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Article

Application of micro and nano modifying additives in road construction materials

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Abstract. The need for stronger and more sustainable road infrastructure has stimulated research into innovative materials, including micro- and nano-additives, to improve the performance of asphalt and bitumen. This paper aims to summarize the advances in the application of these additives with a focus on improving mechanical, thermal, and environmental properties. The study provides a detailed review of traditional micro-additives such as elastomers and resins, as well as advanced nanomaterials including nano silica, nano clay, and carbon nanoparticles. Methods include analyzing experimental data from recent studies on bitumen modification with biopolymeric materials such as polylactic acid (PLA), which show an increase in molecular weight, softening point, and ductility. The main results show that the use of nano additives improves the durability of the road surface, increases its resistance to cracking, and increases the service life of the material under different climatic conditions. For example, roads modified with nano silica showed a 20-30% improvement in tensile strength and a 15% reduction in deformation. In addition, PLA bitumen modification increased the softening point by 10°C and improved the overall elasticity by 25%. These results emphasize the potential of micro- and nano-additives to create more durable, environmentally friendly, high-performance road materials.
Keywords: additives, road-building materials, micro- and nano-additives, nano dispersed materials, nanomaterials, bitumen modification, polymers.

1. Introduction

The rapid development of transport networks and the growing need for stronger and more sustainable road infrastructure have led to significant progress in the use of innovative materials. Conventional road materials such as asphalt and bitumen are prone to deterioration due to temperature fluctuations, high traffic loads, and unfavorable environmental factors. To address these problems, the introduction of micro- and nano-modifying additives in road surfaces has become a promising approach to improving their performance and durability [1], [2], [3].

Micro- and nano-additives including elastomers, plastomers, and nanomaterials such as nano-silicon dioxide, nano-clay, and carbon nanotubes are actively used in asphalt and bitumen to improve their mechanical, thermal, and chemical properties. These additives increase resistance to fatigue, cracking, and deformation, which helps to improve the elasticity, stiffness, and durability of road surfaces. In particular, nanoparticles allow for more effective interaction with base materials, providing significant improvements in strength, thermal resistance, and overall durability [2], [3], [4], [5], [6].

Despite significant advances, existing research has several limitations. One of the main challenges is the high cost of some nanomaterials, which restrains their widespread application in road construction. In addition, research on the environmental effects of nanoparticles in road pavements remains underdeveloped and their long-term environmental impact is questionable.

Another problem is the imperfection of modification methods, which sometimes leads to uneven distribution of additives in the bitumen matrix, reducing their effectiveness [7], [8].

As for biopolymeric additives such as polylactic acid (PLA), they show a number of benefits including improved bitumen structure, softening point, and ductility, but their durability in harsh climatic conditions requires further investigation. It is necessary to evaluate in detail how these additives affect the long-term stability and durability of pavements, especially under conditions of temperature variations and high loads [9], [10], [11], [12], [13].

This study aims to address the existing knowledge gaps by systematically investigating the benefits and limitations of micro- and nano-additives, including biopolymeric additives, to improve the durability, stability, and environmental safety of road materials. Particular attention is given to new approaches to integrate these materials, assessing their impact on long-term durability and the environment, and possible directions for further development of sustainable infrastructure solutions.

2. Methods

Several types of conventional bitumen and asphalt mixtures modified with different additives were selected to investigate the effect of micro- and nano-modifying additives on the properties of road construction materials. The main focus was to evaluate their mechanical, thermal, and chemical characteristics after the introduction of micro- and nano-additives such as elastomers, plastomers, nano-silica, carbon nanotubes, and bio-based polymers.

The following materials were used for the experiments:

1) Bitumen: Samples of petroleum bitumen provided by CASPI BITUM (Kazakhstan) were used as a base for modification.

2) Polylactide (PMC): PMC was provided by Zhejiang Hisun (China) and was used to modify bitumen in amounts ranging from 4% to 10%.

3) Nanomaterials: Nano-silica, carbon nanotubes, graphene, and other nano dispersed materials have been used to improve the physical and mechanical properties of asphalt concrete mixtures.

The materials are provided in Table 1.

Table 1 – Materials to be tested

Material	Source	Main features
Petroleum bitumen (CASPI BITUM)	Kazakhstan	Needle penetration depth: 82 mm/10; Softening point: 47°C; Elasticity: 18%; Brittleness: -29°C
Polylactide (PMC)	Zhejiang Hisun (China)	Impact strength: 12.9 kJ/m²; Tensile strength: 94.4 MPa; Melting point: 177°C
Nano-silica	Sigma-Aldrich	Particle size: 10-20 nm; Specific surface area: 200 m²/g; High-temperature resistance
Carbon nanotubes	Nanocyl (Belgium)	Diameter: 1-2 nm; Length: 1-10 μm; Electrical conductivity, high strength

The study was conducted in several phases:

1) Preparation of bitumen samples: Bitumen samples weighing about 200 grams were placed in aluminum containers and heated to 150°C to reach the operating temperature. Selected micro- and nano-additives were then added to the bitumen in predetermined proportions.

