Advanced material design for high-performance asphalt pavement in high-altitude roads on the Tibetan Plateau

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Abstract: Building sustainable and durable roads on the Tibetan Plateau at altitudes exceeding 4,500 meters poses significant engineering challenges due to extreme environmental conditions, including intense UV radiation, drastic temperature fluctuations, and low oxygen levels. This review investigates the critical criteria that asphalt materials must satisfy to endure these conditions and outlines a detailed material design plan for road construction in such high-altitude terrains.

The analysis identifies key performance requirements such as thermal stability, cold resistance, UV resistance, and superior adhesion properties. To address these needs, the review explores the integration of advanced materials like SBS-modified bitumen, anti-aging agents, UV stabilizers, and high-durability aggregates. The study also emphasizes the importance of optimized mix designs and modern production techniques like warm mix asphalt technology to enhance workability and durability.

Furthermore, the review highlights the necessity of rigorous testing protocols, including dynamic shear rheology and bending beam rheometry, to ensure compliance with high-altitude specifications from previous publications. By employing a strategic combination of modified binders, performance-enhancing additives, and precise engineering methods, the proposed asphalt design offers a resilient solution to withstand the Tibetan Plateau's unique challenges.

This paper contributes to the field of pavement engineering by providing a comprehensive framework for the development of asphalt materials tailored to extreme environments, promoting long-term road sustainability in high-altitude regions.

Keywords: Tibetan Plateau; High-altitude road construction; Asphalt material design; Thermal stability; UV resistance; SBS-modified bitumen; Pavement engineering; Modified binders; Anti-aging agents.

1. INTRODUCTION

Constructing roads on the Tibetan Plateau presents unique challenges due to its extreme environmental and geographical conditions. The region's high altitude, averaging over 4,500 meters above sea level, is characterized by low oxygen levels, drastic diurnal temperature variations, and intense ultraviolet radiation, all of which impose severe constraints on conventional road construction materials. In the 21st century, researches have been conducted on the design and construction of asphalt pavement structures in permafrost regions of the Tibetan Plateau. As a result, the asphalt pavement with typical structures have been proposed for the permafrost regions (Ma et al., 2006). The Tibetan Plateau's subfreezing temperatures and frequent freeze-thaw cycles can cause traditional asphalt to crack and deteriorate prematurely. Additionally, the high-altitude environment accelerates oxidation and aging processes in asphalt, leading to brittleness and loss of elasticity over time. The annual variation rates of temperature and the average minimum temperature in January are both positive, and the temperature is higher than the annual average minimum warming amplitude (Liu et al., 2014; Wang, 2005). To meet these challenges, asphalt must satisfy a set of stringent criteria, including enhanced thermal stability, resistance to cracking, improved elasticity, and reduced susceptibility to UV-induced aging. Innovations such as polymer-modified asphalt, nanomaterial additives, and specialized binders have been developed to address these issues. The permafrost develops in loose sediments and strata of various terrains and geomorphic units, and basically distributes continuously in large areas (Yin et al., 2014). In the middle part of permafrost, the ground temperature decreases by about 1° C for every 1° increase in latitude from the south to the north. The ground temperature decreases 0.6° C–1.0° C for every 100 m elevation increase (Wang, 2008).

This paper investigates the essential criteria for asphalt application on the Tibetan Plateau and proposes a detailed material design plan. Researchers (Huang, 2017; Mao et al., 2017; Wang, 2016b, 2017) conducted studies on the structural deformation characteristics of high-grade road base pavement in the perennial permafrost zone from 2016 to 2017. By integrating advanced material science techniques, such as polymer modification and nanotechnology, the proposed design aims to deliver high-performance asphalt that can withstand the plateau's extreme environment.

2. DETAILED CRITERIA FOR ASPHALT ON THE TIBETAN PLATEAU

2.1. Low-Temperature Performance

Flexibility at Low Temperatures: Asphalt used in the Tibetan Plateau must remain flexible at extremely low temperatures, often dropping below -20°C during the winter. As temperatures decrease, bitumen becomes brittle, which can cause cracking under the strain of traffic loads or temperature-induced stresses. This brittle failure occurs when the asphalt cannot accommodate the thermal contraction of the pavement.

Modification for Flexibility: To address this, Polymer-Modified Bitumen (PMB) is commonly used. Polymers, like Styrene-Butadiene-Styrene (SBS), improve the ductility of the bitumen at low temperatures by increasing its elasticity and preventing it from cracking. These polymers also provide a better response to temperature variations, enhancing the material’s overall flexibility and lowering its brittleness index (Bri).

Testing: Low-temperature performance can be assessed using the Bending Beam Rheometer (BBR) and Dynamic Shear Rheometer (DSR) to measure the creep stiffness and resilience of the asphalt binder at low temperature stability.

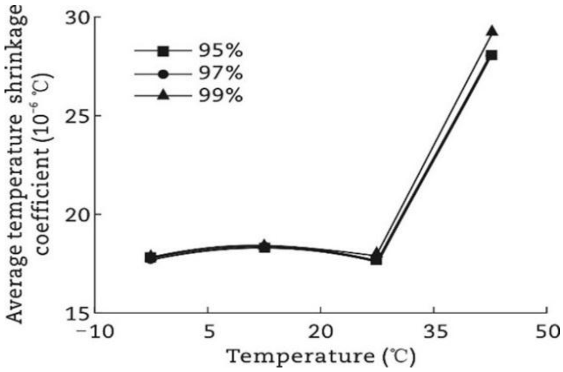

Figure 1. Relationship between average temperature shrinkage coefficient and test temperature (Shaa et al., 2022).

Resisting Rutting and Deformation: During the summer, the Tibetan Plateau can experience high daytime temperatures, leading to softening of asphalt and the potential for rutting or deformation, especially under heavy traffic. Asphalt should possess a high softening point to resist such effects.
Materials for High-Temperature Stability: High-penetration bitumen is beneficial for improving high-temperature stability, as it has a higher resistance to softening. Additionally, rubberized asphalt, which involves incorporating crumb rubber from tires, can enhance viscoelasticity and improve rut resistance by increasing the asphalt's elastic recovery. This is crucial for maintaining the structural integrity of the road under load and heat.

