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MODIFYING ASPHALT CONCRETE WITH WASTE PAPER AND POLYMER ADDITIVES FOR ENHANCED PAVEMENT PERFORMANCE

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ABSTRACT: Improving the durability and performance of asphalt concrete pavements under high traffic loads and adverse climatic conditions remains a key challenge in road construction. One promising approach is the modification of bituminous binders and asphalt mixtures using secondary raw materials, which can enhance material properties while addressing environmental concerns. This study evaluates the effectiveness of various modifiers, including raw rubber, polyvinyl acetate, polyacrylamide, wax, and a paraffin–styrene/PVP copolymer, as well as cellulose fibers from waste paper and polyethylene terephthalate fibers for asphalt concrete modification. The research methods included standard bitumen tests, atomic force microscopy analysis of bitumen microstructure, and mechanical testing of asphalt concrete. The results showed that the addition of 1.5–2% raw rubber to BND 90/130 bitumen provided the most significant improvement in physico-mechanical and adhesive properties. Cellulose fiber reinforcement increased the compressive strength of asphalt concrete, whereas polyethylene terephthalate fibers led to a reduction in strength. Microstructural analysis confirmed substantial changes in bitumen morphology after modification. The study demonstrates that the combined use of rubber-modified bitumen and polymer-treated cellulose fibers is an effective solution for improving asphalt concrete performance. The proposed approach enables the utilization of secondary waste materials in road construction, contributing to both enhanced pavement durability and sustainable waste management.All tests were performed on at least three replicate specimens, and results are presented as mean ± standard deviation.

Keywords: Modified Bitumen, Asphalt Concrete, Waste Paper, Cellulose Fiber, Rubber, Adhesion, Atomic Force Microscopy.

1. INTRODUCTION

Modern requirements for road pavements are driven by the continuous growth of traffic loads and the need to ensure durability under climatic influences. Asphalt concrete, the primary material for pavement layers, must possess high strength, shear resistance, crack resistance, and water resistance. The bituminous binder plays a key role in forming these properties, and its quality can be significantly improved by introducing modifying additives.

Traditionally, polymer additives (styrene-butadiene-styrene, ethylene vinyl acetate, etc.) are used to modify bitumen; however, these increase the final product cost. In this regard, developing resource-saving technologies using secondary raw materials—such as industrial and household waste—is relevant. The Republic of Kazakhstan faces a shortage of its own road bitumen, a significant portion of which is imported. Concurrently, the country has accumulated substantial volumes of unutilized waste, such as paper and plastic, which can be used as raw materials for producing modifiers. At the same time, research indicates that modifying low-grade bitumen (e.g., grade 50/70) with specific additives can achieve, or even surpass, the temperature-rheological characteristics of higher grades, offering a cost-effective and efficient solution for enhancing pavement durability across various climatic conditions [2]. Despite significant progress in this field, most existing studies, including work on polymer-modified low-grade bitumen [3] and the use of natural asphalts [4], focus on modifying either the binder alone or the mixture matrix alone. Studies investigating the synergistic effect of combined modification (elastomer in the binder + discrete reinforcement with fibers from secondary raw materials), as well as the direct correlation between microstructural evolution (by AFM) and macroscopic performance properties, are practically absent. This work aims to fill this gap. Its originality lies in: (1) the holistic assessment of a dual-modification system targeting both the binder and the asphalt concrete matrix; (2) the application of quantitative AFM analysis to establish a correlation between morphological changes in modified bitumen and its adhesive/mechanical properties; and (3) the development of a practical scheme for producing modifiers from waste paper, thereby bridging laboratory innovation and potential industrial implementation. Comprehensive studies incorporating rheological analysis and rutting tests demonstrate that polymer modifiers such as Butonal NS, PR Plast, and Titan significantly increase bitumen viscosity and stiffness, providing a substantial improvement in rutting resistance at high temperatures [3]. In a similar vein, the use of natural alternatives, such as Asbuton asphalt, demonstrates the potential to create durable, porous asphalt mixtures that can be laid at reduced temperatures and exhibit high resistance to degradation in the Cantabro test, confirming the feasibility of non-conventional binders in pavement construction [4]. A critical consideration for the Asbuton application is its requirement for higher mixing and compaction temperatures, which can be effectively addressed by incorporating synthetic zeolite to facilitate warm mix asphalt technology, potentially maintaining or even enhancing the pavement's stiffness modulus [5]. Furthermore, studies indicate that using plastic waste, specifically polyethylene terephthalate (PET), in asphalt mixtures can significantly enhance their Marshall stability and resistance to permanent deformation, underscoring the potential of waste as a valuable resource [9]. In parallel, engineering solutions employing geosynthetic materials for base and pavement reinforcement demonstrate high effectiveness for stabilizing problematic soils and rehabilitating existing roads, offering additional avenues for comprehensive pavement durability enhancement [10].

