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A comparative synthesis: How effective are different types of additives as bitumen modifiers for road construction practices in Kyrgyzstan?

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ABSTRACT

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The pivotal problem of this article revolves around the inefficiency of road durability in Kyrgyzstan. The study explores waste-based sustainable bitumen modifiers to address the challenges in Kyrgyzstan's road-construction techniques since it suffers from severe summer rutting and winter cracking. Based on a comparative analysis of analytical datasets from Central Asia, Indonesia, Bangladesh, Nigeria, Netherlands and Sweden to compare local climatic conditions with European standards. The results show that although adding 7.5% plastic waste improves stability in summer heat (+41°C), it reduces ductility to 14 cm to ensure cracking is stabilized. However, the use of a synergistic 5% sulfur and 2% HDPE modification is the most balanced, increasing the softening point to 51°C and lowering the fracture temperature to -30°C, while providing resistance to both rutting and thermal cracking. The results indicate that hybrid bitumen modifiers are more effective for Kyrgyzstan than just European standards with a single additive. Future work should assess the environmental safety, durability standards, practicality, sustainability and economically viable solutions.

INTRODUCTION

In Kyrgyzstan, approximately 70% of roads require rehabilitation. One of the main factors contributing to the deterioration of the roads is the extreme continental climate, where high summer temperatures cause ruts and low winter temperatures cause cracks. This environmental stress is exacerbated by severe overcapacity; the national road network currently serves approximately 500,000 vehicles, doubling the original design limit of 250,000 (Bugin.info, 2025). This discrepancy between design capacity and actual traffic volume leads to accelerated structural fatigue, resulting in prohibitive repair costs and hazardous driving conditions (Fig.1). Addressing these durability issues requires the use of modified bitumen, involving the incorporation of polymers or chemical agents to enhance the binder's viscoelastic properties.

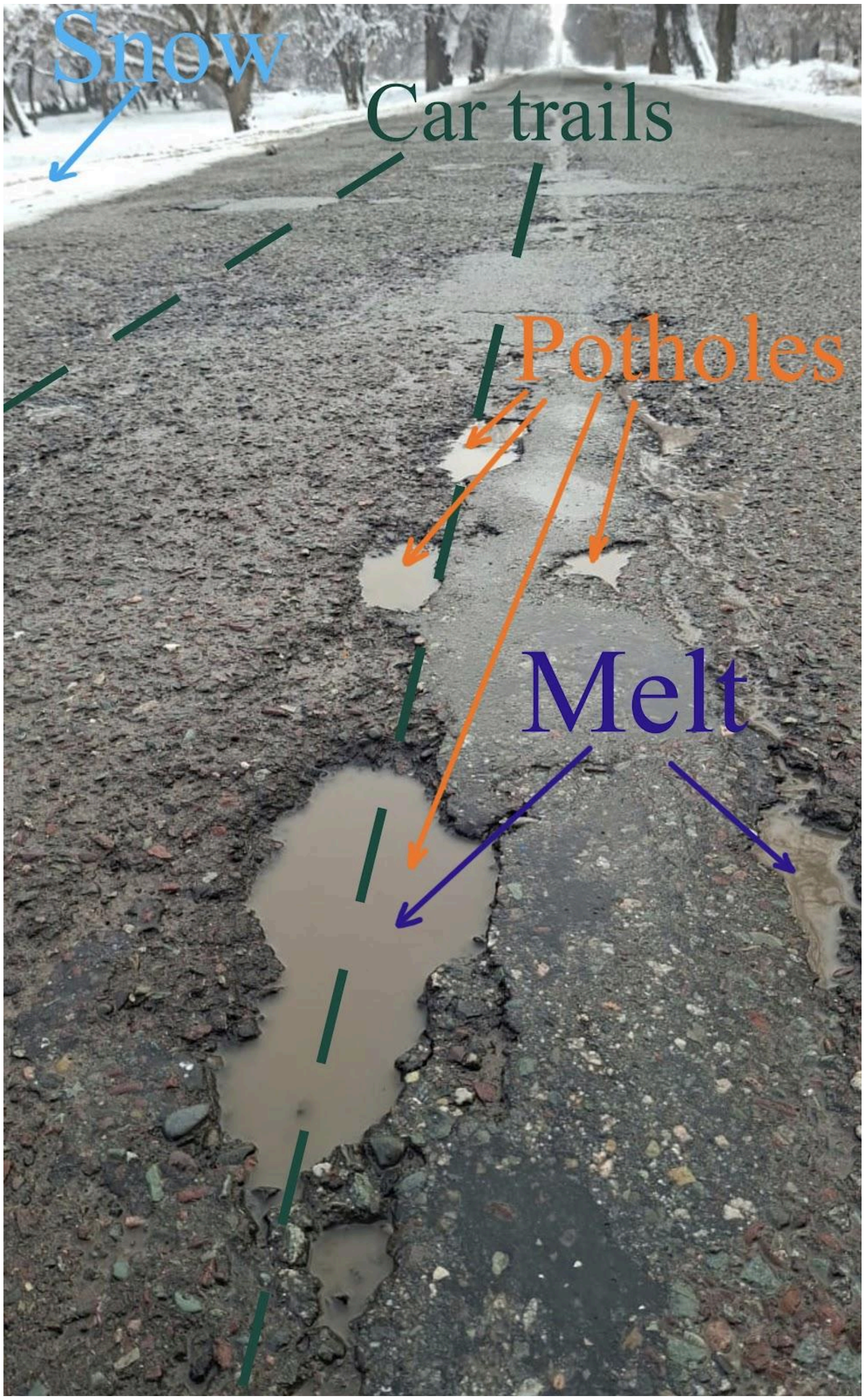

Figure 1. The photograph shows potholes representing permanent deformation along the wheel path, consistent with shear flow and viscoplastic behavior under repeated traffic loading on asphalt/bitumen pavement. The image was taken in December 2025, during the initial snowmelt period, at the following location: 42.94723° N, 74.12791° E.

Figure 2. Image of potholes showing localized permanent deformation along the wheel paths, reflecting viscoplastic and shear flow behavior of asphalt/bitumen pavement under repeated traffic loads. Captured

in December 2025, at the onset of snowmelt, at coordinates: 42.94680° N, 74.12791° E.