Testing: The Softening Point test (ASTM D36) and the High Shear Viscosity test are essential in assessing the asphalt’s performance under high temperatures.

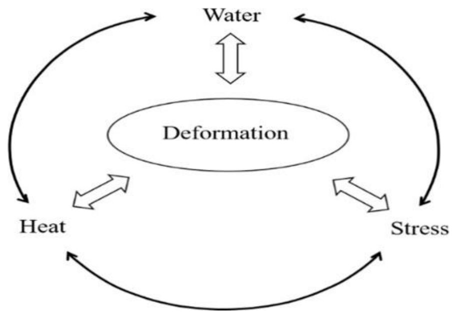

Figure 2. Mechanism of coupled heat-moisture-stress of froze soil (Shaa et al., 2022).

2.2. Resistance and radiation

Impact of UV Radiation: The Tibetan Plateau's high altitude results in greater exposure to UV radiation, which accelerates the aging of asphalt. Prolonged UV exposure can cause the asphalt to oxidize, leading to embrittlement and surface cracking.

Enhancing UV Resistance: The use of antioxidants and UV stabilizers in the asphalt mix can significantly improve its ability to withstand UV degradation. Hindered amine light stabilizers (HALS) and anti-oxidants like Sulfur compounds help in absorbing UV radiation and reducing the oxidative degradation of the bitumen, which extends the service life of the asphalt.

Testing: Accelerated aging tests, such as the RTFOT (Rolling Thin Film Oven Test) and UV aging tests, can be performed to evaluate the effect of UV radiation on bitumen.

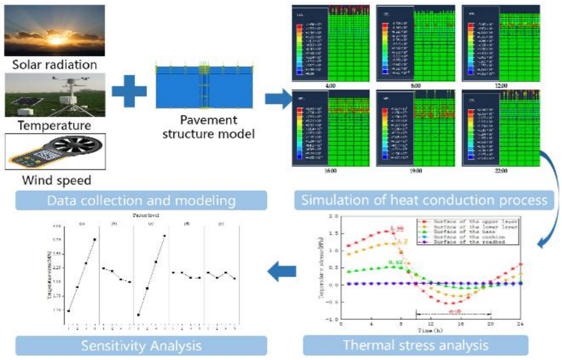

Figure 3. Research route for the temperature and thermal stress field of asphalt pavement on the Tibetan Plateau (Li et al., 2024).

2.3. Water Resistance

Stripping and Moisture-Induced Damage: The region’s varying precipitation levels and freeze-thaw conditions necessitate asphalt that can resist moisture stripping, a phenomenon where water infiltrates the asphalt and causes the binder to lose adhesion with the aggregates, leading to the deterioration of the surface.

Improving Water Resistance: Polymer-modified binders can help improve the bond between the asphalt and aggregate particles, reducing the impact of moisture on the mix. Additionally, waterproofing agents such as polymeric emulsions or silane-based additives can be incorporated to further enhance water resistance.

Testing: The Boiling Water Test and the Moisture Susceptibility Test (such as the Tensile Strength Ratio test) can be used to measure the asphalt’s ability to resist moisture-induced damage.

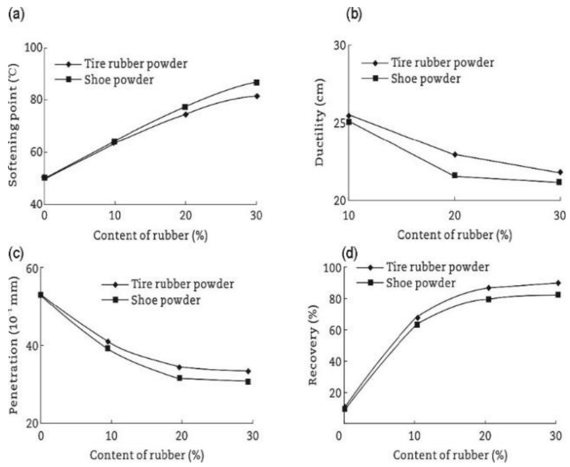

Figure 4. The influence of crumb rubber based on different contents and types (Ye et al., 2003). (a) Softening point. (b) Ductility. (c) Penetration. (d) Recovery.

2.4. Low-Temperature and Moisture Damage

Freeze-Thaw Resistance: Asphalt on the Tibetan Plateau must be resistant to damage caused by repeated freeze-thaw cycles, where water infiltrates the asphalt and expands during freezing, leading to cracking and degradation. This can be exacerbated by the region's high-altitude conditions, which induce rapid temperature fluctuations between day and night.

Design Considerations: Asphalt mixtures should be designed to balance resilient modulus (the resistance to deformation) with moisture resistance. Modified binders, particularly those with rubber or polymeric modifications, can help to improve the mixture’s performance under freeze-thaw conditions. Additionally, ensuring proper aggregate grading and minimizing void spaces within the mixture reduces the potential for water infiltration.

Testing: Freeze-thaw durability is commonly tested using the Freeze-Thaw Durability Test and the Indirect Tensile Test to assess the mixture’s ability to resist water-induced cracking under low temperatures.

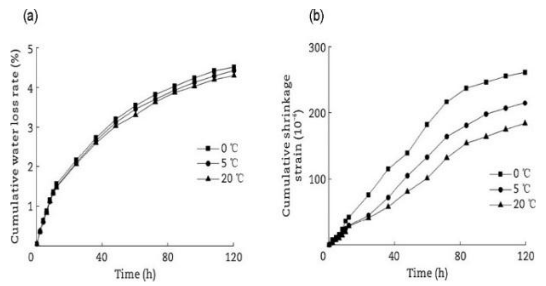

Figure 5. The relationship between the drying shrinkage characteristics and the test temperature (Shaa et al., 2022). (a) Cumulative Moisture evaporation rate. (b) Dry shrinkage strain at different times.