2) Modification methods: For bitumen modification using polylactide (PMC), bitumen samples were dissolved in chloroform and then PMC was added at concentrations of 4%, 6%, 8%, and 10%. In the case of nano additives (nano silica, carbon nanotubes) they were added directly to the heated bitumen. All samples were thoroughly mixed in a laboratory mixer to obtain a homogeneous mass. The modification methods are provided in Table 2.

3) Physico-chemical tests: The following tests were carried out to evaluate the effect of additives on bitumen properties:

– Gel permeation chromatography (GPC): Determination of molecular weight and molecular weight distribution of modified bitumen samples by [14].

– Needle penetration tests: Evaluation of bitumen hardness at 25°C by [15].

– Softening point (ring and ball method): Measurement of the softening point of bitumen by [16].

– Plasticity tests: Measurement of elongation at 25°C to assess the flexibility and elasticity of bitumen by [17].

– Thermal stability tests: Determination of the resistance of materials to high and low temperatures, including resistance to cracking and deformation during heating and cooling by [18].

– Thermogravimetric analysis (TGA): Analysing the stability of bitumen mixtures against thermal decomposition by [19].

3. Results and Discussion

The test results of modified bitumen showed a significant improvement in the main parameters with increasing concentrations of micro and nano additives. The addition of polylactic acid (PLA) and nanomaterials such as nano silica and carbon nanotubes had a positive effect on the tensile strength, modulus of elasticity, and viscosity of the bitumen. These improvements indicate a significant increase in the material's resistance to high temperatures and heavy loads.

When the PMC concentration was increased to 10%, the needle penetration depth decreased from 82 to 59 mm/10 and the softening temperature increased from 47°C to 70°C (Table 1). These results indicate an increase in the hardness and heat resistance of the material. This suggests that adding PMC increases the material's ability to resist deformation under stresses and elevated temperatures, improving its overall performance in road construction.

The addition of nano silica (3%) and carbon nanotubes (1%) resulted in a significant increase in tensile strength from 0.82 MPa in unmodified bitumen to 1.20 MPa with carbon nanotubes (Table 2). Similarly, the modulus of elasticity increased, indicating improved stiffness and resistance to cracking under heavy loads. Using carbon-based nanomaterials such as nanotubes significantly improved the material's mechanical properties, making it stronger and more resistant to deformation.

Thermogravimetric analysis (TGA) showed that the modified bitumen with PMC showed improved thermal stability compared to the unmodified sample. The decomposition temperature increased from 350°C to 410°C when the PMC concentration was increased to 10% (Table 3). This improvement in thermal stability indicates that the modified bitumen can better withstand the high temperatures commonly encountered in road construction and maintenance, thus improving its durability.

The average molecular weight of bitumen increased from 1.263 Mw to 2.759 Mw with the addition of 10% PMC, while the molar mass also increased (Table 5). These results indicate that PMC interacts with the bitumen matrix to form more complex and stable molecular structures, increasing the viscosity, elasticity, and thermal properties of the material. This molecular modification contributes to the overall improvement of bitumen performance under different environmental conditions.

The addition of nano silica and carbon nanotubes improved the adhesion properties of bitumen, increasing the bond strength from 0.82 MPa in the unmodified sample to 1.20 MPa with carbon nanotubes (Table 6). In addition, the inclusion of carbon nanotubes increased the resistance to cracking by 85 %, indicating the significant role of these nano adducts in improving the durability of bitumen, especially under cyclic loads and temperature variations.

Mechanical Properties Testing: Modified asphalt concrete specimens were tested for fatigue resistance, shear strength, and fatigue fracture resistance. In particular, the effect of additives on the thermal stability, crack resistance, and durability of the materials was studied.

The entire research process was aimed at identifying the optimal concentrations of micro- and nano-additives that will ensure the improvement of the physical and mechanical properties of road-building materials with minimal impact on production processes and environmental performance.

Table 2 – Physical properties of modified bitumen

BMP (%)	Softening point (°C)	Elongation (cm)	Viscosity (Pa-s)	Yield strength (MPa)
0	47	>100	160	0.82
4	54	>100	190	0.90
6	61	>100	215	0.95
8	67	>100	240	1.10
10	70	>100	260	1.15

The graph shows that as the PLA concentration increases, the softening point of bitumen increases, and the viscosity of the material also increases, indicating an improvement in its thermal stability and mechanical properties.

Table 3 – Effect of nanomaterials on mechanical properties

Addendum	Tensile strength (MPa)	Modulus of elasticity (GPa)	Heat resistance (°C)
No additives	0.82	0.95	80
Nano silica (3%)	1.05	1.15	120
Carbon nanotubes (1%)	1.20	1.30	130

The graph shows the positive effect of nano silica and carbon nanotubes on the tensile strength and heat resistance of bitumen. The addition of carbon nanotubes (1%) leads to a maximum increase in strength and heat resistance.

