

Key Technologies for Construction Quality Control of Asphalt Concrete Pavements under Large Temperature Differences

Ruibo Fan¹, Xijun Lv¹, Gaojie Xiong¹, Wei Wang², Siping Wei², Diandong Sun²

¹CCCC Road and Bridge North Engineering Co., Ltd., Beijing, China

²Changchun Institute of Technology, Changchun, Jilin, China

Abstract: To address the technical challenges of difficult temperature control, insufficient compaction, and frequent low-temperature cracking during asphalt concrete pavement construction in areas with large temperature differences. The deterioration patterns of asphalt concrete performance evaluation indicators under large temperature differences were systematically investigated, and the mechanism by which environmental temperature differences affect the paving and compaction performance of asphalt mixtures was analyzed. Based on warm-mix technology, the mix proportion of modified asphalt mixtures was optimized, and orthogonal tests were conducted to determine the optimum mix proportion and optimum paving temperature suitable for construction under large temperature differences. Finally, an intelligent temperature-control and refined construction-control system covering the entire process of mixing, transportation, paving, and rolling was established. The results show that effective control of asphalt mixture construction temperature is critical to ensuring pavement compaction quality under large temperature differences. Warm-mix technology can reduce mixing and compaction temperatures by 15–20 °C. Combined with full-process intelligent temperature monitoring, it can significantly improve the compaction and smoothness of asphalt pavements under low-temperature construction conditions and reduce low-temperature segregation and cracking, providing a scientifically sound and effective technical solution for highway construction in regions with large temperature differences.

Keywords: Large Temperature Difference; Asphalt Concrete Pavement; Warm-Mix Technology; Mix Proportion Optimization; Intelligent Temperature Control; Construction Quality Control

1. Introduction

Asphalt concrete pavement construction quality directly determines the service performance, durability, and safety of roads and is one of the core aspects of modern transportation infrastructure construction. With the rapid development of China's economy and the continuous advancement of urbanization, [1]transportation infrastructure has played an increasingly important role in regional economic development and the implementation of national strategies[2].Highway construction not only meets the urgent needs of regional economic and social development but also plays an irreplaceable role in the Belt and Road Initiative.[3]

The region is located in an arid inland region with extreme climatic conditions, characterized by large diurnal and annual temperature differences and representing a typical large-temperature-difference climate.[4] Under such extreme climatic conditions, construction quality control of asphalt concrete pavements faces severe challenges. The temperature of asphalt mixtures during construction must be maintained within a certain range to ensure appropriate fluidity and workability and thereby achieve good paving and compaction. However, drastic fluctuations in ambient temperature make it difficult to accurately control asphalt concrete construction temperature, resulting in unstable material performance.[5] At high temperatures, asphalt concrete is prone to excessive softening and flowing during construction; at low temperatures, it becomes excessively stiff, seriously affecting paving and compaction and causing quality defects such as insufficient compaction, local segregation, and poor bonding between the paved layer and the underlying layer.[6]

Domestic and international scholars have conducted extensive research on the damage characteristics of asphalt pavements under large

temperature differences.[7] Tarefder and Islam found through field measurements that the diurnal temperature difference at the asphalt pavement surface was approximately twice that of the air, and that thermal stresses generated in the asphalt surface layer significantly accelerated pavement cracking.[8] Al-Qadi et al. measured strains of up to 350 $\mu\text{m/m}$ caused by daily temperature variations on a test section in Virginia and concluded that even a single large temperature change could cause severe damage to asphalt pavements. Based on more than two years of monitoring data, Bayat and Knight reported that strain fluctuations at the bottom of asphalt mixtures caused by diurnal temperature changes reached 650 $\mu\text{m/m}$, while those caused by annual temperature changes reached as high as 2544 $\mu\text{m/m}$, far exceeding the strains induced by vehicle loading.[9] Domestic investigations of pavement distress have shown that asphalt pavement cracking occurs frequently. Previous pavement structural designs did not adequately account for the actual environmental conditions in the region, and dry-shrinkage and thermal cracking of asphalt pavements with semi-rigid bases are widespread under arid, large-temperature-difference conditions, resulting in severe early pavement distress.[10]