2.5. Durability

Resistance: Due to the rugged terrain, heavy traffic (including military and transport vehicles), and extreme environmental conditions, the asphalt must demonstrate high resistance to fatigue cracking, wear, and surface deterioration over time.
Enhancing Durability: To improve the long-term durability of the pavement, the use of high-modulus asphalt mixtures that incorporate higher levels of coarse aggregates and polymers can enhance the structural stability of the road. Additionally, the asphalt should maintain low void content to reduce susceptibility to aging and moisture infiltration.
Testing: Fatigue testing and Dynamic Modulus Testing are essential in determining the mix's ability to withstand repetitive traffic loading without deteriorating.

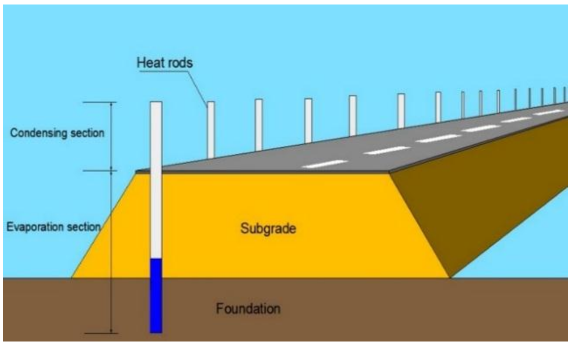

Figure 6. Heat rod roadbed schematic diagram (Shaa et al., 2022).

2.6. Granular Composition

High-Quality Aggregates: The aggregates used in asphalt mixes for the Tibetan Plateau should be resistant to weathering and freeze-thaw damage. The granular composition should feature strong, angular aggregates like basalt or granite, which are known for their high durability and resistance to wear and tear under extreme temperature fluctuations.

Coarse Aggregates for Freeze-Thaw Resistance: Coarse aggregates should be selected for their ability to resist the effects of freeze-thaw cycles, which are prevalent in the region. Using aggregate sources with low absorption rates and high durability ratings is critical for ensuring the longevity of the asphalt under freeze-thaw conditions.
Testing: Aggregate Durability Tests, such as Los Angeles Abrasion and Freeze-Thaw Durability Tests, are conducted to ensure the quality and longevity of aggregates in the asphalt mixture.

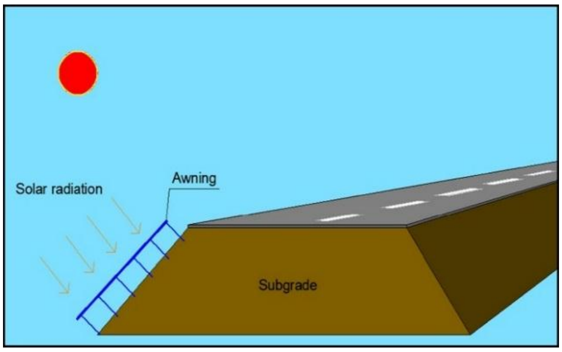

Figure 7. Awning roadbed schematic diagram (Shaa et al., 2022).

3. MATERIALS AND PREPARATION PLAN FOR ASPHALT ON THE TIBETAN PLATEAU

The successful preparation of asphalt for use in the harsh conditions of the Tibetan Plateau requires carefully selected materials and a tailored preparation plan. These materials must be chosen for their ability to perform under extreme temperature fluctuations, high UV radiation, moisture infiltration, and heavy traffic. The key components in the material design plan are as follows:

3.1. Bitumen Selection

Polymer-Modified Bitumen (PMB): As mentioned earlier, PMB is essential for enhancing the asphalt's performance under low temperatures and high stresses. Polymers such as Styrene-Butadiene-Styrene (SBS), Ethylene-Vinyl-Acetate (EVA), or Polyethylene (PE) are commonly added to bitumen to improve its viscoelastic properties, increasing its flexibility in low temperatures and enhancing its resistance to deformation in high temperatures.
Crumb Rubber Modified Asphalt (CRMA): This is another effective modification, particularly for high-temperature stability. The addition of rubber particles derived from waste tires helps reduce rutting by increasing the elasticity of the binder. CRMA also contributes to the low-temperature performance of the asphalt and is an eco-friendly modification.
Selection Process: The selection of the right bitumen grade is crucial, with penetration grade bitumen

(60/70) being a common base. For extreme high and low temperatures, modified bitumen with improved rheological properties should be selected. The Super pave Performance Grading (PG) system can be used to grade bitumen based on the temperature conditions of the Tibetan Plateau.

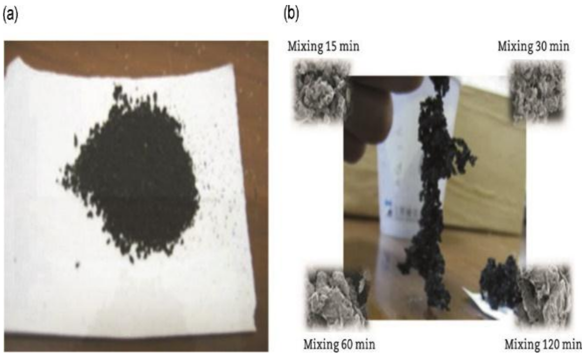

Figure 8. Rubber powder. (a) Untreated rubber powder. (b) The state of rubber powder under different mixing times (Wang and Cao, 2011).

3.2. Aggregates Selection

Coarse Aggregates: The selection of aggregates is vital for the durability and resistance of the asphalt to freeze-thaw cycles, abrasion, and weathering. High-quality aggregates, like basalt or granite, are preferred because they are highly durable and resist weathering under high-altitude conditions. Coarse aggregates should be angular in shape for better interlocking and improved load distribution. Aggregates must also be tested for their resistance to freezing and thawing, using standards like the Los Angeles Abrasion Test and Freeze-Thaw Durability Test to ensure their suitability for harsh conditions.

Fine Aggregates: Fine aggregates, such as sand, must also be well-graded to improve the workability and stability of the mix. These aggregates should exhibit low water absorption and should be free from clay or fine materials that could reduce bonding strength.

Aggregate Gradation: Proper gradation ensures that the asphalt mixture has an optimal balance between void content, stability, and flexibility. Dense-graded aggregates are typically preferred for use in high-traffic areas, as they enhance the mixture's stability and resistance to wear.