The global pursuit of sustainable infrastructure has intensified research into waste valorization. Recent studies published in the GEOMATE journal further advance this field. Research on bio-asphalt derived from coconut shell biomass highlights its potential for modifying and rejuvenating aged bitumen, contributing to circular economy models [8]. Investigations into polyurethane modification report alterations in the characteristic "bee-like" morphology of bitumen, linked to enhanced resistance to oxidative aging [6]. Concurrently, performance assessments of porous asphalt containing modified bitumen and plastic waste confirm the viability of such composites [7], while other works detail the improvement in asphalt mixture performance using optimally graded plastic bottle waste [9].

Despite these significant advances, a clear research gap exists in the combined and systematic application of elastomer-modified bitumen with mechanically reinforcing cellulose fibers sourced from a ubiquitous waste stream like paper. Most existing studies focus on either binder modification or mixture reinforcement independently. Furthermore, a comprehensive microstructural analysis that explicitly links the morphological changes induced by such combined modifiers to the macro-scale mechanical and performance properties of asphalt concrete is notably lacking.

This work aimed to investigate the influence of various waste-derived modifiers (paper and household plastic) on the physical, mechanical, and performance properties of bitumen and asphalt concrete mixtures, addressing the identified gap. The main tasks included: selection and evaluation of the effectiveness of bitumen modifiers; investigation of the adhesive properties of the modified binder; study of the influence of cellulose and polymer fibers on asphalt concrete properties; analysis of microstructural changes in bitumen using atomic force microscopy; and development of a concept for a technological line for producing modifiers. The originality of this research lies in: (1) the holistic assessment of a dual-modification system targeting both the binder and the mixture matrix, (2) the application of AFM to establish a correlation between microstructural evolution in modified bitumen and its macroscopic adhesive/mechanical behavior, and (3) the proposition of a practical industrial schematic for producing modifiers from waste paper, thereby bridging laboratory innovation and potential field application.

The paper is structured as follows: after the introduction, the Research Significance is stated. Section 2 details the materials and methods. Section 3 presents and discusses the results on bitumen modification, adhesion, microstructure, and asphalt concrete performance. Finally, conclusions and practical implications are summarized.

Furthermore, the application of such modified asphalt concretes extends beyond traditional roadways. They show promise for use in airport runways requiring high fatigue resistance, heavy-duty industrial pavements subjected to extreme loads, and in cold regions where thermal cracking is a major concern. The integration of waste materials also aligns with global sustainability goals and green building certifications, making this technology attractive for environmentally conscious infrastructure projects worldwide.

Recent advancements in the field, such as the use of Buton rock asphalt (Israil et al., 2025) and polymer-modified low-grade bitumen (Alibayeva et al., 2025), have further demonstrated the potential of hybrid modification systems. However, most studies remain limited to single-modifier approaches or lack comprehensive micro-macro correlation analysis linking microstructural evolution to macro-scale performance.

2. RESEARCH SIGNIFICANCE

This study presents a novel approach by synergistically combining rubber-modified bitumen with cellulose fibers from waste paper — a dual-modification system rarely investigated. Its originality is demonstrated through the holistic evaluation of both binder and matrix modification, the application of Atomic Force Microscopy to establish a direct correlation between microstructural evolution and macro-scale performance, and the development of a practical industrial schematic for producing modifiers from waste paper. This research uniquely bridges the gap between individual modification techniques and provides a sustainable solution that enhances pavement durability while valorizing two waste streams, offering scientific innovation with direct practical applicability in road construction.