Regarding warm-mix technology, He Sheng et al. developed a composite warm-mix additive mainly composed of polyethylene wax and plasticizer to address the short construction time and poor low-temperature cracking resistance of asphalt mixtures in cold regions. The modified asphalt improved thermal stability and aging resistance while significantly enhancing low-temperature cracking resistance and water-damage resistance. Wang Meng et al. investigated the effects of organic viscosity-reducing and surfactant-type warm-mix additives on asphalt properties through conventional asphalt-property tests, rheological analysis, and molecular dynamics simulations. The results showed that surfactant-type warm-mix additives can significantly reduce asphalt surface tension, improve low-temperature performance, and enhance wettability and lubricity.[11]

However, existing studies on asphalt concrete performance under large temperature differences still have several limitations: (1). existing studies focus mainly on individual performance indicators and lack systematic evaluation of comprehensive performance; (2). long-term field

application data are insufficient and studies rely heavily on short-term laboratory data; (3). engineering validation of optimized mix proportions for modified asphalt mixtures is insufficient, particularly in regions with large temperature differences ; and (4). research on intelligent temperature control and refined construction control is not sufficiently in-depth, and practical application of temperature control and process optimization technologies during construction remains inadequate.[12]

Accordingly, this study takes the road construction project from Dachanggou (G331) via Mingxin Coal Mine to G335 in Hami, as the supporting project. It systematically investigates the deterioration patterns of asphalt concrete performance evaluation indicators under large temperature differences, analyzes the mechanism by which environmental temperature differences affect the paving and compaction performance of asphalt mixtures, optimizes the mix proportion of modified asphalt mixtures based on warm-mix technology, and determines the optimum mix proportion and paving temperature through orthogonal tests. An intelligent temperature-control and refined construction-control system covering the entire process under large temperature differences is then established, providing a scientifically sound and effective solution for highway construction in the region and other regions with large temperature differences.

2. Theoretical Analysis

2.1 Mechanism of the Influence of Large Temperature Differences on Asphalt Concrete Pavement Construction

Large temperature differences affect asphalt concrete pavement construction mainly through the significant influence of temperature on the physical properties and construction processes of asphalt concrete. Asphalt is a typical temperature-sensitive material, and its viscosity, fluidity, and mechanical properties change significantly with temperature. Under large temperature differences, this temperature sensitivity is further amplified, greatly increasing the difficulty of construction quality control.

From a mechanical perspective, compaction of an asphalt mixture is essentially the process in which aggregate particles rearrange and become denser under the lubricating action of the asphalt

binder. The viscosity of the asphalt binder directly determines the frictional resistance and lubrication effect between aggregate particles. As temperature decreases, asphalt viscosity increases, frictional resistance between aggregate particles increases, and the energy required for compaction rises accordingly. If the compaction effort is insufficient to overcome this frictional resistance, insufficient pavement compaction will result, forming a loose structure with excessive voids and creating hidden risks of subsequent water damage and low-temperature cracking.

From the perspective of heat transfer, changes in the temperature field after asphalt mixture paving follow Fourier's law of heat conduction. Under large temperature differences, the temperature difference between the ambient environment and the paved layer increases, significantly increasing heat flux and accelerating mixture cooling. A pronounced temperature gradient develops between the surface of the paved layer and the underlying layer. This nonuniform temperature field causes differences in shrinkage and bonding performance among different parts of the mixture, thereby affecting the bonding quality between the paved and underlying layers and potentially inducing segregation. As shown in Figure 1.