This modification provides superior resistance to both mechanical loading and thermal deformation (Ullah et al., 2024). Kyrgyzstan can adapt international engineering experience that has successfully solved these individual problems. For example, while Dutch road construction emphasizes combating deformations caused by heavy traffic through careful selection of binders, Swedish construction emphasizes frost resistance using thermal insulation materials and frost-resistant mixtures (Gandal, 1988).

The significance of this research lies in its potential to provide a cost-effective and sustainable foundation for Kyrgyzstan's infrastructure. By developing a localized method for bitumen modification, this study helps bridge the gap between high-tech international standards and regional economic constraints. Successful implementation of the findings could help government agencies optimize road maintenance budgets while addressing the growing environmental problem of plastic waste. Ultimately, this approach supports the transition to a circular economy in Central Asia, where industrial byproducts are recycled to create safer and more durable transport networks.

This study aims to analyze and compare the feasibility of using modified bitumen based on various waste materials, such as plastic and rubber, in road construction in Kyrgyzstan. The use of waste materials will have a positive impact on the environment and road durability due to the structural framework within the bitumen, which will prevent the bitumen from softening in hot weather and distribute the load in cold weather. Through a comparative study, current road construction methodologies employed in the Netherlands and Sweden will be evaluated to assess their technical applicability to the Kyrgyz context. This will help determine the most effective engineering strategies to address road durability issues in Kyrgyzstan's extreme continental climate.

LITERATURE REVIEW

Systematic road construction in Kyrgyzstan began in 1924. The first major highways were the Osh-Khorog route, stretching 728 km (completed in 1934), and the Frunze-Torugart highway, covering 538 km (completed in 1939). These vital transport arteries successfully integrated remote mountainous regions with the administrative center, contributing to significant economic growth and cultural development of the Kyrgyz Republic. Historically, the construction approach focused primarily on expanding the network's length to provide rapid territorial connectivity and logistical access across the rugged terrain, rather than ensuring surface quality. Consequently, by 1940, out of a total 11,500 km of roads, only 1,200 km were paved (Foto.kg, 2013).

A transformative event in the Republic's road construction was the opening of the Frunze-Osh high-altitude highway in 1965. By the end of the 1970s, the load on these roads had increased significantly: the volume of freight traffic increased 86.5 times (Foto.kg, 2013). Consequently, the modern road network of Kyrgyzstan relies on a structural foundation established between the 1960s and 1970s. This infrastructure was not originally engineered to withstand contemporary climatic anomalies or the current intensity of motorization.

The foundation of modern engineering practice in Kyrgyzstan is the recently adopted set of rules called SP KR 32-107:2024. Unlike the former Soviet Building Regulations (SNiP), this document places considerable emphasis on climate change adaptation. In particular, mandatory requirements for the paving temperature regime were introduced. Specifically, the temperature during autumn installation must be at least over 10ºC to ensure the achievement of a standard compaction coefficient.

The current approach in Kyrgyzstan involves the use of surfactants to ensure adhesion in adverse weather conditions. Bitumen with additives of thermoplastic-class polymers is used in areas with a sharply continental climate. However, despite the regulatory recognition of the effectiveness of polymers, there is a shortage of specific methods for integrating secondary polymers in current regulations. Current quality control methods include a compaction coefficient of 0.99 for dense asphalt concrete mixtures of Type A (high stone content) and Type B (medium stone content) and a standardized roughness control method where a texture depth of 1.0 mm is set for the surface.

According to Clause 10.2 (SP KR 32-107:2024, 2024), the improvement of asphalt concrete quality in Kyrgyzstan is achieved through methods of physicochemical activation of mineral materials, as well as the use of surfactants or polymers. Thus, the current regulatory framework establishes a technical foundation for the use of modifying additives. However, the lack of detailed parameters for the use of secondary polymers in the regulations limits the practical implementation of these provisions. Therefore, the study of the effect of recycled plastic on the viscosity-temperature properties of bitumen is a necessary step to achieve the standard values of density (compaction coefficient of 0.99) and roughness (texture depth of 1.0 mm) in the difficult climate of the republic.

Since the SP KR 32-107:2024 regulation prescribes the use of surfactants and polymers but does not contain standardized protocols for their specific application, scientific circles have recently made efforts to adapt innovative road technologies to these regional climatic conditions. A key contribution to this debate is the study by Shambilova et al. (2025), who established a 'Climatic Rheology Profile' for Central Asia using sophisticated Viscoelastic-Viscoplastic (VE-VP) modeling. Their research proved that the "wet" method of bitumen modification not only reduces the carbon footprint but also significantly enhances pavement durability. Crucially, their Life-Cycle Assessment (LCA) reveals that while the wet method optimizes binder performance, the alternative 'dry' method can inadvertently increase global warming potential and microplastic emissions at high concentrations. However, the authors emphasize that without calibrating models to local temperature gradients, European frameworks remain merely qualitative and fail to provide accurate performance predictions for this region.

Global evidence shows that road construction strategies vary significantly based on income levels and climate. In countries with hot and humid climates, such as Indonesia, the main problem is the poor compatibility of bitumen with multilayer plastic waste. To solve this problem, Chalid et al. (2025) propose the use of non-ionic surfactants, such as PEG 400, as coupling agents to synthesize stable Polymer Modified Bitumen (PMB). This allows for a homogeneous mixture and improves elasticity, specifically increasing ductility to 100 cm, which is critical for crack prevention. This methodology sets a baseline for managing structural parameters when high Plastic Waste Content (PWC) is introduced into binders.

At the same time, Nigeria's experience shows the importance of working with natural resources. Loto et al. (2025) investigated the modification of natural bitumen using 5-7.5% recycled polyethylene (LDPE). The results of their work prove that such an additive significantly increases the Marshall stability and thermal stability of the material, which makes it resistant to rut formation in hot conditions. However, the authors warn that exceeding a 10% threshold leads to the agglomeration of plastic, which subsequently deteriorates the binder's properties.

A synthesis of these methods is the most suitable for Kyrgyzstan. While Swedish studies (Hellman et al., 2025) focus on the mechanical properties of Reclaimed Asphalt Pavement (RAP), their experience is less relevant due to the high moisture sensitivity of such mixtures. In Kyrgyzstan, this sensitivity could lead to premature pavement failure during mountain snowmelt periods.