3. MATERIALS AND METHODS

3.1. Bitumen and Modifiers

The research object was petroleum road bitumen grade BND 90/130, complying with ST RK 1373-2005. Modifiers included raw rubber, polyvinyl acetate (PVA), polyacrylamide (PAA), wax, and a paraffin-styrene/PVP copolymer. To modify the asphalt concrete mixture, cellulose fibers obtained by grinding waste paper in an LMC-1M laboratory mill to a particle size of 0.1–1.0 mm, and fibers from PET bottle waste, manually cut to dimensions of 4–5 cm in length and 0.1–0.3 cm in width, were used. The mineral part of the asphalt concrete mixture consisted of granite crushed stone. As an additional context for the use of waste in bituminous binders, the potential of bio-asphalt derived from coconut shell biomass for modifying and rejuvenating aged bitumen is considered [8].

Modifiers were introduced into preheated bitumen at a fixed temperature of 170°C in an amount of 1.5–2% by weight of the bitumen. The choice of this concentration range was based on a preliminary analysis of literature data on elastomeric modifiers and consideration of technological constraints associated with an unacceptable increase in viscosity at higher rubber content, which complicates mixing and paving. Mixing was carried out under constant mechanical stirring (shear rate ~ 500 rpm) for 45 minutes to ensure homogeneous distribution. Afterward, the samples were cooled to room temperature and conditioned for 24 hours before testing.

3.2. Characterization of Fibrous Fillers

Two types of fibrous fillers were used in the work:

1. Cellulose fibers (CF), obtained by mechanical grinding of waste paper in an LMC-1M laboratory mill. The particle size was 0.1–1.0 mm, bulk density was 120–150 kg/m³, and natural moisture content was 5–7%. To prevent ignition and improve wetting with bitumen, the fibers were pre-treated with a 3% aqueous-polymer solution (polyvinyl acetate dispersion) followed by drying at 60°C to constant weight.
2. Polyethylene terephthalate fibers (PET fiber), obtained by manually cutting waste plastic bottles. The fiber dimensions were 4–5 cm in length and 0.1–0.3 cm in width. Bulk density was 80–100 kg/m³. No pre-treatment of the fibers was carried out.

3.3. Asphalt Concrete Mixture Composition

The mineral part of the asphalt concrete mixture met the requirements of GOST 9128-2013 for a dense fine-grained mixture type B. The aggregate gradation is as follows: 100% passes through a 20 mm sieve, 95% passes through 15 mm, 80% passes through 10 mm, 60% passes through 5 mm, 42% passes through 2.5 mm, 30% passes through 1.25 mm, 22% passes through 0.63 mm, 16% passes through 0.315 mm, 10% passes through 0.14 mm, and 6% passes through a 0.14 mm sieve (material smaller than 0.14 mm). The bitumen (original or modified) content in all mixtures was 5.5% by weight of the mineral part. The content of fibrous fillers (CF or PET) was 0.5% by weight of the total mixture.

3.3. Bitumen Testing Methods

Penetration: the depth of needle penetration was determined using a penetrometer according to GOST 11501-78 at a temperature of 25°C, a load of 100 g, and a duration of 5 seconds. The result was expressed in tenths of a millimeter (0.1 mm).

Softening point: determined by the Ring and Ball method (R&B) in accordance with GOST 11506-73. The softening point was taken as the temperature at which the bitumen sample in a brass ring deformed under the weight of a 3.5 g steel ball and touched the bottom plate of the apparatus.

Adhesive Properties: the adhesion of bitumen to the surface of the mineral material (granite crushed stone) was assessed using a five-point scale according to GOST 12801-98. The method is based on a visual analysis of the preservation of the bitumen film on crushed stone grains after boiling them in water for 30 minutes.

The adhesive properties were evaluated using a standard five-point scale in accordance with GOST 12801-98. Pre-heated granite aggregate was immersed in the test binder for 15 seconds, then conditioned at room temperature for one hour. Subsequently, the coated aggregate samples were boiled in distilled water for 30 minutes, followed by cooling and visual inspection. The retention of the bitumen film on the aggregate surface was assessed: a score of 5 indicated complete film retention, while a score of 1 signified complete detachment. This procedure is visually summarized in Figure 3, which shows representative granite samples after testing with different modifiers.