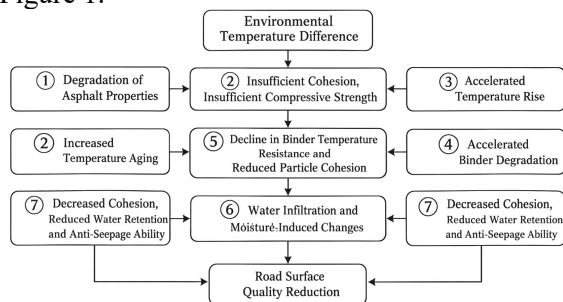


Figure 1. Mechanism of the Influence of Large Temperature Differences on Asphalt Concrete Construction

Temperature changes also significantly affect the evaporation rate of water in asphalt mixtures. Under drastic temperature fluctuations, the rate of water evaporation in the mixture changes sharply. Particularly in cold environments, excessive water evaporation can reduce mixture cohesion, directly affecting the adhesion between asphalt and aggregate and weakening the pavement's resistance to water damage and its long-term durability.

2.2 Distribution Characteristics of the

Temperature Field within the Base Layer

The distribution characteristics of the temperature field within the base layer under large temperature differences are one of the key factors affecting the paving quality of asphalt concrete. During paving, heat from asphalt concrete is dissipated not only to the ambient atmosphere but also conducted to the cooler underlying layers (base and subgrade). The temperature condition of the underlying layer directly determines the rate of temperature change at the bottom of the paved layer and consequently affects mixture cooling and compaction.

To investigate the distribution characteristics of the temperature field within the base layer under large temperature differences, this study combined numerical simulation with field monitoring. Based on COMSOL finite-element software, a mathematical model of the temperature field distribution in the pavement base under large temperature differences was established. The characteristics of the temperature field distribution within the base under different environmental temperature differences were simulated, and the range of environmental temperature differences that must be overcome during asphalt concrete paving was identified.

The numerical simulation results show that, under large temperature differences, the temperature field within the base exhibits obvious nonlinear distribution characteristics. The closer a base section is to the surface, the greater the amplitude of temperature variation with diurnal environmental fluctuations; temperatures in deeper sections are relatively stable. This nonuniform temperature-field distribution enhances the “heat-absorption effect” of the underlying layer on the paved layer during construction and accelerates heat loss from the bottom of the paved layer. As shown in Figure 2.

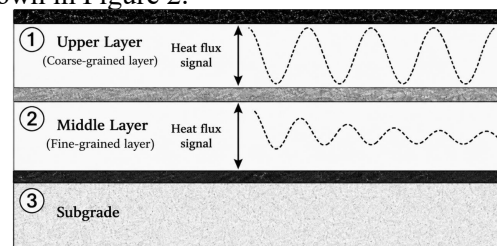


Figure 2. Schematic Principle of Temperature Field Distribution within the Base Layer

According to the numerical simulation and field monitoring results, the environmental

temperature difference that must be overcome during asphalt concrete paving in the project area can reach 20–25 °C. During periods of drastic diurnal temperature differences, the time required for the paved layer to cool from a high-temperature state to the effective compaction-temperature range is significantly shortened. This places higher technical requirements on asphalt mixture design and construction temperature control.

2.3 Temperature Dependence of Asphalt Mixture Construction Performance

The construction performance of asphalt mixtures, including workability, compactability, and forming quality, is closely related to their temperature state. Taking the environmental temperature difference during asphalt mixture paving as the cooling criterion, this study systematically analyzes the effects of temperature on the high-temperature stability, low-temperature cracking resistance, and water stability of modified asphalt. As shown in Figure 3.

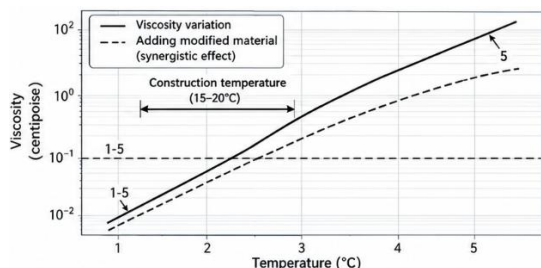


Figure 3. Modified Stone Waves with Added Warm Mix Agent

The high-temperature stability of modified asphalt is reflected in its ability to resist deformation and flow under high-temperature conditions. As temperature increases, asphalt viscosity decreases, and modified asphalt is more prone to flow deformation at high temperatures, affecting the stability of the paved layer before rolling. Low-temperature cracking resistance reflects the ability of asphalt to resist cracking at low temperatures. As temperature decreases, asphalt becomes harder and more brittle, its toughness decreases, and cracking is highly likely to occur under thermal stress. From the perspective of asphalt rheological properties, asphalt viscosity follows a certain functional relationship with temperature. In warm-mix technology, adding warm-mix additives can effectively reduce asphalt viscosity at mixing and compaction temperatures, thereby significantly lowering construction temperature