Evidence from research conducted by Syzdyk et al. (2025) demonstrates that using PP H350 polypropylene increases the softening point of bitumen to 66.2°C. This is vital for preventing rutting during hot Central Asian summers, marking a sharp contrast to practices in the Netherlands, where the focus is frequently placed on viscosity at moderate temperatures due to their more temperate maritime climate. Furthermore, a study of the Dutch asphalt sector (Ruiz et al., 2025) identifies that even in advanced markets, the scaling of sustainable innovations is often hindered by a lack of long-term durability validation and risk-reduction systems. For Kyrgyzstan, this underscores the necessity of adapting international standards to a harsh continental climate during the preliminary phase before attempting large-scale implementation. This body of research suggests that while European innovations offer a strong foundation, their effectiveness in Kyrgyzstan depends entirely on mechanistic recalibration and climate-specific engineering.

METHODS

This study is based on a secondary meta-synthesis and comparative analysis of published data on the effectiveness of bitumen modifiers under the sharply continental of Kyrgyzstan. The authors did not conduct original laboratory tests, mechanical simulations, or scanning electron microscopy (SEM).

The literature search was carried out using Scopus, Google Scholar, and the repository of the Ministry of Transport and Communications of the Kyrgyz Republic. Publications were selected if they reported quantitative indicators directly linked to pavement defects typical of the region: resistance to rutting (via softening point and penetration) and resistance to low-temperature cracking (via ductility and brittle fracture temperature). Preference was given to studies providing open numerical data rather than isolated graphical trends, in order to reduce the influence of data blackboxing, a common problem in pavement research where raw values are not disclosed.

Because direct empirical data on bituminous binders under Kyrgyz conditions remain scarce, values from other regions with comparable climatic stress were also included: Central Asia, Indonesia, Nigeria, the Netherlands, and Sweden. These figures were normalized and compared against the requirements of the newly adopted SP KR 32-107:2024 code, as well as the Performance Grade temperature ranges relevant to the republic's high-altitude routes.

Analytical results

Climatic Comparative Analysis

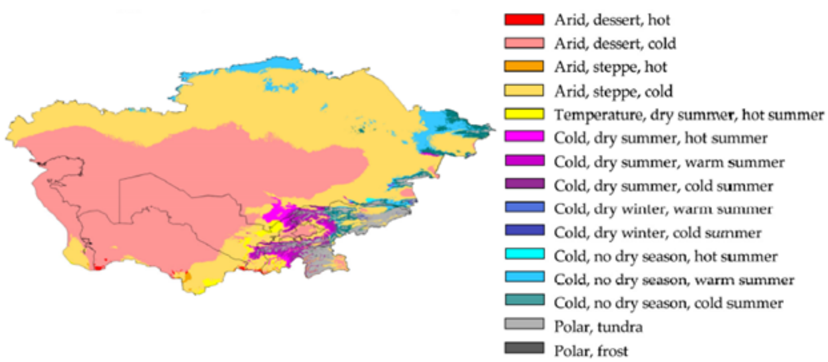

Figure 3. Regional climate distribution in Central Asia (1980-2016) based on the Köppen-Geiger classification system. Source: Shambilova et al. (2025), adapted from Beck et al. (2023).

Climate-Driven Degradation in High-Altitude Regions

Mountainous and high-altitude areas, such as the Tien Shan and Pamir, experience extreme factors including intense radiation, high diurnal temperature fluctuations, and moisture penetration. These conditions lead to photostress and thermal cyclic fatigue. Evidence from research conducted by Xie et al. (2025) demonstrates that the combined effects of UV radiation and freeze-thaw cycles significantly degrade structural stability and reduce the fatigue strength of asphalt mixtures. Consequently, effective engineering requires a multi-level approach that integrates polymer grids, UV stabilizers, and climate-specific laboratory testing.

Comparative Analysis of International Engineering Practices

The climates of Kyrgyzstan, the Netherlands, and Sweden differ significantly, requiring distinct engineering solutions. In the Netherlands, where the climate is wet and mild, the primary focus is on preventing road deformation. Dutch engineers utilize rubber additives to increase elasticity and advanced drainage systems to mitigate water damage. In contrast, Sweden faces extreme cold, where the main challenge is bitumen brittleness. Swedish engineering relies on polymer modification to improve low-temperature flexibility and prevent cracking.

Adapting Solutions for Kyrgyzstan's Environment

However, Kyrgyzstan experiences a unique combination of both extreme heat and severe cold. Applying Dutch or Swedish methods in isolation would be insufficient: the Swedish approach alone may lead to rutting during hot summers, while the Dutch method could result in winter cracking. Therefore, a comparative analysis of additives is necessary to identify modifiers adaptable to these specific fluctuations.

Rheological Parameters and Climatic Stressors

The decisive climatic factors in Central Asia include enormous daily temperature ranges, harsh solar radiation, and freeze-thaw cycles. To maintain performance, the rheological properties of the binder must ensure high stiffness (G*) and a low phase angle (δ) during peak heat. Conversely, at sub-zero temperatures, low Bending Beam Rheometer (BBR) stiffness values are essential to allow for internal stress relaxation and prevent cracking. Recent findings by Zheng et al. (2024) suggest that road degradation is driven by peak daytime temperatures and accumulated UV radiation rather than annual averages. Thus, laboratory protocols must include RTFOT/PAV aging combined with UV and moisture cycling to accurately simulate the Kyrgyz environment.