3.4. Atomic Force Microscopy (AFM)

The microstructure of bitumen films was investigated using a "Jeol JSPM-5400" scanning probe microscope (Japan) in semi-contact mode. Samples in the form of thin films applied to a substrate were scanned at room temperature. The microscope's resolution was 60 Å, with magnification ranging from 10,000 to 100,000 times. Surface topography and phase contrast were analyzed to identify "bee-like" structures and other domains.

3.5. Statistical Analysis of Results

For each type of bitumen and asphalt concrete mixture, at least three specimens were tested (n=3). For the adhesion test, five replicates were used (n=5). For AFM analysis, at least three different areas on the surface of each sample were scanned. The results in the tables are presented as the arithmetic mean value ± standard deviation (mean ± SD).

3.6. Preparation and Compaction of Asphalt Concrete Specimens

The asphalt concrete mixture was prepared by mixing heated mineral aggregate, bitumen (original or modified), and a modifier (cellulose fiber or PET fibers). The hot mixture was then placed into cylindrical molds and compacted using a mechanical press under a static load of 40 MPa, held under load for 3 minutes to ensure proper densification. This pressure was chosen to achieve a density and residual porosity equivalent to compaction with 75 blows of a standard Marshall hammer (equivalent to ~35-40 MPa for 71.4 mm diameter specimens) and is a common laboratory practice for this type of testing. The obtained cylindrical specimens with a diameter of 71.4 mm were extracted and conditioned before mechanical testing.

- Compressive Strength: determined on a press at temperatures of 20°C and 50°C and calculated as the ratio of the breaking load to the cross-sectional area of the specimen.
- Water Saturation: determined as the ratio of the mass of water absorbed by the specimen after vacuuming and soaking in water to the mass of the dry specimen, expressed as a percentage.

4. RESULTS AND DISCUSSION

The results of determining the leading physico-mechanical indicators of original and modified bitumen are presented in Tables 1 and 2. The original BND 90/130 bitumen met the standard requirements: penetration depth was 99 (0.1 mm), softening point was 43°C.

As seen in Table 2, the addition of raw rubber led to the most significant improvement in the set of properties: the softening point increased to 45°C, 2°C higher than the original bitumen and the norm. At the same time, penetration (92) remained within the norm, indicating the preservation of the necessary penetration hardness. Additives such as wax, PVA, PAA, and paraffin with a styrene/PVP-copolymer composition either slightly changed the properties or reduced the softening point (to 38–40°C), which can be interpreted as a plasticizing effect.

The improved performance of rubber-modified bitumen, as evidenced by the increased softening point and maintained penetration (Table 2), correlates with the more pronounced and ordered "bee-like" microstructure observed via AFM (Figure 5). This suggests that the raw rubber promotes the formation of a reinforced asphaltene matrix, which is responsible for enhanced elastic and thermal properties. Conversely, additives like wax and PVA, which showed a plasticizing effect (reduced softening point, Table 2), likely disrupt this matrix, as indirectly supported by less distinct microstructural features (Figures 4, 7) and poorer adhesive performance (Table 3).

4.1. Adhesion Properties

The improved adhesion upon the introduction of rubber is likely due to an increase in system polarity and enhanced bitumen wetting (Fig. 3, image b). Visual analysis of Figure 3 clearly shows near-complete film retention on the granite aggregate treated with rubber-modified bitumen, corresponding to the maximum score of 5 (Table 3). In contrast, the sample with PVA additive (Fig. 3, image e) exhibits significant film peeling, which aligns with the lowest adhesion score of 3. The reduced adhesion observed with PVA requires further study, but it may be due to the formation of a weak boundary layer between the bitumen and the mineral surface.

Table 1. Physical and mechanical properties of the original bitumen

Indicator	Norm for bitumen grade BND-90/130	Actual result
Depth of needle penetration, 0.1 mm, min: at 25 °C	91-130	99
Softening point by Ring and Ball, °C, min	Not less than 41	43

Table 2. Physical and mechanical properties of modified bitumen

Parameter	Modifying additive					Norm for bitumen grade BND-90/130
	Wax	Rubber	PVA	PAA	Paraffin+ styrene /PVP-copolymer	
Depth of needle penetration, 0.1 mm, min: at 25 °C	120	92	115	122	125	91-130
Softening point by Ring and Ball, °C, min	38	45	40	39	38	Not less than 41

To assess the reproducibility of the adhesion test results, tests were conducted for five replicates of each sample. The results, presented in Table 3, confirm the high stability of the indicator for the rubber modifier (5 points in all replicates).