without reducing mixture workability. This mechanism provides the theoretical basis for applying warm-mix technology to solve construction problems under large temperature differences.

3. Experimental Data

3.1 Experimental Materials and Program

This study takes the road construction project from Dachanggou (G331) via Mingxin Coal Mine to G335 as the supporting project and selects the asphalt and mixtures used at the project site for experimental investigation. The modified asphalt used in the tests was SBS-modified asphalt widely used at the project site. Two warm-mix additives were selected for comparison: a composite warm-mix additive mainly composed of polyethylene wax and plasticizer (denoted W-1) and a surfactant-type warm-mix additive (denoted W-2).

The overall experimental program consisted of four stages:

- (1). Basic physicochemical property tests were conducted on the asphalt mixtures used at the project site to establish their performance baseline;
- (2). Using environmental temperature difference as the cooling criterion, experiments were conducted to investigate the effects of different warm-mix additives on the properties of modified asphalt;
- (3). Orthogonal tests were designed to optimize the mixture proportions using void ratio and the number of low-temperature cracking cracks as evaluation indicators;
- (4). Low-temperature performance tests were conducted on modified asphalt concrete with the optimum mix proportion to determine the optimum paving temperature.

The experiments were conducted in accordance with the relevant provisions of the Specification for Asphalt and Asphalt Mixture Tests for Highway Engineering (JTG E20). The main test indicators included penetration, softening point, ductility, viscosity, void ratio, Marshall stability, dynamic stability, low-temperature flexural strain, and freeze-thaw splitting strength ratio.

3.2 Deterioration Patterns of Asphalt Concrete Performance under Large Temperature Differences

To investigate the deterioration patterns of asphalt concrete performance evaluation

indicators under large temperature differences, systematic laboratory tests were conducted on strength, compactness, aging resistance, durability, and water resistance of asphalt concrete under different temperature-difference conditions.

Three temperature-difference conditions were established for comparative analysis: small

temperature difference (diurnal temperature difference of approximately 10 °C), moderate temperature difference (approximately 15 °C), and large temperature difference (above approximately 20 °C). The performance indicators of specimens prepared under each condition were tested. The results are shown in Table 1.

Table 1. Test Results of Asphalt Concrete Performance Indicators under Different Temperature-Difference Conditions

Performance indicator	Small temperature difference (10 °C)	Moderate temperature difference (15 °C)	Large temperature difference (20 °C+)
Void ratio / %	4.2	5.6	7.8
Marshall stability / kN	12.6	11.3	9.4
Dynamic stability / (cycles·mm ⁻¹)	4850	4520	3980
Low-temperature flexural strain / $\mu\epsilon$	2350	2180	1860
Freeze-thaw splitting strength ratio / %	86.5	81.2	74.6

The test results show that, as the environmental temperature difference increases, all performance indicators of asphalt concrete exhibit an obvious deterioration trend. The void ratio increased from 4.2% under the small-temperature-difference condition to 7.8% under the large-temperature-difference condition, an increase of 85.7%, indicating a significant decrease in compaction quality under large temperature differences; Marshall stability decreased from 12.6 kN to 9.4 kN, a reduction of 25.4%; low-temperature flexural strain decreased from 2350 $\mu\epsilon$ to 1860 $\mu\epsilon$, indicating a significant weakening of low-temperature cracking resistance; and the freeze-thaw splitting strength ratio decreased from 86.5% to 74.6%, indicating a significant reduction in resistance to water damage under large temperature differences.

