaw resistance strength of the original pavement material. The freeze-thaw resistance stability reached 88.8%, significantly higher than that of the original asphalt pavement material (72.3%). Further analysis revealed that the primary reason is that the nanoscale SiO_2 antifreeze agent can fill the gaps between aggregates, reducing the amount of water infiltrating during freeze-thaw cycles. Meanwhile, SBS enhances the adhesion between asphalt and aggregates, further reducing the risk of freeze-thaw spalling in asphalt pavement materials, meeting the project's freeze-thaw resistance requirements for pavement in winter [3].

4.2. Low-temperature crack resistance test

The low-temperature crack resistance of the material was tested through the low-temperature bending test method. Specimens measuring 250×30×35mm were fabricated and subjected to bending loading at a temperature of -10°C and a rate of 50mm/min, with the maximum flexural tensile stress, flexural strain, and flexural stiffness modulus recorded. A smaller maximum flexural tensile stress indicates better low-temperature ductility of the material, while a larger flexural strain indicates stronger low-temperature crack resistance.

The test results showed that the average maximum flexural tensile stress of the optimized mixture materials was 13.18 MPa, a 29.3% reduction compared to the original pavement material. The average maximum flexural strain was 2920με, a 57.8% increase compared to the original asphalt pavement. Further analysis revealed that the primary reason is that the SBS modifier significantly improves the low-temperature ductility of the asphalt, effectively reducing cracks in the pavement caused by temperature stress under low-temperature conditions, meeting the project's low-temperature crack resistance requirements for pavement [4].

4.3. High-temperature stability test

The high-temperature stability of materials was tested using the rutting test method. Test specimens measuring 300×300×50 mm were fabricated and subjected to loading at a rate of 42 cycles/min under conditions of 60°C and 0.7 MPa. The reciprocal of the rate of change in rutting depth per unit time (DS) was used as the evaluation metric. A higher DS value indicates better high-temperature stability of the material.

The test results showed that after 60 minutes of testing, the rutting depth of the optimized mixture material was 2.1 mm, significantly lower than that of the original pavement asphalt material (5.8 mm). The DS value was 3,720 cycles/min, representing a 135.4% increase compared to the DS value of the original pavement asphalt material. Further analysis revealed that the primary reason for this is the more stable skeleton provided by the coarse aggregates in the Class II gradation. With the assistance of the optimal asphalt-aggregate ratio, the amount of rutting deformation caused by high-temperature flow in the asphalt pavement material is significantly reduced, making it suitable for the heavy-duty transportation demands under high-temperature conditions in this research [5].

4.4. Aging resistance test

The aging process of materials during service was simulated using both short-term and long-term aging methods. In the short-term aging method, the simulation temperature was 163°C, and the simulation time was 75 minutes. In the long-term aging method, the simulation temperature was 100°C, the pressure was 2.1 MPa, and the time was 20 hours. Before and after the aging simulation, the ductility of the asphalt material at 15°C and the penetration at 25°C were tested. Based on the test results, the ductility retention rate and the change in penetration index were calculated to evaluate the aging resistance of the material. A higher ductility retention rate after aging indicates better aging resistance of the material. A lower rate of change in the penetration index after long-term aging indicates better durability of the material [6].

The test results showed that the ductility retention rate of the optimized mixture material after short-term aging was 85%, and after long-term aging, it was 76%, both significantly higher than those of the original pavement material (68% and 59%, respectively). The rate of change in the penetration index after long-term aging was 126.2%, significantly lower than that of the original pavement material (247.4%). Further analysis reveals that the primary reason is the excellent synergistic effect between SBS and nano-SiO_2 during the optimization process. This synergy causes the asphalt to oxidize and harden, significantly reducing the temperature sensitivity variation of the asphalt material. As a result, the optimized asphalt pavement exhibits superior long-term performance, aligning with the actual pavement requirements of the project [7].

4.5. Verification of project application effectiveness

To further validate the road performance of the optimized material proportions, the engineering unit conducted a one-year (1a) follow-up monitoring of the asphalt pavement with optimized proportions after construction completion in this project. The monitoring data were compared with those from the original pavement after one year of application [8]. The comparison revealed that the proportion of freeze-thaw spalling area in the optimized asphalt pavement material significantly decreased, the density of low-temperature transverse cracks significantly reduced, and the maximum depth of high-temperature rutting significantly diminished, meeting the project's requirements for controlling high-temperature rutting depth. Moreover, the pavement structural strength index consistently remained at a high level, and the overall pavement performance was highly stable, as shown in the comparative data in **Table 3**.

Table 3. Comparison of application effects between optimized proportion asphalt materials and traditional materials in the project

No.	Performance indicator	Original pavement	Optimized pavement	Improvement	Performance requirement	Post-optimization compliance
1	Freeze-thaw Scalling Area Ratio (%)	8	1.2	85%	≤ 5	Yes
2	Low-temperature Transverse Crack Density (cracks/km)	0.03	0.005	83.3%	≤ 0.02	Yes
3	High-temperature Rutting Maximum Depth (mm)	12	2.3	80.8%	≤ 5	Yes
4	Pavement Structural Strength Index (SSI)	0.75	0.92	22.7%	≥ 0.85	Yes

The verification of practical application effectiveness indicates that the optimized asphalt pavement material is better suited to the extreme climatic conditions of the project area compared to the original pavement material. It effectively resists extreme weather conditions such as low-temperature freeze-thaw cycles and high-temperature exposure, meeting the project's anticipated design requirements [9]. The rational application of optimized proportion materials in this project can further enhance the durability of the asphalt pavement and holds significant promotional value for road engineering pavement construction under similar extreme climatic conditions [10].

Disclosure statement

The author declares no conflict of interest.

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