3.3. Additives and Modifiers

Antioxidants and UV Stabilizers: To improve the resistance of asphalt to UV radiation and prevent degradation due to oxidation, additives such as hindered amine light stabilizers (HALS) and sulfur-based antioxidants are incorporated into the binder. These additives absorb UV radiation and reduce the oxidation of bitumen, which extends the service life of the pavement. These additives help maintain the rheological properties of the binder over time, preventing cracking and brittleness.

Waterproofing Agents: To enhance water resistance and minimize moisture-induced damage, silane-based waterproofing agents and polymeric emulsions are often added to the binder. These agents form a hydrophobic layer around the aggregates, reducing moisture infiltration and preventing stripping.

Fiber Reinforcement: In some cases, adding fibers, such as polypropylene fibers or cellulose fibers, can improve the stability and crack resistance of the asphalt. The fibers help distribute stresses more evenly across the surface and prevent the formation of cracks due to fatigue.

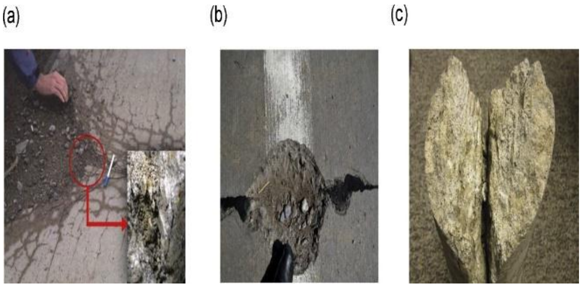

Figure 9. Forms of structural damage to concrete pavements on the plateau. (a) Exposed bone and spalling of concrete pavements. (b) Severe damage at structural joints in concrete pavements. (c) Freeze-thaw damage at structural joints in concrete pavements (Wang et al., 2018d).

3.4. Mix Design and Preparation

Hot Mix Asphalt (HMA): The most commonly used form of asphalt for road construction is Hot Mix Asphalt (HMA). The preparation of HMA involves heating the bitumen to a temperature of around 160°C - 180°C and mixing it with pre-heated aggregates. The mixing process ensures that the binder coats the aggregates uniformly, creating a stable and durable mixture. The temperature must be controlled carefully to avoid over-heating, which can degrade the binder, especially with modified bitumen.

Warm Mix Asphalt (WMA): In some regions, Warm Mix Asphalt (WMA) technology is used, which allows for mixing and compacting the asphalt at lower temperatures (approximately 120°C - 140°C). This reduces energy consumption and emissions during production, which is particularly important in high-altitude areas where environmental impact must be minimized.

Mix Design Methodology: The Marshall Mix Design and Super pave Mix Design are the most commonly used methodologies to determine the optimal binder content, aggregate gradation, and additives required for the mix. These methods evaluate factors such as voids in mineral aggregate (VMA), voids filled with bitumen (VFB), flow properties, and stability to ensure the mix will perform adequately under traffic and climatic conditions.

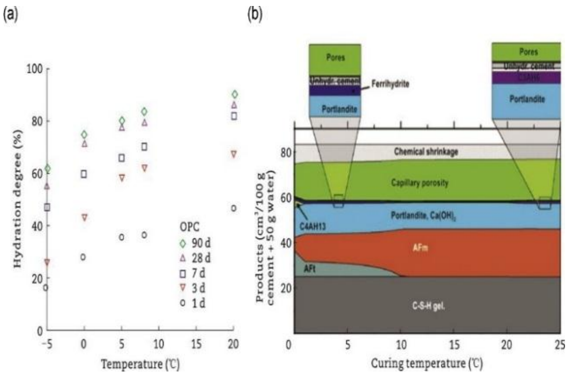

Figure 10. Influence of temperature on cement hydration process. (a) Hydration degree. (b) Hydration products (Liu et al., 2017a).

3.5. Quality Control and Testing

Performance Testing: The Dynamic Modulus Test and Fatigue Testing are essential to evaluate the asphalt's performance under repetitive loading. These tests simulate the stresses that the pavement will experience under traffic and environmental conditions.

Moisture Susceptibility: The Tensile Strength Ratio (TSR) test is used to assess the asphalt's resistance to moisture-induced damage by measuring the tensile strength of the asphalt mixture before and after conditioning in water. This helps predict the potential for stripping or loss of bond between the binder and aggregates.

Low-Temperature Testing: The Bending Beam Rheometer (BBR) and Direct Tension Test (DTT) are used to measure the creep stiffness and ductility of the binder at low temperatures. These tests ensure that the asphalt will remain flexible and resistant to cracking at low temperatures, even in extreme cold conditions.

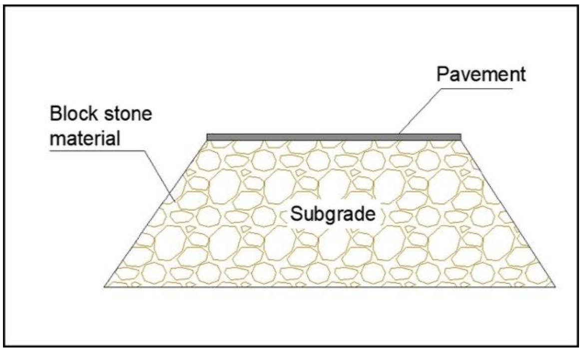

Figure 11. Block-stone embankment schematic diagram (Shaa et al., 2022).

3.6. Preparation Plan

Material Procurement and Testing: Before mixing, all raw materials (bitumen, aggregates, and additives) should undergo rigorous testing for quality, including particle size distribution, moisture content, and resistance to weathering. Testing should be carried out according to international standards, such as ASTM or AASHTO specifications.

Mixing Process: Once the materials are selected and tested, the mixing process begins. The binder and aggregates are heated to the appropriate temperatures and mixed in a batch plant or drum plant. For Warm Mix Asphalt (WMA), special additives are added to lower the mixing and compaction temperatures. The mixture is then transported to the construction site and compacted to the required density and thickness.