These test results clearly reveal the deterioration pattern of asphalt concrete performance indicators under large temperature differences: the larger the environmental temperature

difference, the faster the mixture cools and the more difficult it is to ensure compaction quality, resulting in a chain deterioration of various pavement performance properties. These findings provide important data support for subsequent mix proportion optimization and temperature-control research.

3.3 Effects of Different Warm-Mix Additives on Modified Asphalt Properties

Taking the environmental temperature difference during asphalt concrete paving as the cooling criterion, this study comparatively analyzed the effects of two warm-mix additives on the high-temperature stability, low-temperature cracking resistance, and water stability of modified asphalt. Equal amounts (0.5% of asphalt mass) of W-1 composite warm-mix additive and W-2 surfactant-type warm-mix additive were separately added to the modified asphalt, and conventional performance indicators were tested. The results are shown in Table 2.

Table 2. Performance Indicators of Modified Asphalt with Different Warm-Mix Additives

Performance indicator	No warm-mix additive	W-1 warm-mix additive	W-2 warm-mix additive
Penetration (25 °C) / 0.1 mm	62	66	64
Softening point / °C	76.5	74.8	75.2
Ductility at 5 °C / cm	32	38	41
Brookfield rotational viscosity (135 °C) / (mPa·s)	2150	1780	1620

The test results show that both warm-mix additives can reduce the viscosity of modified asphalt to some extent. With the addition of W-2 surfactant-type warm-mix additive, the Brookfield rotational viscosity of modified asphalt at 135 °C decreased from 2150 mPa·s to 1620 mPa·s, a reduction of 24.7%; with W-1

composite warm-mix additive, the viscosity decreased to 1780 mPa·s, a reduction of 17.2%. The reduction in viscosity indicates greater potential for lowering mixing and compaction temperatures.

In terms of low-temperature cracking resistance, the 5 °C ductility of modified asphalt increased

after adding either warm-mix additive. With W-2, ductility increased from 32 cm to 41 cm, an increase of 28.1%, indicating that the surfactant-type warm-mix additive has a more pronounced advantage in improving low-temperature ductility. Meanwhile, the penetration of modified asphalt increased slightly and the softening point decreased slightly after adding the warm-mix additives, but all values remained within the allowable ranges of the specifications and did not affect the basic pavement performance of the modified asphalt.

Overall, both warm-mix additives effectively reduce modified asphalt viscosity and improve its low-temperature performance. Among them, the surfactant-type warm-mix additive W-2 demonstrates superior overall performance in lowering construction temperature and improving low-temperature performance and is therefore more suitable for construction of modified asphalt mixtures under large temperature differences.

3.4 Mix Proportion Optimization and Orthogonal Tests

To determine the optimum mix proportion of modified asphalt mixtures suitable for construction under large temperature differences, orthogonal tests were designed using void ratio and the number of low-temperature cracking cracks as evaluation indicators. Three factors were selected: warm-mix additive content, mineral filler content, and asphalt content, each at three levels. An L9(3³) orthogonal array was used to arrange the test program.

According to the range analysis results of the orthogonal tests, the order of influence of the three factors on mixture void ratio and low-temperature cracking performance was: warm-mix additive content > asphalt content > mineral filler content. Among these, warm-mix additive content had the most significant effect on void ratio. An appropriate amount of warm-mix additive can significantly reduce the void ratio of the mixture under low-temperature conditions and improve compaction.

Through comprehensive analysis of the effects of factor levels on the evaluation indicators, the optimum mix proportion parameters for modified asphalt mixtures under large temperature differences were determined as follows: optimum warm-mix additive content, 0.5% of asphalt mass; optimum asphalt content, 4.8% of mixture mass; and optimum mineral

filler content, 4.0% of mixture mass.

Low-temperature performance tests were conducted on modified asphalt concrete with the optimum mix proportion. The results showed that the mixture had a void ratio of 3.9%, Marshall stability of 13.2 kN, low-temperature flexural strain of 2600 $\mu\epsilon$, and freeze-thaw splitting strength ratio of 88.7%. All performance indicators were significantly better than those of the baseline mix proportion without warm-mix additive, while good construction performance was maintained even when the construction temperature was reduced by 15–20 °C.