Table 3. Adhesion of modified bitumen to granite aggregate (according to GOST 12801-98, n=5)

Sample	Adhesion, points
BND 90/130 (original)	4.0 ± 0.0
Wax	4.0 ± 0.0
Rubber	5.0 ± 0.0
PVA	3.2 ± 0.4
PAA	4.0 ± 0.0
Paraffin+ styrene/PVP-copolymer	4.0 ± 0.0

4.2. Quantitative Microstructural Analysis by AFM

Atomic force microscopy was used to study the microstructure of the original bitumen and bitumen with additives of rubber, PET (dissolved in DMF), and PVA. The obtained images are presented in Figs. 4-7.

All images show so-called "bee-like" structures, which in the literature are associated with asphaltenes. Comparative analysis showed that the introduction of modifiers affects the size, distribution, and contrast of these structures. In particular, the sample with rubber (Fig. 5) exhibits a more pronounced, ordered structure than the original bitumen, which may correlate with improvements in its rheological and adhesive properties. The presence of such structures is considered an indicator of good bitumen performance characteristics, such as elasticity and aging resistance. It is noteworthy that other studies on polymer modifiers, such as polyurethane, also report alterations in the "bee-like" morphology, including reductions and dispersion of these structures, which may be linked to enhanced resistance to oxidative aging [6].

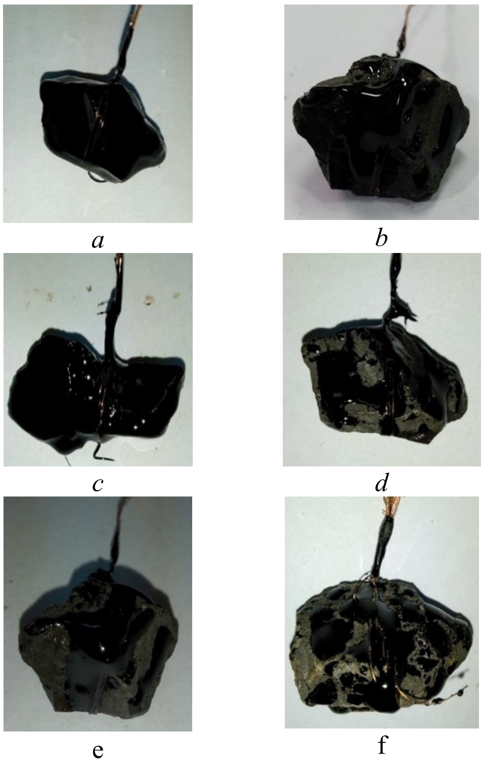
a *b* *c* *d* e f

Fig. 3. Appearance of granite crushed stone after the boiling adhesion test: a – control crushed stone, b – with rubber, c – with PAA, d – with wax, e – with PVA, f – with polymer mixture. Digital photographs (macro mode).

To move from a qualitative description to a quantitative assessment, an analysis of the AFM images was performed using Gwyddion software. For each sample, the root mean square surface roughness (Rq) and the average size of the "bee-like structures" (asphaltene domains) were calculated. The results are presented in Table 4 and in Figs. 4-7. The analysis shows that modification with rubber leads to an increase in domain size and a decrease in roughness compared to the original bitumen, indicating the formation of a more ordered microstructure.