Compaction: Compaction should be performed while the asphalt is still hot, using appropriate rollers to achieve the desired density and void content. The compaction process ensures the asphalt mixture achieves maximum stability and resistance to deformation under traffic.

Table 1. Summary of deterioration forms and mechanisms of plateau cement paste and concrete under freeze-thaw coupling of chloride and salt under the combined effect of chloride salt and freeze-thaw (Wang et al., 2019b).

Exposure Condition	4 Mg	20 Mg	4Ca	20Ca
Paste Specimens Soaking for 84 days				
Observed Phenomena up to 84 days	Double layer - a white thin film layer on the surface of an expansive layer; no clear deterioration can be observed.	A 3–5 mm thick crystal layer formed; no deterioration can be observed on the specimen when the layer was removed.	A white thin crystal layer was formed on the surface of specimen. No deterioration can be observed.	A white think film was formed and scaling related cracks can be observed.
Mainly Formed Phases	Brucite; calcite; Ettringite; Friedel's salt	Brucite; MgOXY; bischofite; calcite; tachyhydrite (with mother solution)	Calcite; Friedel's salt	CaOXY; calcite; Friedel's salt
Mechanism Verification	Partially comply with Mechanism 4	Comply with Mechanism 3	No deterioration mechanism	Comply with Mechanism 1
Control Concrete Samples Soaking for 180 days				
Observed Phenomena up to 180 days	Expansive layer formed on the surface of paste and the thickness of the layer increased with time.	No cracking was observed up to 140 days of soaking but severe cracking occurred thereafter, mostly around coarse aggregate.	No deterioration can be observed.	Scaling can be observed before about 80 days and severe cracking occurred thereafter causing concrete specimens to fall apart.

4. MATERIAL DESIGN PLAN FOR ASPHALT ON THE TIBETAN PLATEAU

The material design plan for asphalt to be used on the Tibetan Plateau must account for the extreme environmental conditions, including low and high temperatures, high-altitude UV radiation, moisture-induced damage, and heavy traffic. A comprehensive approach involves selecting appropriate materials and designing an asphalt mix that will ensure the pavement's durability, flexibility, and resistance to environmental stresses. This plan will outline the specific design steps, material selection, and testing processes needed to prepare asphalt suitable for these challenging conditions.

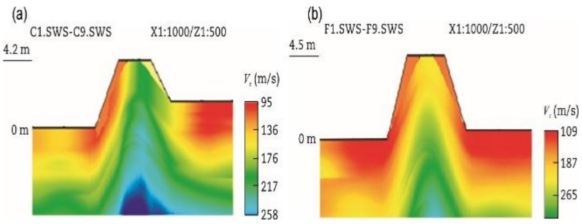

Figure 12. Cross-sectional view of roadbed tested by surface wave meter. (a) Roadside water. (b) Sunny-shady slope (Mao et al., 2013).

4.1. Material Selection

The first step in the material design process is selecting the components that will make up the asphalt mixture. Each component must be carefully chosen based on its performance in the extreme conditions of the Tibetan Plateau.

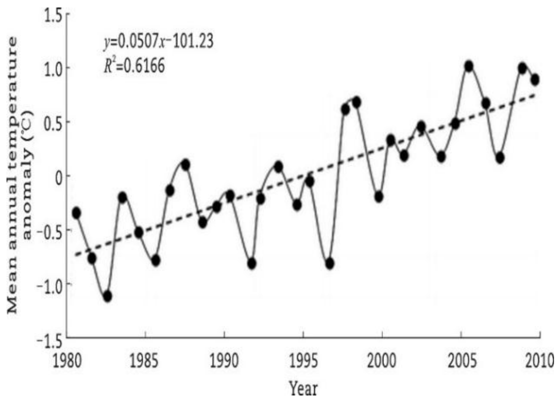

Figure 13. Climate change in QTP from 1980 to 2010 (Li and Wu, 2005).

4.1.1. Bitumen Selection

Polymer-Modified Bitumen (PMB): Polymer modification improves the low-temperature flexibility and high-temperature stability of asphalt. For the Tibetan Plateau, SBS (Styrene-Butadiene-Styrene) and EVA (Ethylene-Vinyl-Acetate) are common polymer modifications used to enhance the bitumen's performance. These modifications increase the viscoelasticity of the binder, helping to reduce cracking at low temperatures and improving resistance to rutting at high temperatures.

Crumb Rubber Modified Asphalt (CRMA): The addition of crumb rubber derived from recycled tires is an effective method to enhance both low- and high-temperature performance. Rubberized asphalt increases elasticity and reduces the chance of permanent deformation (rutting) under heavy traffic and high temperatures. Additionally, it can improve the water resistance of the asphalt and its fatigue resistance.

Selection of Bitumen Grade: The Performance Graded (PG) system should be used to select the appropriate bitumen grade. For the Tibetan Plateau, bitumen with PG 64-22 (suitable for moderate climates) or PG 70-22 (for areas with high temperatures) is recommended. These grades will ensure that the bitumen performs well at both high and low temperatures.

4.1.2. Aggregate Selection

Coarse Aggregates: Coarse aggregates, which make up a significant portion of the asphalt mix, should be carefully chosen for their durability and resistance to freeze-thaw cycles. Aggregates such as basalt, granite, or limestone are preferred because they have a high specific gravity, which enhances their strength and resistance to weathering. Aggregates should be tested for their water absorption, abrasion resistance, and freeze-thaw stability to ensure their performance under extreme environmental conditions.

Fine Aggregates: Fine aggregates, such as sand, should be well-graded and free from clay or other materials that might reduce the bonding strength between the binder and the aggregate. The use of well-graded fine aggregates helps to ensure proper workability and stability of the mixture.

Gradation of Aggregates: The aggregates should be blended to create a dense gradation that minimizes void content and increases stability. The typical aggregate gradation used for the Tibetan Plateau might follow the Super-pave mix design method, ensuring that the mix is stable under heavy traffic loads while maintaining the required flexibility.