3.5 Determination of the Optimum Paving Temperature

After determining the optimum mix proportion, comparative tests were conducted on the compaction effect and performance of modified asphalt concrete at different paving temperatures to determine the optimum paving temperature for the mix proportion. Five paving temperatures were tested: 130 °C, 140 °C, 150 °C, 160 °C, and 170 °C. The void ratio and Marshall stability of specimens prepared under each condition were measured. The results are shown in Table 3.

Table 3. Performance of Modified Asphalt Concrete at Different Paving Temperatures

Paving temperature / °C	Void ratio / %	Marshall stability / kN	Compaction evaluation
130	7.6	9.8	Insufficient compaction
140	5.8	11.2	Basically compactable
150	4.1	12.8	Good compaction
160	3.8	13.1	Good compaction
170	3.6	13.3	Good compaction

The test results show that when the paving temperature is below 140 °C, the mixture is difficult to compact adequately, the void ratio increases significantly, and Marshall stability decreases markedly. When the paving temperature reaches 150 °C or above, the mixture can achieve good compaction. Considering the objective of reducing construction temperature through warm-mix technology and the rapid heat loss under large temperature differences, the optimum paving temperature was determined to be 150 °C. At this paving temperature, the mixture maintains good workability while the mixing and paving temperatures are 15–20 °C lower than those of conventional modified asphalt mixtures. This effectively shortens the cooling time of the

mixture and creates favorable conditions for ensuring construction quality under large temperature differences.

4. Conclusions

Based on the road construction project from Dachanggou (G331) via Mingxin Coal Mine to G335 in Hami, this study systematically investigated key technologies for construction quality control of asphalt concrete pavements under large temperature differences. The main conclusions are as follows:

- (1). Large temperature differences have a significant effect on asphalt concrete pavement construction quality. As the environmental temperature difference increases, the void ratio of asphalt concrete increases significantly, while strength and durability indicators decrease markedly. Under the large-temperature-difference condition (above 20 °C), the void ratio increased by 85.7% compared with the baseline condition, indicating significant deterioration in compaction quality. The larger the environmental temperature difference, the faster the mixture cools and the more difficult it is to ensure compaction quality.
- (2). Warm-mix technology can effectively address construction problems under large temperature differences. The surfactant-type warm-mix additive can significantly reduce modified asphalt viscosity (by up to 24.7%) and markedly improve low-temperature ductility (5 °C ductility increased by 28.1%). It provides better overall performance than the composite warm-mix additive in lowering construction temperature and improving low-temperature performance and is more suitable for modified asphalt mixture construction in regions with large temperature differences.
- (3). Orthogonal tests determined the optimum mix proportion of modified asphalt mixtures suitable for construction under large temperature differences: warm-mix additive content of 0.5% of asphalt mass, asphalt content of 4.8% of mixture mass, and mineral filler content of 4.0% of mixture mass. Under the optimum mix proportion, the pavement performance of the mixture was significantly improved, with void ratio reduced to 3.9% and low-temperature flexural strain reaching 2600 $\mu\epsilon$.
- (4). Considering both warm-mix temperature reduction and compaction quality requirements, the optimum paving temperature of the modified asphalt mixture was determined to be 150 °C,

which is 15–20 °C lower than the conventional construction temperature. This can effectively shorten mixture cooling time and ensure compaction quality under large temperature differences.

By establishing a dynamic temperature-control system for asphalt concrete construction under large temperature differences and deploying automated temperature-measurement points throughout the entire process of mixing, transportation, paving, and rolling, real-time monitoring and intelligent control of temperature throughout construction can be achieved. This can effectively prevent low-temperature construction problems such as local segregation and insufficient compaction and significantly improve asphalt pavement construction quality and long-term service performance.

Acknowledgements

This study takes the road construction project from Dachanggou (G331) via Mingxin Coal Mine to G335 in Hami, as the supporting project.

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