Parameter	Cold Continental Zone (Northern Kazakhstan, Mongolia)	Hot Semi-Desert Zone (Southern Uzbekistan, Turkmenistan)
Köppen–Geiger climate type	Dfb/Dfc (cold continental)	BSh/BWk (hot semi-desert)
Typical air temperature range, °C	−40…+35	−5…+50
Estimated pavement surface temperature, °C	Tmin: −34…−40 ∣ Tmax: +60…+64	Tmin: −10…−16 ∣ Tmax: +68…+72
Dominant climatic stressors	Freeze–thaw cycling (40–120 cycles/year), thermal shock, low-temperature cracking	UV radiation, oxidative aging, rutting, surface hardening
Design traffic class (typical)	Standard–Heavy (S–H)	Heavy–Very Heavy (H–V)
Target PG grade (Climate-Rheology based)	PG 64−34 (H)	PG 70−22 (V)
DSR G/sin δ (RTFO), kPa*	≥2.20 at 64 °C	≥2.20 at 70 °C
MSCR J_{nr}, kPa^{-1}	≤2.0 (heavy traffic)	≤1.0 (very heavy traffic)
MSCR R, %	≥20	≥25
BBR stiffness S (60 s), MPa	≤300 at −34 °C	≤300 at −22 °C
BBR m-value	≥0.300	≥0.300
Primary performance risks	Thermal cracking, moisture damage, aging under freeze–thaw	Rutting, oxidative hardening, UV-induced embrittlement
Recommended modification strategy	Elastomeric polymers (SBS 3–5%), crumb rubber 10–15%, biopolymer + plasticizer systems	High-temperature polymers (SBS 4–6%), recycled plastics (4–8%), antioxidants
Key aging protocols for validation	RTFO + PAV + freeze–thaw cycling	RTFO + PAV + UV + thermal aging
Climate Rheology Profile emphasis	Low-temperature relaxation and crack resistance	High-temperature stiffness, rutting and UV resistance

Table 1. Quantitative correlation between climate and rheology. Source: Shambilova et al. (2025).

Source	Scenario/Method	Title 3	Title 4
[166]	Wet vs. dry; data from recyclers (Australia)	The wet process in most scenarios reduces GWP compared to virgin polymers; the dry process increases GWP at higher RPP contents	Cost savings are achievable with local recycling and moderate polymer contents; the dry process requires optimization.
[167]	Review of waste-to-road studies	Recycled plastics improve rutting and fatigue performance, but LCA results are highly sensitive to logistics and pellet production technology.	Economic benefits occur only when service life increases and local recycling facilities are available.
[168]	Performance review	Improved mechanical properties (rutting resistance, stiffness) at polymer contents of approximately 2–6%.	Plant modernization is often required; ROI depends on polymer price and maintenance savings.
[176]	Abrasion → microplastics	Microplastic release observed during wear, particularly for the dry method and under cold/acidic conditions.	Potential environmental costs (stormwater treatment, regulatory risks) may become economically significant when scaled up.
[175]	Emissions and engineering properties	Possible reduction in PAH and VOC emissions; mixed outcomes regarding GWP.	Field validation is needed before firm economic conclusions can be drawn.

Table 2. Synthesis of environmental and economic impacts of polymer-modified and recycled asphalt binders. Source: Shambilova et al. (2025).

Findings from existing research on road construction techniques

Statistical analysis of load/traffic in Kyrgyzstan

The total vehicle fleet across key national corridors amounts to approximately 500,000 units, whereas the local daily traffic load concentrated directly within the Bishkek agglomeration exceeds 700,000 vehicles. This volume is almost three times the original road capacity. Since standard bitumen has low fatigue strength and cannot withstand such intense loads, asphalt deforms under current conditions. To withstand double the load, the material must reach a Marshall stability of at least 8 kN (a measure of the maximum load the mixture can carry), as established in the study by Loto et al.

To account for extreme temperature variations in Kyrgyzstan, laboratory datasets are classified according to the climatic factors they are designed to address.

High-Temperature Stability and Rutting Resistance

1. Softening Point Test

The Softening Point test (Ring and Ball method) is an important indicator of the thermal stability of a binder. It determines the temperature at which bitumen changes from a semi-solid to a liquid state. This test is essential for assessing the resistance of road pavement to rutting. When the softening point is excessively low, the asphalt binder softens during periods of high ambient temperature. This subsequently leads to irreversible structural deformation under the influence of traffic loads.

Kyrgyzstan experiences extreme continental heat, with summer temperatures reaching 43°C. However, due to the effects of solar radiation, the temperature of the road surface can exceed this ambient value by 20-30°C. Standard bitumen (grade 100/130) is highly susceptible to degradation as it typically has a softening point of around 43-47°C. To ensure pavement stability, the binder must be modified to achieve a softening temperature of at least 50-55°C.

Note on data heterogeneity: Initial values for pure bitumen (without modifiers) vary considerably across the synthesized studies due to differences in the grade of the base binder. For instance, Jexembayeva et al. (2024) used a hard industrial-grade bitumen (softening point 72°C), while Rakhimov (2025) used a soft road bitumen (43°C) typical for the region. Direct numerical comparison between such binders is therefore error-prone; their joint analysis is more appropriate when evaluating relative change (in percent) and structural trends driven by additives, rather than absolute values.

An analysis has been synthesized regarding several additives: Recycled PET, Polypropylene (PP H350), and a Sulfur-HDPE hybrid. Data analysis (Table 3) shows that Recycled PET leads to a significant increase in the softening point, ranging from 72°C to 100°C (Jexembayeva et al., 2024).

PET Content (%)	Softening Point (°C)
0% PET	72
1% PET	75
3% PET	78
5% PET	85
8% PET	98
10% PET	99
12% PET	100

Table 3. Softening Point of Bitumen Modified with Recycled PET (Jexembayeva et al., 2024)

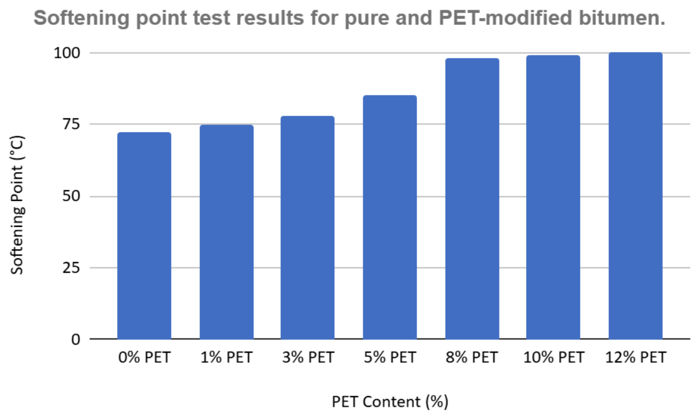

Figure 4. Softening point test results for pure and PET-modified bitumen (recalculated after Jexembayeva et al., 2024)

Although the PET modification provides the greatest margin in terms of thermal characteristics, it is important to compare these results with synergistic hybrids, which may have more balanced properties. As shown in Table 4, the modification using Sulfur and High-Density Polyethylene (HDPE) provides a targeted improvement that perfectly matches the climatic needs of Kyrgyzstan.