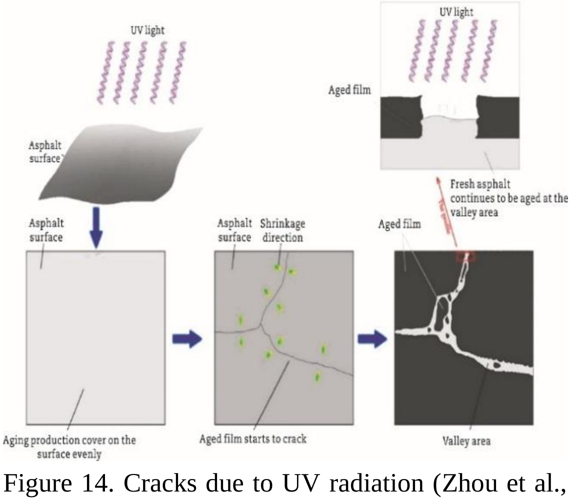

Figure 14. Cracks due to UV radiation (Zhou et al., 2019).

4.1.3. Additives and Modifiers

UV Stabilizers and Antioxidants: The high altitude of the Tibetan Plateau leads to greater exposure to UV radiation, which accelerates the oxidation of the asphalt. To mitigate this, UV stabilizers and antioxidants are incorporated into the binder. Common UV stabilizers like hindered amine light stabilizers (HALS) and sulfur-based antioxidants help prevent oxidation and keep the asphalt binder flexible over time.

Waterproofing Agents: The asphalt binder can be further enhanced by adding polymeric emulsions or silane-based waterproofing agents. These additives create a hydrophobic barrier that prevents water infiltration into the asphalt, reducing the risk of stripping (loss of adhesion between binder and aggregates) and moisture-induced damage.

Fibers: Polypropylene or cellulose fibers can be added to the asphalt to enhance fatigue resistance and crack control. The fibers help distribute stress evenly across the pavement, preventing the development of surface cracks under traffic loads.

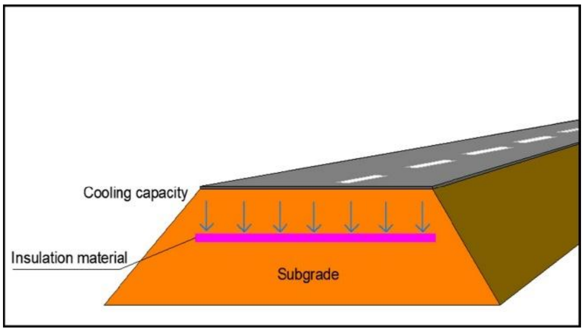

Figure 15. Thermal insulation board application schematic diagram (Shaa et al., 2022).

4.2. Mix Design Process

The mix design process involves determining the optimal proportion of bitumen, aggregates, and additives to achieve the desired performance characteristics. This process includes several steps:

4.2.1. Selection of Design Parameters

Binder Content: The binder content must be carefully selected based on the gradation of the aggregates, the traffic load, and the climatic conditions. The amount of binder influences the workability, durability, and flexibility of the asphalt. Typically, the binder content is between 4-7% of the total mixture by weight.

Void Content: To ensure good compaction and performance under heavy traffic, the mix should have adequate voids in the mineral aggregate (VMA). The void content must be balanced to avoid rutting or cracking, with typical air voids in the finished mix ranging from 3-5%.

Compaction: Proper compaction is essential for ensuring the asphalt mix achieves the required density and void structure. The Marshall Mix Design or Super-pave Mix Design can be used to determine the optimal compaction level. In the Tibetan Plateau's high-altitude conditions, achieving the proper compaction is critical to preventing deformation under load.

Table 2. Typical asphalt pavement structure (Mao et al., 2017).

Traditional asphalt pavement structure		Typical structure of existing asphalt pavement	
1	2	1	2
Bituminous surface treatment (3–4 cm)	Bituminous surface treatment (3–4 cm)	Modified asphalt concrete layer (5–9 cm)	Modified asphalt concrete layer (4–10 cm)
Interstitial gravel base (20 cm)	Gravel leveling layer (4 cm)	Semi-rigid base (18–20 cm)	Binder course (8–15 cm)
Gravel cushion (15–20 cm)	Schist base (20 cm)	Gravel cushion (15–20 cm)	Semi rigid base (20–36 cm) Gravel cushion (15–20 cm)

4.2.2. Laboratory Testing of Mix

Marshall Stability and Flow: The Marshall Stability test is used to assess the strength of the asphalt mix under load. It measures the maximum load the asphalt mix can withstand before failure, ensuring the mixture's ability to resist rutting and deformation.

Dynamic Modulus Test: The dynamic modulus test measures the stiffness of the asphalt mix, which is crucial for evaluating its ability to resist deformation under traffic. This test is particularly important for assessing the viscoelastic properties of modified bitumen.

Fatigue Resistance Test: The fatigue test measures the asphalt's ability to resist cracking under repeated traffic loads. This test is particularly useful for ensuring that the asphalt will perform well under the heavy traffic expected on the Tibetan Plateau.

Low-Temperature Performance: Bending Beam Rheometer (BBR) and Direct Tension Test (DTT) are used to assess the creep stiffness and ductility of the asphalt binder at low temperatures. These tests ensure that the asphalt will remain flexible at temperatures that can drop below -20°C.

Water Resistance Test: The Tensile Strength Ratio (TSR) test is conducted to evaluate the water resistance of the asphalt mix. This test assesses the asphalt's resistance to moisture-induced damage by comparing the tensile strength of the mix before and after it has been subjected to moisture.