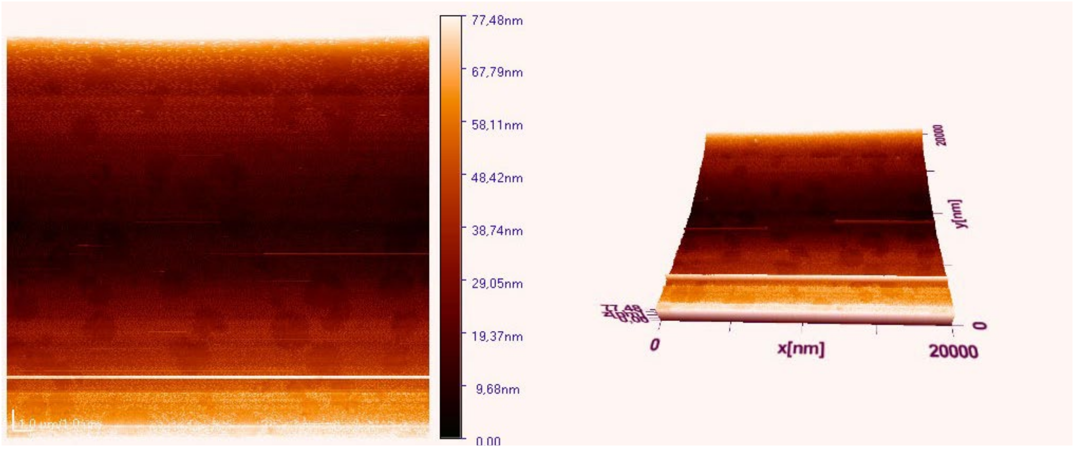

Fig. 4. Original BND 90/130. The scale bar corresponds to 1 µm

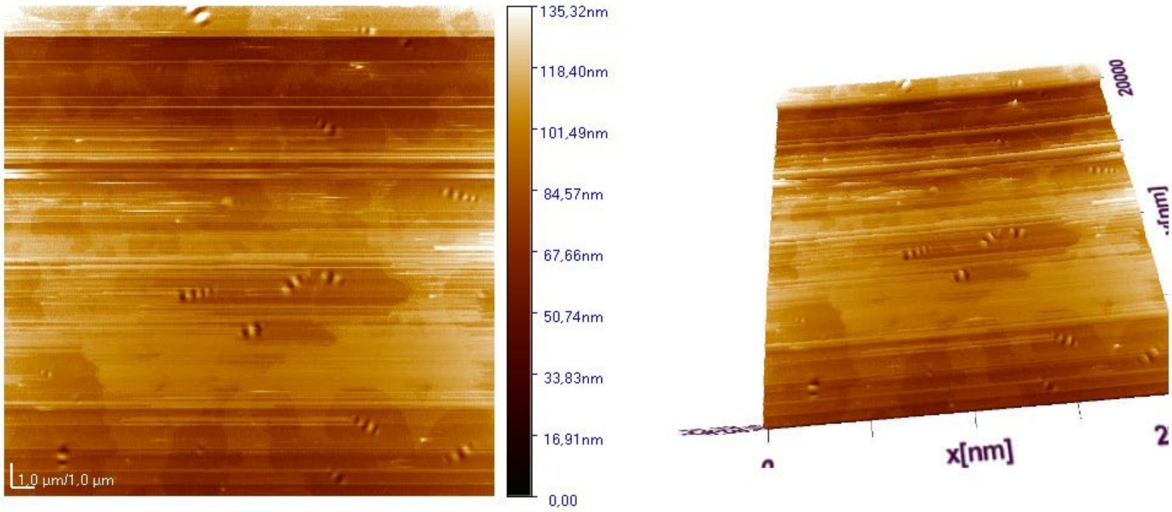

Fig. 5. Original BND 90/130 with raw rubber additive. The scale bar corresponds to 1 µm

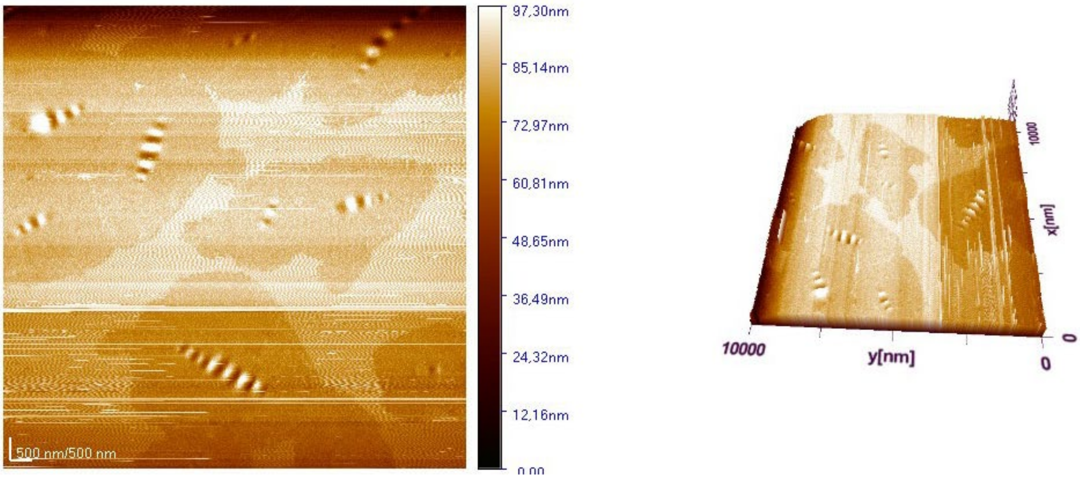

Fig. 6. Original BND 90/130 with PET additive, dissolved in DMF. The scale bar corresponds to 1 µm

