Comprehensive analysis of flexible pavement performance in continental climate conditions: A case study from Uzbekistan

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Abstract: This paper presents a detailed investigation into the structural and functional performance of asphalt pavements under continental climatic conditions, with a focus on Uzbekistan. The study combines multi-year field observations, material testing, climate modeling, and finite element analysis to evaluate the impact of freeze-thaw cycles, thermal stresses, and moisture variations. A new pavement performance index (PPI) is proposed, integrating rutting, cracking, and roughness into a unified metric. Empirical results from three road segments (Tashkent-Samarkand, Fergana-Andijan, and Bukhara-Navoi) are used to validate the model. Recommendations are provided for climate-resilient pavement design strategies applicable across Central Asia.

Keywords: flexible pavement, climatic stress, rutting, thermal cracking, Uzbekistan, finite element modeling, performance index

1. Introduction

1.1 Background Global Road networks consume approximately 1.6 billion tons of asphalt annually, making asphalt one of the most utilized construction materials in modern infrastructure. However, traditional petroleum-based bituminous binders, which constitute the main component of asphalt mixes, are derived from non-renewable fossil resources and contribute significantly to greenhouse gas emissions. In fact, it is estimated that the production and use of these conventional binders account for nearly 3% of transport-sector-related emissions. With the growing urgency to combat climate change and achieve sustainability goals, the pavement engineering community has increasingly turned its attention to greener alternatives.

Bio-based modifiers, such as lignin, tall oil, and waste cooking oil, as well as recycled asphalt materials (RAP), have emerged as viable solutions to reduce the carbon footprint of road construction. These materials not only help conserve natural resources but also improve certain performance characteristics of asphalt mixes, such as low-temperature flexibility and fatigue resistance. Integrating such eco-friendly binders into national road infrastructure can significantly contribute to the development of carbon-neutral or even carbon-negative pavements in the near future. Nevertheless, their long-term performance, especially in regions with severe climatic variations like Uzbekistan, remains a subject of ongoing research and field validation.

1.2 Regional Context Pavement infrastructure in continental climates faces severe durability challenges due to high thermal amplitude, freeze-thaw cycles, and moisture infiltration. Uzbekistan, located in Central Asia, exemplifies these challenges with ambient temperatures ranging from -25°C in winter to +45°C in summer. The country has over 42,000 kilometers of paved roads, including more than 4,000 kilometers of international transit corridors that serve as critical links in the Central Asian transport network. A significant portion of these roads, particularly in mountainous or arid regions, are subject to seasonal stressors that accelerate pavement degradation.

In recent years, road modernization efforts in Uzbekistan have focused on surface rehabilitation and material innovation; however, the performance of existing pavements remains highly variable depending on climatic subzones. For example, pavements in the Ferghana Valley often face higher moisture infiltration risks, while desert roads near Karakalpakstan suffer from oxidative aging due to prolonged heat exposure. These variabilities underscore the need for localized design standards and long-term monitoring frameworks. This study evaluates the structural behavior of flexible pavements subjected to such stressors and proposes predictive strategies for improved service life.

2. Background and Literature Review

According to Huang (2004), temperature gradients significantly affect binder viscosity and stiffness. Chen & Scullion (2010) demonstrated that rutting is accelerated under repeated thawing periods, particularly when base courses retain moisture. Pavement deterioration in cold regions has been studied extensively in Canada and Russia, but similar research in Central Asia is scarce.

Recent developments in binder technology have brought polymer-modified binders (PMBs) to the forefront due to their enhanced resistance to deformation and aging. Studies by Airey et al. (2013) and Zhang et al. (2017) also suggest that the use of nanomaterials, bio-asphalts, and hybrid additives can significantly improve durability and adaptability to temperature extremes. However, most of these studies focus on laboratory-scale evaluations, while field data from semi-arid continental climates are lacking.

This gap underlines the importance of evaluating real-world performance of different pavement materials in Uzbekistan. The following sections present empirical data and simulation results to fill this void and guide future pavement design practices in the region.

3. Methodology

3.1 Site Selection

Three representative highway sections were selected:

- Section A: Tashkent-Samarkand Highway (high traffic)
- Section B: Fergana-Andijan Road (moderate traffic, mountainous terrain)
- Section C: Bukhara-Navoi Road (arid zone, low traffic)

3.2 Data Collection

- Pavement Condition Index (PCI)
- Rutting depth (RD), mm
- Crack Density (CD), m/km
- International Roughness Index (IRI), m/km
- Subgrade modulus (Ev2), MPa
- Average Daily Temperature (ADT), °C
- Precipitation & Freeze-Thaw Cycles

3.3 Laboratory Testing

Core samples from each section were tested for:

- Bitumen Penetration and Softening Point
- Marshall Stability and Flow
- Resilient Modulus (MR)

3.4 Finite Element Model (FEM)

A multilayered pavement structure was simulated using ANSYS with temperature-dependent material properties:

- Asphalt Layer: Viscoelastic
- Base/Subbase: Granular, Mohr-Coulomb
- Subgrade: Elastic-Plastic

4. Results

Table 1: Pavement Performance Parameters (2020-2024 Average)

Section	RD (mm)	CD (m/km)	IRI (m/km)	PCI	PPI
A	12.8	56.2	2.4	74	0.68
B	18.6	92.4	3.8	61	0.52
C	10.1	34.5	1.8	82	0.76

5. Discussion

Section B showed the worst performance due to steep gradients and water accumulation. The finite element analysis revealed tensile stresses exceeding 1.2 MPa at the asphalt base interface during thawing in March, leading to crack initiation. The use of conventional 60/70 penetration grade bitumen in these conditions proved inadequate. Resilient modulus decreased by 28% after repeated freeze-thaw cycles.

6. Recommendations

Replace 60/70 bitumen with polymer-modified bitumen (PMB 25/55-60) for increased flexibility.

Elevate subbase layer thickness by 20% in mountainous terrains.

Apply geotextile interlayers to mitigate crack propagation.

Integrate weather sensors for predictive maintenance alerts.

Adopt hybrid binder systems containing bio-based modifiers for sustainability.

7. Conclusion

This study confirms that continental climates impose significant structural and functional challenges on flexible pavements. A combination of material innovation, structural redesign, and predictive maintenance can enhance road longevity. The proposed Pavement Performance Index (PPI) offers a practical tool for monitoring and comparing pavement performance across varying climates. Further research is recommended on the integration of hybrid binders and real-time sensor data to support adaptive maintenance planning.

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