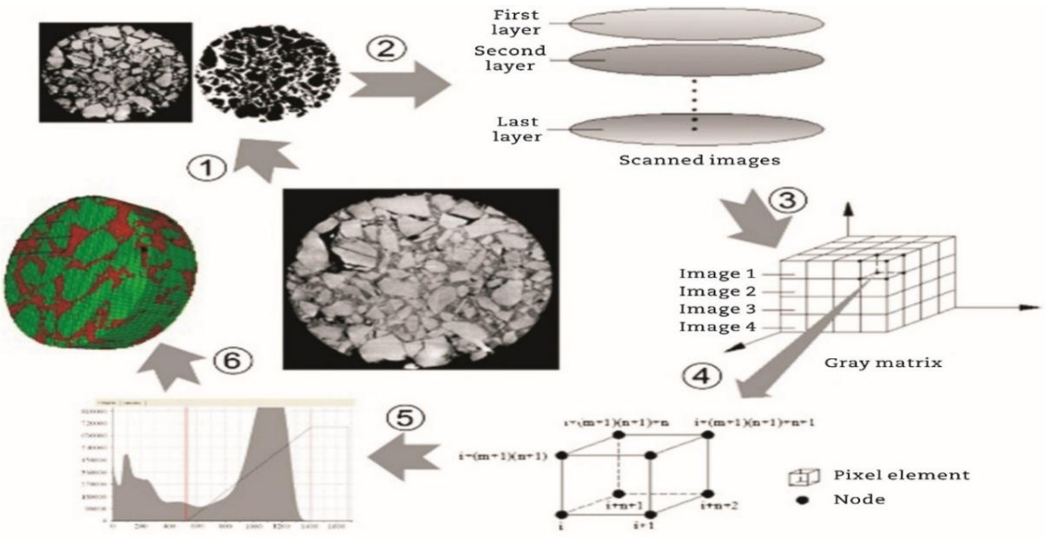

Figure 16. 3D modeling of asphalt concrete (Wang et al., 2018d, Wang et al., 2018c, Wang et al., 2018b, Wang et al., 2018a).

4.3. Performance-Based Design

The final material design should ensure that the asphalt mix performs well across a range of environmental conditions and traffic loads. The mix must exhibit:

- Low-temperature flexibility to prevent cracking during cold seasons.
- High-temperature stability to resist rutting and deformation in the summer months.
- Moisture resistance to prevent water infiltration and stripping.
- Fatigue resistance to withstand heavy traffic loads without cracking or premature wear.

4.4. Super-pave Mix Design

- The Super-pave system (Superior Performing Asphalt Pavements) is an advanced mix design method that focuses on performance-based specifications. The Super-pave method incorporates traffic volume, climate, and regional materials to design mixes tailored to local conditions. For the Tibetan Plateau, Super-pave's focus on rutting, fatigue cracking, and low-temperature cracking ensures that the asphalt mix is optimized for long-term performance.

Table 3. QTP pavement distress statistics (Dou et al., 2003).

Distress type	Percentage (%)	Distress causes
Surface wave	26.37	Permafrost thaw and sink
Surface subsidence	17.57	Permafrost thaw and sink
Cracks	36.16	Combined factors
Loose type	16.79	Asphalt aging

5. CHALLENGES IN DESIGNING ASPHALT FOR THE TIBETAN PLATEAU

Designing asphalt for use on the Tibetan Plateau, with its extreme environmental and geographical conditions, presents a number of unique challenges. These challenges primarily relate to the high altitude, temperature fluctuations, moisture variation, and heavy traffic loads that roads in this region must endure. Below are some key challenges in creating suitable asphalt for this region:

5.1. Extreme Temperature Fluctuations

Challenge: The Tibetan Plateau experiences dramatic temperature swings, ranging from freezing cold in the winter (below -20°C) to high temperatures during summer (over 30°C in some areas). These variations create stresses on asphalt, leading to cracking in cold temperatures and rutting in hot temperatures.

Problem: Asphalt needs to be both low-temperature flexible to avoid cracking and high-temperature resistant to prevent deformation. Achieving both properties simultaneously is challenging, especially at high altitudes where the physical properties of materials can behave differently compared to lower altitudes.

Figure 17. The thermal cracks on road of Tibetan Plateau (Li et al., 2024).

5.2. High UV Radiation Exposure

Challenge: The high-altitude environment of the Tibetan Plateau results in stronger ultraviolet (UV) radiation, which accelerates the degradation of asphalt over time. UV rays cause oxidation of the asphalt binder, leading to brittleness, cracking, and wear.

Problem: Asphalt needs to be resistant to UV degradation. The addition of UV stabilizers and antioxidants is essential to prevent long-term damage from UV exposure. However, finding suitable materials that maintain their properties under such intense UV radiation can be difficult.

Figure 18. Pavement cracks in alpine and high-altitude areas (Shaa et al., 2022).

5.3. Freeze-Thaw Cycles and Moisture Damage

Challenge: The region's freeze-thaw cycles, combined with seasonal precipitation, lead to moisture infiltration into the asphalt. This causes stripping (loss of adhesion between the binder and aggregates) and cracking under stress.
Problem: Asphalt must maintain its water resistance to prevent moisture-induced damage, such as stripping or freeze-thaw damage. Achieving this while ensuring the asphalt remains flexible and durable at both low and high temperatures is complex.

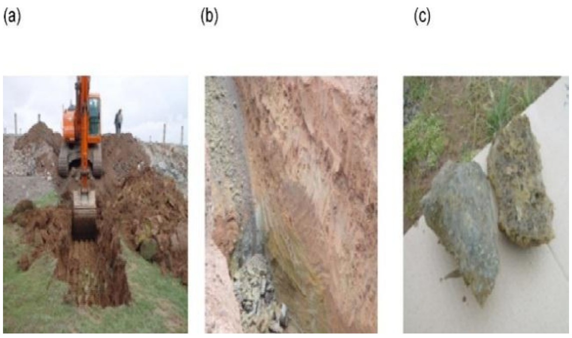

Figure 19. The section of excavating in site. (a) Excavation. (b) The section. (c) The ice lens (Mao et al., 2014).

5.4. Heavy Traffic and Load Stress

Challenge: The Tibetan Plateau experiences heavy traffic, including military vehicles, trucks, and construction vehicles, which impose substantial stresses on road surfaces. The rough terrain also accelerates wear on the road surfaces, creating challenges in maintaining durability.

Problem: Asphalt needs to be resistant to fatigue, rutting, and deformation under heavy traffic loads. Materials that are durable enough to withstand high traffic and rugged terrain conditions are difficult to optimize, and the mix must also ensure low maintenance costs.