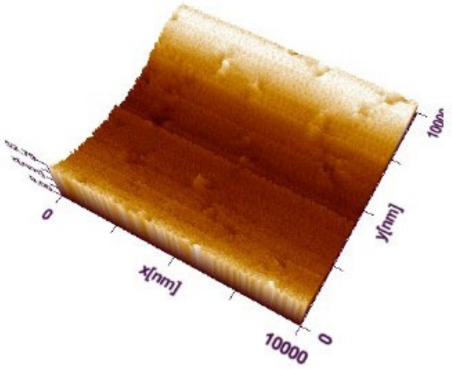

Fig. 7. Original BND 90/130 with PVA additive. The scale bar corresponds to 1 µm

4.3. Properties of Asphalt Concrete

The effect of fiber additives on the properties of asphalt concrete was investigated, and the test results are presented in Table 5.

Table 4. Quantitative microstructure parameters of bitumen by AFM

Sample	Average domain size, µm	Rq, nm
BND 90/130 (original)	0.85 ± 0.20	12.5 ± 2.1
BND 90/130 + rubber	1.20 ± 0.25	8.7 ± 1.5
BND 90/130 + PET (in DMF)	0.60 ± 0.15	18.3 ± 3.0
BND 90/130 + PVA	0.55 ± 0.10	20.1 ± 2.8

Table 5. Physical and mechanical properties of asphalt concrete specimens (n = 3, mean ± SD)

Parameter	Fiber type	GOST 9128–2013 requirements
Compressive strength, MPa		
at 20°C (min)	Cellulose fiber: 8.1 ± 0.3	≥ 2.5
	PET fiber: 2.5 ± 0.4	≥ 2.5
at 50°C (min)	Cellulose fiber: 4.3 ± 0.2	≥ 1.3
	PET fiber: 1.3 ± 0.3	≥ 1.3
Water saturation, %	Cellulose fiber: 3.47 ± 0.15	1.5–4.0
	PET fiber: 3.48 ± 0.20	1.5–4.0

The best compressive strength indicators were obtained for the specimen reinforced with cellulose fiber, both at 20°C (8.1 MPa) and at 50°C (4.3 MPa). This exceeds the requirements of GOST 9128-13 (2.5 MPa and 1.3 MPa, respectively) by more than three times for the test at 20°C. The water saturation of this specimen was 3.47%, which is within the optimal range of 1.5–4.0%.In contrast, the use of PET fibers led to a sharp decrease in strength (2.5 MPa at 20°C and 1.3 MPa at 50°C), which only meets the minimum normative requirements. To visualize the fracture pattern and fiber distribution, macrophotographs of specimen sections were prepared (Fig. 8). The section of thespecimen with PET fiber (Fig. 8b) clearly shows large fiber inclusions and zones of local pore accumulation, confirming the hypothesis of their role as stress concentrators. In the specimen with cellulose fiber (Fig. 8a), the structure is more homogeneous. This adverse effect is explained by the massive size of the used fibers (4–5 cm), which prevents their uniform distribution in the matrix and the creation of an effective reinforcing structure. This finding aligns with established research, which indicates that the positive effect of polymer waste is contingent upon achieving a fine dispersion.

Fig. 8. Macrosections of fractured specimen surfaces: (a) specimen with cellulose fiber, (b) specimen with PET fiber (arrows indicate zones of fiber and pore accumulation).

Literature data indicate that effective PET use is possible only with fine dispersion (particle size <1–2 mm). In particular, research has demonstrated that PET can enhance the stability and raveling resistance of porous asphalt when used as an acceptable additive in Asbuton-based mixtures [7]. This is consistent with other studies in which incorporating an optimal percentage of ground PET bottle waste into hot asphalt concrete mixtures using the wet method significantly increased Marshall stability, indicating improved resistance to deformation [9]. The approach of reinforcing with large polymeric fibers thus requires careful analysis. In contrast, the use of geosynthetic materials, such as grids or cells, can provide more reliable and predictable reinforcement for road structures, as confirmed by field trials [10].