Modifier Composition	Softening Point (°C)
Control (Unmodified Bitumen)	43
3% Sulfur + 2% HDPE	54
5% Sulfur + 2% HDPE	51

Table 4. Comparison of Softening Point for Sulfur and HDPE Modification (Rakhimov, 2025)

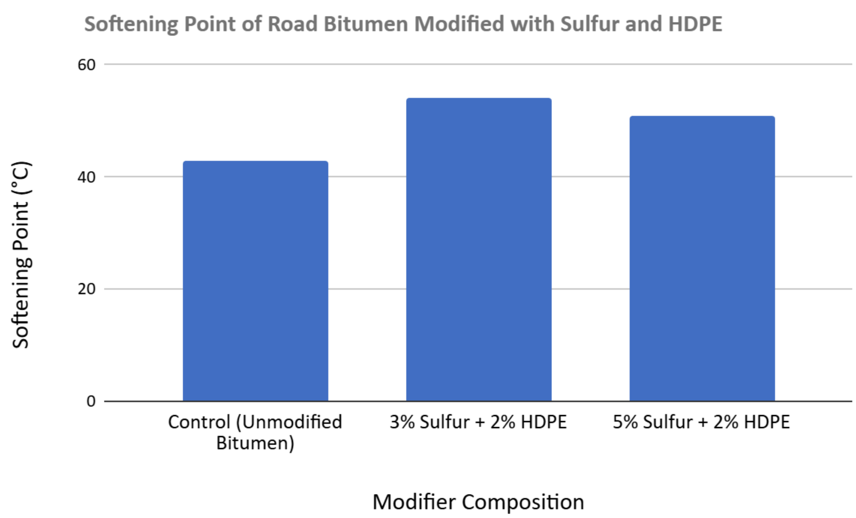

Figure 5. Comparison of softening point values for bitumen modified with Sulfur and HDPE (Data sourced from Rakhimov, 2025)

Furthermore, comparison with other modifiers shows that while Polypropylene (PP H350) increases the softening point to 66.2°C (Syzdyk et al., 2025), the 3% Sulfur + 2% HDPE blend reaching 54°C (Rakhimov, 2025) is the most viable option. This modification effectively exceeds the maximum ambient temperature threshold of 43°C while avoiding the excessive stiffness and potential deterioration of other mechanical properties associated with PET concentrations above 8-10%, which, according to Jexembayeva et al. (2024), high modifier dosages also make such applications economically less viable for large-scale projects.

2. Penetration Test

The Penetration Test measures the hardness or consistency of bitumen by determining the depth (in tenths of a millimeter, 0.1 mm) to which a standard loaded needle penetrates a sample at a temperature of 25°C. The penetration test is used to determine the hardness of the binder, which is essential to resist irreversible structural deformation, such as rutting. It also helps engineers assess whether the bitumen is soft enough to provide adequate flexibility and noise reduction in road construction. In cities such as Bishkek, heavy traffic (more than 700,000 vehicles) combined with summer heat causes asphalt to undergo viscous flow, forming deep waves and ruts.

A lower penetration value indicates a harder road surface capable of supporting heavier loads without settling during the hot season. An analysis has been synthesized regarding recycled PET, Plastic Waste Content (PWC), and chemical surfactants like PEG 400 and Span 60. These additives act as structural reinforcers that fill the bitumen matrix and increase its viscosity and pressure resistance. A comparative benchmarking of waste-derived modifiers was performed to evaluate their viability for Kyrgyzstan's infrastructure, utilizing integrated datasets from Jexembayeva et al. (2024) (Recycled PET), Syzdyk et al. (2025) (PEG/Span 60), and Rabbani et al. (2025) (Plastic Waste Content).

PET Content (%)	Penetration at 25°C (0,1 mm)
0% PET	96
1% PET	73
3% PET	71
5% PET	67
8% PET	56
10% PET	53
12% PET	50

Table 5. Impact of Recycled PET on Bitumen Penetration (Jexembayeva et al., 2024)

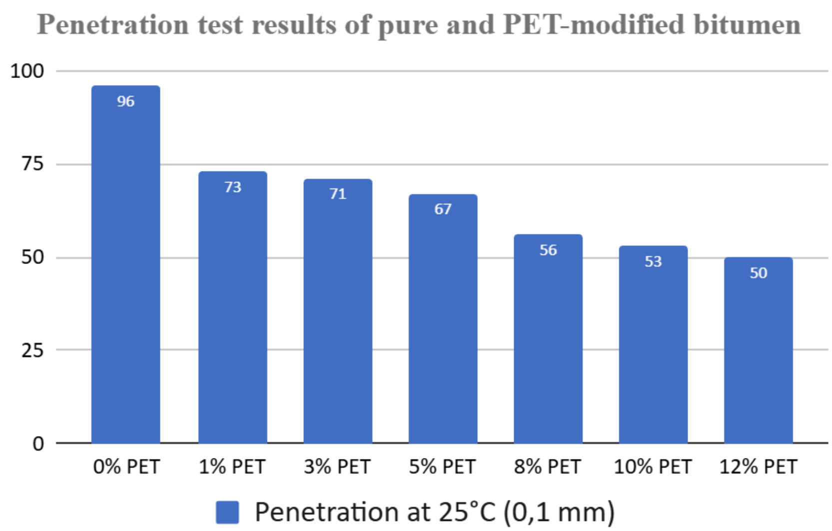

Figure 6. Penetration test results at 25°C for pure and PET-modified bitumen (recalculated after Jexembayeva et al., 2024)

The data analysis reveals that recycled PET effectively strengthens bitumen, reducing penetration from 96 to 50 dmm, which is a reduction of approximately 48%. While chemical surfactants such as Span 60 result in even lower penetration values (20.6 dmm), PET-modified samples maintain a more moderate penetration range. However, a comparison with softening temperature data shows that the PET hardening effect reaches a plateau above 10%, where a further increase in concentration in the work reduces thermal stability.