5.5. Aggregate Quality and Performance

Challenge: The high-altitude region poses challenges in sourcing high-quality aggregates. Aggregate particles can degrade faster due to freeze-thaw cycles and the natural weathering of materials in extreme climates. Poor quality aggregates result in asphalt mixtures that are weak, prone to wear, and degrade faster under traffic stress.

Problem: Selecting strong, durable aggregates resistant to weathering and freeze-thaw cycles is difficult. The aggregates must also bond well with the binder to ensure long-term pavement stability.

5.6. Designing for Long-Term Durability

Challenge: Due to the remote location and harsh environmental conditions, maintenance and repair of roads on the Tibetan Plateau are logistically challenging and costly. Therefore, designing asphalt with long-term durability is essential to minimize the need for frequent repairs.
Problem: Achieving a balance between performance (flexibility, resistance to wear) and durability (long lifespan, minimal maintenance) is difficult, especially with the additional constraints of high altitude and extreme weather.

5.7. Material Availability and Cost

Challenge: The availability of materials suitable for the unique conditions of the Tibetan Plateau, such as high-quality bitumen and specialized additives, can be limited or expensive. Logistics are complicated by the plateau's remote location and high transportation costs.
Problem: Finding cost-effective solutions to modify and enhance the properties of asphalt while maintaining cost efficiency is a major challenge. The costs of importing specialized materials or additives could make road construction financially unsustainable in the long term.

5.8. Environmental Impact and Sustainability

Challenge: The environmental impact of using certain additives, such as rubberized asphalt or polymer-modified bitumen, raises concerns about the sustainability of materials. Furthermore, the

construction process itself may disturb delicate ecosystems in the region.
Problem: Balancing the need for performance-enhancing materials with the goal of environmentally sustainable practices is challenging. The long-term ecological impact of such road infrastructure projects needs to be carefully considered.

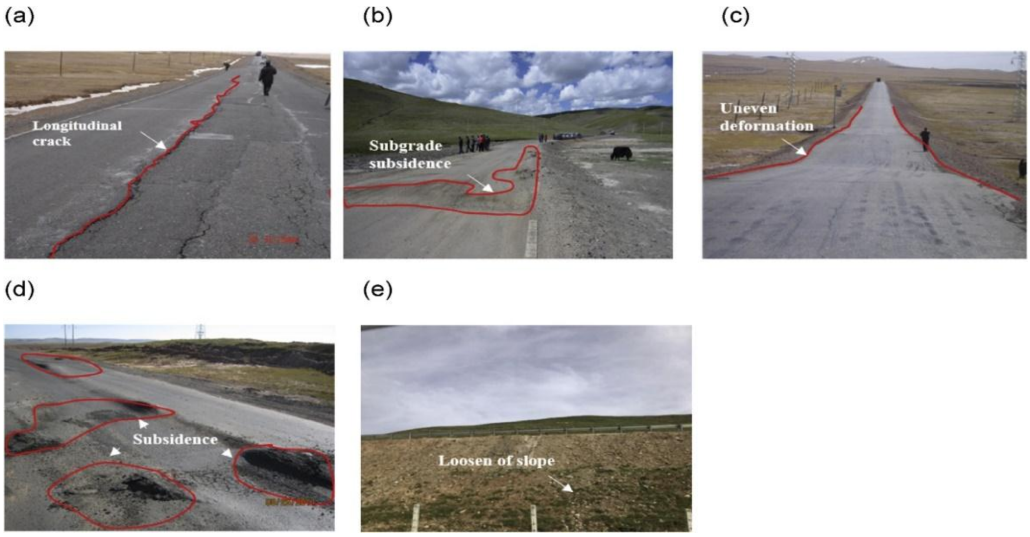

Figure 20. Typical pavement diseases in permafrost regions along the Tibetan Highway (Shaa et al., 2022). (a) Longitudinal cracks. (b) Subgrade subsidence. (c) Uneven deformation. (d) Subsidence caused by frost boil. (e) Slope failure.

5.9. Lack of Comprehensive Performance Data

Challenge: There is a lack of comprehensive long-term performance data for asphalt pavements used in the extreme conditions of the Tibetan Plateau. The region's unique climatic conditions (high altitude, cold temperatures, etc.) require special testing protocols that may not be well-established.
Problem: Without detailed and region-specific performance data, it is difficult to predict the asphalt's behavior under various stress conditions, which hinders the effective design of asphalt mixes that will withstand the plateau's harsh environment for long periods.

6. CONCLUSIONS

The design of asphalt for road construction on the Tibetan Plateau presents unique challenges due to its extreme environmental conditions, including high altitude, drastic temperature fluctuations, intense UV radiation, and heavy traffic loads. To ensure the long-term durability and performance of asphalt in this region, it is essential to develop materials that meet specific criteria, such as low-temperature flexibility, high-temperature stability, UV resistance, and moisture durability.
Key strategies include the use of polymer-modified bitumen (PMB), rubberized asphalt, UV stabilizers, and waterproofing agents to enhance the asphalt's resilience to temperature changes, moisture infiltration, and UV degradation. Moreover, selecting high-quality, weather-resistant aggregates is critical to ensuring the structural integrity of the pavement under the rugged conditions of the plateau.
However, several challenges remain in optimizing asphalt for the Tibetan Plateau, including the difficulty of sourcing materials, maintaining cost-effectiveness, and ensuring long-term sustainability. Additionally, limited performance data in similar high-altitude regions presents challenges in predicting the asphalt's long-term behavior under such extreme conditions.
Despite these challenges, research advancements in asphalt technology, coupled with innovative material design, offer promising solutions for constructing durable and cost-efficient roads in this remote and harsh region. Further studies and long-term field testing are necessary to refine these approaches and to establish best practices that can be applied to other similar environments. Ultimately, the successful development of asphalt for the Tibetan Plateau could contribute valuable insights for road construction in other high-altitude, extreme-climate regions globally.

Credit authorship contribution statement
Md Mizanur Rahman: Methodology, Writing – original draft, review & editing; Qianqian Wang: Investigation, Writing – review & editing; Yang

Meng: Investigation, Writing – review & editing; Liu Youlin: Writing – review & editing, Supervision; Zuhua Zhang: Supervision; Hegoi Manzano: Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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