5. DISCUSSION OF RESULTS AND STUDY LIMITATIONS

The conducted studies established a direct correlation between microstructural changes and macroscopic properties. The most ordered microstructure of bitumen with rubber (Table 4) correlates with maximum adhesion (5 points) and high strength of the asphalt concrete. Cellulose fiber provides effective dispersion reinforcement, increasing compressive strength by more than 3 times relative to the standard requirements. The low efficiency of large PET fiber is explained by uneven distribution and defect formation, visualized in Fig. 8.

Despite the obtained results, the work has several limitations. First, the dosage of the rubber modifier (1.5–2%) was chosen based on preliminary data and is not the result of statistical optimization (e.g., by response surface methodology). Second, rheological tests (DSR, MSCR), necessary for quantifying the bitumen's resistance to rutting at high temperatures and fatigue life, were not performed. Third, adhesion was assessed by the qualitative "boiling" method, and quantitative methods (e.g., determination of bonding energy) and FTIR spectroscopy are required to confirm the interaction mechanisms at the interface. Finally, AFM provides information only on surface morphology; scanning electron microscopy (SEM) is necessary to study the bulk structure and modifier distribution. Further research should aim to address these limitations, including composition optimization, conducting extended rheological and mechanical tests (Marshall, ITS, rutting), and field validation.

6.CONCLUSION

Based on the comprehensive studies conducted, the following conclusions can be drawn:

1. Effectiveness of bitumen modifiers: Among the studied additives (raw rubber, PVA, PAA, wax, paraffin+styrene/PVP copolymer), the best combination of properties was achieved by introducing 1.5–2% raw rubber into BND 90/130 bitumen. This led to an increase in the softening point by +2°C (to 45°C) and the achievement of maximum adhesion to granite crushed stone (5 points), while maintaining the penetration index within the standard range (92·0.1 mm).
2. Effect of fibrous fillers: Reinforcing the asphalt concrete mixture with cellulose fiber obtained from waste paper (size 0.1–1.0 mm) is a highly effective method. The compressive strength of the specimens was 8.1 ± 0.3 MPa at 20°C, which is more than three times higher than the GOST standard requirements.
3. Ineffectiveness of large PET fiber: The use of PET fiber sized 4–5 cm led to property degradation (compressive strength at 20°C decreased to 2.5 ± 0.4 MPa), explained by its uneven distribution and the formation of stress concentrators, confirmed by macrostructural analysis.
4. Micro-macro property correlation: Using quantitative AFM analysis, it was established that bitumen modification with rubber leads to an increase in the average size of asphaltene domains (from 0.85 to 1.20 μm) and a decrease in surface roughness, which correlates with the improvement of its adhesive and physical-mechanical properties.
5. Practical significance: The most rational solution is the combination of rubber-modified bitumen and asphalt concrete reinforced with cellulose fiber. The proposed technological scheme for producing the modifier from waste paper has potential for import substitution and resource conservation in the road construction industry; however, it requires further techno-economic and environmental validation under industrial conditions.

7. PROSPECTS FOR PRACTICAL IMPLEMENTATION

For the industrial implementation of the proposed approach, a conceptual technological line for producing modifiers from waste paper was developed. The line includes the following stages: (1) grinding waste paper in a hammer mill to a fraction of 0.1-1.0 mm (capacity ~ 500 kg/h, power consumption 45 kW); (2) treating the obtained cellulose pulp with a 3% polymer solution in a steam-jacketed mixer; (3) drying the finished product in a drum dryer at 80°C to a residual moisture content of 2-3% (energy consumption 0.8 GJ/t); (4) dosing and packaging.

A preliminary techno-economic assessment shows that the production cost of 1 ton of modifier from waste paper is approximately 3-4 times lower than the cost of imported cellulose fibers. From an environmental perspective, recycling 1 ton of waste paper saves 2-3 m³ of wood and reduces CO2 emissions by 600-800 kg compared to landfilling or incineration. This underscores not only the economic but also the environmental feasibility of the proposed technology.

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