Low-Temperature Resilience

Tensile Strength

Tensile strength testing determines the maximum tensile stress a bitumen sample can withstand before structural failure. In the study by Jexembayeva et al. (2024), this is quantified by the degree of elongation (cm) reached before the binder ruptures. Although both parameters are recorded based on sample elongation (cm), the ductility test determines the empirical plasticity of the binder at a constant, slow rate of extension, whereas the tensile strength test evaluates the maximum cohesive stress the polymer matrix can withstand before catastrophic failure under external shear forces. This test evaluates the cohesive strength of the binder. It demonstrates how effectively the bitumen maintains the integrity of mineral aggregates when subjected to the intense tensile and shear forces generated by heavy vehicle tires. High tensile strength is vital for Kyrgyzstan's mountainous infrastructure, such as the Bishkek-Osh highway. These routes endure extreme physical stress from steep inclines, sharp turns, and heavy-duty transit. Without sufficient tensile resistance, the pavement would rapidly undergo fatigue cracking and structural disintegration. The study by Jexembayeva et al. (2024) demonstrates that recycled PET serves as a modifier to create a reinforcing polymer network within the bitumen. This molecular mesh absorbs energy and prevents the rupture of the binder, significantly enhancing the material's strength. The correlation between PET concentration and mechanical reinforcement is analyzed based on the research by Jexembayeva et al. (2024).

PET Content (%)	Tensile Strength at 25°C (cm)
0% PET	64
1% PET	64
3% PET	61
5% PET	163
8% PET	251
10% PET	134
12% PET	111

Table 6. Impact of PET Content on Tensile Strength (Jexembayeva et al., 2024)

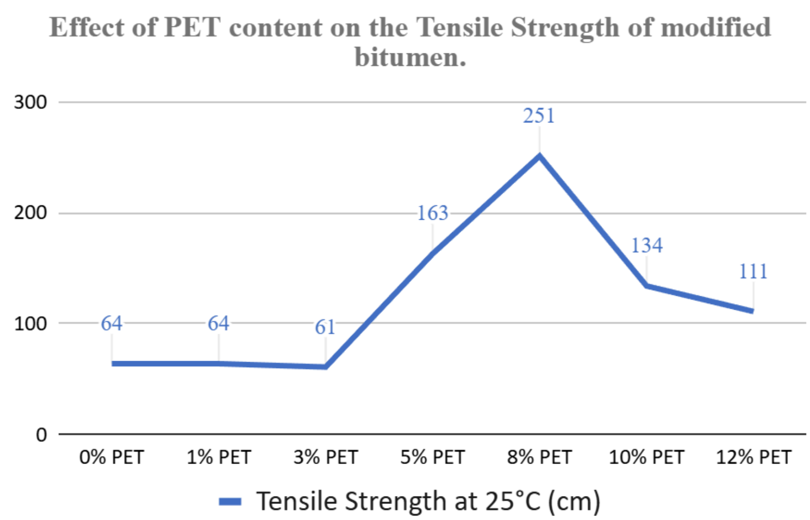

Figure 7. Tensile strength development in bitumen as a function of Recycled PET concentration (recalculated after Jexembayeva et al., 2024)

The data reveals a massive performance peak within the 5% to 8% PET concentration range, where tensile strength reaches maximum values of 163 cm and 251 cm, respectively. At the peak strength of 8% PET, the modified binder is nearly four times more resilient than the unmodified control sample (64 cm). This significant improvement is crucial for determining the maximum tensile stress that the material can withstand, which is extremely important for the cold mountainous regions of Kyrgyzstan. High tensile strength ensures that the road surface can absorb energy and resist cracking during sudden temperature changes. However, the subsequent drop to 111 cm at 12% confirms that exceeding the 8–10% threshold leads to polymer agglomeration, causing a loss of internal cohesion and a reduction in the material's overall structural integrity.

2. Ductility test

The Ductility Test determines the plasticity of bitumen by measuring the distance in centimeters (cm) a standard briquette can be stretched before breaking. This test evaluates the flexibility of the binding agent. High plasticity is a fundamental property of bitumen. Without it, the material becomes brittle and the road surface suffers structural failure under pressure.

In the extreme temperature fluctuations of Kyrgyzstan, bitumen must remain flexible. During cold nights, the pavement contracts. If the plasticity is insufficient (e.g., 8 cm, as observed in certain plastic waste modifications), thermal cracks form immediately.

This analysis compares three distinct approaches. First, Surfactants (PEG 400/Span 60) are used to improve compatibility between plastic and bitumen. Second, LDPE/PWC represents recycled waste plastic used for sustainability. Finally, a Sulfur + HDPE synergistic hybrid is examined for its extreme climate resistance. This study involves a cross-analysis of elasticity data from Chalid et al. (2025), Loto et al. (2025), and Rakhimov (2025).

Additive Type	Dosage (%)	Ductility (cm)
Control (Plastic Only)	0	28.36
PMB + PEG 400	0,1	100.0
PMB + PEG 400	0,3	85.0
PMB + PEG 400	0,5	75.0
PMB + SM (Span 60)	0,1	40.8
PMB + SM (Span 60)	0,3	30.1
PMB + SM (Span 60)	0,5	17.8

Table 7. Impact of Surfactants (PEG 400 and Span 60) on the Ductility of Plastic-Modified Bitumen (Chalid et al., 2025)

Modifier Composition	Ductility (cm)
Control (Unmodified Bitumen)	-
3% Sulfur + 2% HDPE	66
5% Sulfur + 2% HDPE	61

Table 8. Ductility of Bitumen Modified with Sulfur and High-Density Polyethylene (Rakhimov, 2025)

PWC Content (%)	Ductility (cm)

0	20
5	8
7,5 - 10	14

Table 9. Effect of Plastic Waste Content (PWC) on the Ductility of Modified Bitumen (Loto et al., 2025)

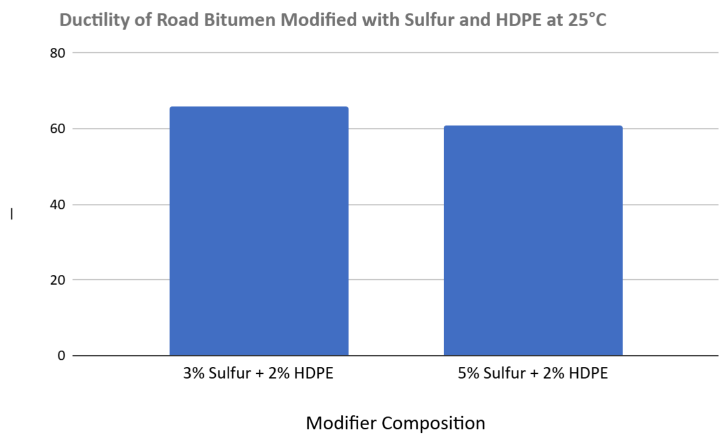

Figure 8. The Effect of Plastic Waste Content (PWC) on the Ductility and Viscoelastic Properties of Modified Bitumen (recalculated after Rakhimov, 2025)

The comparative analysis of the datasets reveals a stark contrast between different modification strategies. According to Table 7 (Chalid et al., 2025), the use of surfactants is the most effective way to restore flexibility in plastic-modified bitumen (PMB). While the control sample (plastic only) has a low plasticity of 28.36 cm, adding PEG 400 at a dosage of 0.1% increases this value to a maximum of 100 cm. This sharp increase of 252% shows that PEG 400 acts as an excellent plasticizer, preventing bitumen brittleness.

In contrast, the results presented in Table 9 (Loto et al., 2025) demonstrate that simple modification using PWC plastic waste leads to dangerously low levels of plasticity. At a 5.0% PWC concentration, ductility drops sharply to 8 cm, confirming that without chemical treatment or synergistic additives, plastic significantly reduces the flexibility of the binder. This loss of elasticity inevitably leads to thermal cracking at low temperatures. However, when the PWC content is increased to the range of 7.5-10%, a partial recovery to 14 cm is observed. Despite this slight increase, the material remains significantly more brittle than the control sample, making it unsuitable for extreme climatic conditions without further modification.

Further analysis of Table 8 (Rakhimov, 2025) shows that dual modification using a Sulfur + HDPE (3% + 2%) hybrid results in a stable ductility of 66 cm. This ratio of hybrid components prevents the brittleness usually associated with high polymer content, as it is practically equivalent to the value for unmodified control bitumen.

3. Low-Temperature Fracture Analysis

The Low-Temperature Fracture test (based on ASTM D3111) determines the brittleness threshold of bitumen. It identifies the specific temperature at which the binder loses its elasticity and cracks under mechanical stress. This test is essential to assess the pavement's endurance in cold climates. In winter, bitumen contracts; if the material is too brittle, it cannot compensate for this shrinkage, leading to immediate structural failure.

In Kyrgyzstan, particularly in regions such as Naryn, winters are severe, and temperatures frequently drop below -25°C. Standard bitumen (PEN 60/70 or 60/90) typically fails at -16°C. This test helps identify a modifier that lowers the cracking threshold to a level corresponding to local winter extremes, preventing the formation of deep thermal cracks.

This study analyzes a synergistic hybrid of technical powdered sulfur and High-Density Polyethylene (HDPE). Sulfur acts as a cross-linking agent that preserves internal flexibility, while HDPE provides the necessary stiffness to maintain the road's structural integrity. A comparative analysis is performed based on data from Rakhimov et al. (2025), specifically focusing on the performance of dual-modified bitumen compared to an unmodified control sample.

Modifier Composition	Fracture Temperature (°C)
Control (Unmodified Bitumen)	-16
3% Sulfur + 2% HDPE	-28
5% Sulfur + 2% HDPE	-30

Table 10. Fracture Temperature of Bitumen Modified with Sulfur and HDPE (Rakhimov, 2025)

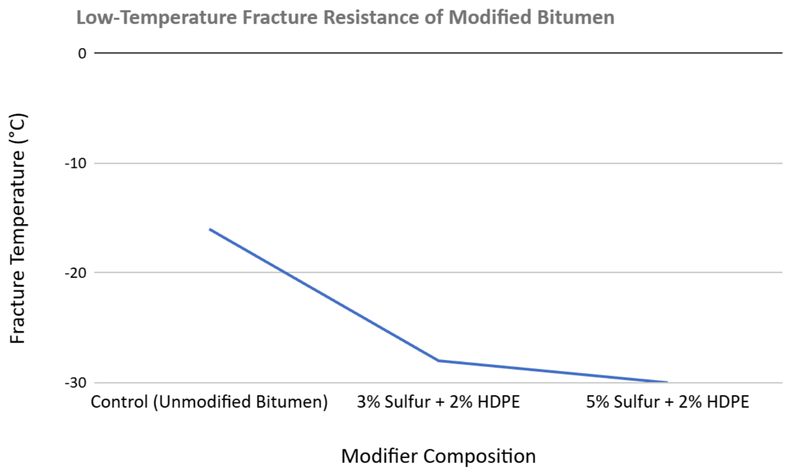

Figure 9. Comparative Impact of Sulfur-HDPE Modification on Bitumen Fracture Temperature (recalculated after Rakhimov, 2025)

The results presented in Figure 9 demonstrate that the combination of 5% Sulfur + 2% HDPE is the most effective formulation for extreme environments. While unmodified bitumen reaches its fracture limit at a relatively moderate temperature of -16°C, this synergistic modification successfully reduces the threshold to -30°C.

This 14°C expansion of the cold-resistance range is critical for the Kyrgyzstan infrastructure. By lowering the brittleness point to -30°C, the modifier ensures the pavement can withstand the thermal contraction stresses typical of high-altitude regions like Naryn. When viewed alongside the improved softening point, this data confirms that the Sulfur-HDPE hybrid creates a robust thermal operating window (54°C to -30°C), effectively shielding the road surface from both summer deformation and winter cracking.

Climate, Sustainability, and Socio-Economic Feasibility

According to environmental activist Vladislav Ushakov, plastic cannot be recycled indefinitely and eventually ends up in landfills (Krasnova, 2025). Currently, the Junxin incineration plant in Bishkek processes approximately 800 to 1,000 tonnes of waste daily, yet it cannot cope with the city's daily inflow of 1,200-1,500 tonnes (Krasnova, 2026). Integrating LDPE/HDPE into road construction addresses this gap by redirecting non-recyclable waste into durable infrastructure.

The most sustainable approach is to use the wet method (high-shear mixing of the polymer additive directly into the liquid bitumen binder). A study by Shambilova et al. (2025) shows that the use of recycled polymers can significantly reduce global warming potential and CO2 emissions compared to virgin polymers. However, for Kyrgyzstan, the environmental benefit depends on local recycling logistics. Domestic waste recycling and the carbon footprint associated with long-distance transportation make locally produced low-density polyethylene an excellent environmentally friendly alternative to imported synthetic additives.

Sustainability in road construction is also determined by Life Cycle Assessment (LCA). Instead of the linear “produce-use-dispose” model, the use of plastic waste contributes to the development of a circular economy. A critical finding from Shambilova et al. (2025) is that environmental benefits are only achieved if the modification actually extends the service life of the road surface. Improved resistance to rutting and thermal cracking with plastic-modified and felt-modified pavements reduces the frequency of repairs, thereby reducing the overall consumption of non-renewable petroleum resources over decades.

The economic viability of the proposed technology is evaluated through a Life Cycle Cost (LCC) framework. Although initial Capital Expenditures (CAPEX) is higher because of plastic collection infrastructure and high-temperature mixing, long-term Operating Expenditures (OPEX) is significantly reduced through enhanced pavement durability and fewer maintenance intervals.

DISCUSSION

1. Climate context and constraints (based on Table 1)

Based on data in Table 1 (Shambilova et al., 2025), Kyrgyzstan's climate can be classified as a hybrid climate, combining the severity of the cold continental zone (Dfb/Dfc) with the loads of the Hot Semi-Desert Zone. For such conditions, the key constraints are extreme freeze-thaw cycles (up to 120 cycles per year) and high solar radiation. According to the geological profile, Kyrgyzstan requires a bit of PG 64-34 or higher. This means the modifier must simultaneously provide high rigidity at +64°C, which is necessary to combat rutting, and maintain relaxation at -34°C to prevent cracking.

2. Optimization of PET modification

Based on a comparative analysis of data, it is evaluated that the optimal balance between durability and climate resistance for summers/high temperatures is achieved with a PET modifier content in the range of 5% to 8%. PET content of 10% and 12% in some cases shows a decrease in quality, including penetration, tensile strength, and water absorption, while the softening point shows minimal improvement. This proves that increasing PET content above 8% will likely lead to economic losses.

3. Trade-off between plasticity and stability

Pure bitumen shows the highest ductility (20 cm), but this does not guarantee pavement stability under actual loads. In Bishkek, summer solar radiation softens unmodified bitumen to the point of plastic shearing and deep rutting, meaning high ductility is more of a liability than an advantage under these conditions.

Adding 7.5–10% PWC addresses this issue: Marshall stability increases from 5.2 kN to 7.8 kN, the softening point rises by 6°C, and the flash point by 47°C. Ductility does drop to 14 cm under this modification, but the loss is offset by a higher modulus of elasticity and improved shear resistance at elevated temperatures, which are the properties most relevant to local climatic demands.

4. Selecting the optimal solution: Sulfur + HDPE

Based on the synthesis and comparison of the reviewed studies, the combination of 5% sulfur and 2% HDPE emerges as the best-performing modifier. It demonstrated the most balanced results among the compositions analyzed, with a brittle fracture temperature of −30°C and a softening point of 51°C — values well suited to Kyrgyzstan's of hot summers and cold winters. Although PET-based modifiers showed higher rigidity at elevated temperatures, the 5% Sulfur + 2% HDPE composition is recommended as the optimal choice for Kyrgyz conditions, given its balance between high-temperature stability and low-temperature crack resistance.

5. Economic and environmental sustainability (based on Table 2)

Based on the analysis in Table 2 (Shambilova et al., 2025), the "wet mixing" method was identified as the most cost-effective approach for Kyrgyzstan, as it significantly reduces the Global Warming Potential (GWP) compared to virgin polymers. The economic efficiency is further reinforced by the use of locally produced secondary polymers and sulfur: a byproduct of regional oil refining. Prioritizing these local materials over expensive imported additives mitigates risks associated with currency fluctuations and high customs duties. While developing internal waste processing infrastructure requires initial investment, these costs are compensated by the increased durability of the road surfaces. Ultimately, the proposed composition (5% sulfur and 2% HDPE) facilitates an extension of the pavement service life, optimizing the state budget by increasing the intervals between road repairs and transforming waste disposal into high-tech infrastructure development.

Strengths and Limitations

A common challenge in this field is the lack of access to original raw datasets, as results are frequently presented only in the form of images or graphs. This phenomenon, known as "data blackboxing," limits the precision of comparative analysis. To address this, this study prioritized peer-reviewed papers that included supplementary datasets or verifiable numerical results to ensure the reliability of the findings.

At the same time, this study relies on heterogeneous secondary data, characterized by differing base bitumen grades, varying national testing standards, and differing chemical origins of the additives used. Furthermore, the key conclusions regarding the effectiveness of the sulfur–HDPE hybrid are based largely on a single regional source (Rakhimov, 2025).

Since no direct laboratory replication or testing of bitumen produced specifically in Kyrgyzstan was carried out within this study, the findings should be regarded as a predictive engineering model rather than a confirmed result. Practical implementation of this technology will require verification using local aggregate materials and binder grades available within the republic, in order to confirm their physico-chemical compatibility.

CONCLUSION

The predominant questions and gaps addressed in this paper was to find which bitumen-modifier would be the best for Kyrgyzstan's climate and also help with sustainability and environmental-friendly yet cost-effectiveness. After making careful and novel synthesis and analysis of results from summarizing datasets on the latest existing research on additives used in Central Asian climate with comparative analysis with other European and North-African/South-Asian countries which helps cover the diverse and extreme climates of Kyrgyzstan, it is concluded that a tentatively synergistic combination of 5% Sulfur and 2% HDPE is the best for the Kyrgyzstan climate. This was based and supported by datasets and analysis of climate, load, softening point, ductility and fracture temperature test to provide an overall framework for ascertaining the effectiveness of the chosen synergistic combination of 5% Sulfur and 2% HDPE.

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