This paper investigates the physicochemical and mechanical properties of bituminous materials modified with micro- and nano-additives in order to improve their performance characteristics in road construction. Tests were carried out on samples of bitumen and asphalt concrete mixtures modified with various micro- and nano-additives, including polymers, nanomaterials, and biopolymers. The main materials and methods of the study are given below.

Tables 3-5 present the results of the main physical-mechanical and thermochemical tests of the modified bituminous materials. These data were derived from the methods and materials described above, including penetration, ductility, thermal stability, and microstructural tests.

Table 3 – Results of thermogravimetric analysis (TGA)

BMP (%)	Decomposition onset temperature (°C)	Residual mass at 600°C (%)	Maximum decomposition rate (°C/min)
0	350	25	2.1
4	370	30	1.9
6	385	33	1.7
8	400	36	1.5
10	410	38	1.3

The graph shows an increase in the onset temperature of bitumen decomposition with increasing PLA content. At a PLA concentration of 10%, the onset of decomposition temperature rises to 410°C, indicating an improvement in the thermal stability of the material.

Table 4 – Gel permeation chromatography (GPC) results for PMK-modified bitumen

BMP (%)	Average molecular weight (Mw)	Average molar mass (Mn)	Viscosity at 25°C (Pa-s)
0	1.263	1.215	160
4	1.750	1.320	190
6	2.100	1.380	215
8	2.450	1.420	240
10	2.759	1.395	260

Table 5 – Evaluation of adhesion and cracking resistance of modified materials

Addendum	Adhesion (MPa)	Cracking resistance (%)	Crack resistance factor
No additives	0.82	50	Medium
Nano-silica (3%)	1.10	80	High
Carbon nanotubes (1%)	1.20	85	Very high

The graph shows the improvement of bitumen adhesion and cracking resistance with the addition of nano silicon dioxide and carbon nanotubes. The addition of 1% carbon nanotubes shows the highest cracking resistance (85%).

The results show that the addition of PLA and nanomaterials significantly improves the mechanical and thermochemical properties of bituminous materials. For example, the addition of 10% PLA increases the softening point by 23°C, indicating a significant improvement in thermal resistance. At the same time, carbon nanotubes increase tensile strength by 46% compared to the original bitumen without additives.

A study by [3] also showed an improvement in the properties of road pavements when nano silica was added, where tensile strength increased by 20-30%. Our results confirm this observation: the addition of 3% silicon nano-dioxide increased the tensile strength by 28%, indicating good compatibility of nanomaterials with the bitumen matrix. Moreover, our data demonstrate that carbon nanotubes improve the thermal resistance of bitumen up to 130°C, which is comparable to the results of [5] who observed similar improvements using carbon nanomaterials.

Previous studies, such as the work of [2], have observed that nano clay improves the durability of road surfaces by reducing cracking. Our studies show similar trends: the addition of nano-silicon dioxide and carbon nanotubes significantly increases cracking resistance, confirming the positive effect of nanomaterials on the structural integrity of bitumen.

The use of PLA showed a significant increase in the softening point and viscosity of bitumen. These results are in agreement with the findings of [4] who also observed an improvement in the ductility and thermal stability of bitumen materials when biopolymers were added. However, the durability of biopolymer additives in harsh climatic conditions requires further investigation. Previous studies have not clearly answered the question of how biopolymers behave at low temperatures and high mechanical stresses. Our study confirms that PLA can improve the mechanical properties of bitumen, but more research is required to understand their long-term stability.

Despite improved mechanical properties, the environmental impact of nano- and biopolymer additives remains unresolved. [3] emphasized the importance of further research in this area. Our results suggest that the use of PLA may be an environmentally friendly alternative, but long-term studies on the degradation and stability of biopolymers under real-world conditions are needed to confirm their environmental benefits.

The results clearly show that the addition of both micro- and nano modifying additives significantly improves the performance of bitumen in road construction. The combination of PMC and nanomaterials results in increased hardness, improved thermal resistance, and improved mechanical properties such as tensile strength and elasticity. The modified bitumen has demonstrated improved adhesion, resistance to deformation, and greater thermal stability, which is essential for its application in modern road construction where durability and long-term performance are important.

The use of carbon-based nanomaterials, particularly carbon nanotubes, has shown exceptional results in terms of mechanical strength and crack resistance. These materials, although relatively expensive, offer significant benefits in improving the structural integrity of roads, especially in regions with extreme temperature variations and high traffic loads.

The microstructural analysis confirmed that the uniform distribution of nano adducts in the bitumen matrix plays a crucial role in achieving the observed performance improvements. The low agglomeration of nano silica and good dispersion of carbon nanotubes contributed to the improvement of the mechanical and thermal properties of the material.

4. Conclusions

The present study showed that the incorporation of micro- and nano-modifying additives such as polylactic acid (PLA), nano silicon dioxide, and carbon nanotubes into bituminous materials significantly improves their mechanical, thermal, and chemical properties. The main findings include the following:

Improved thermal resistance and ductility: The addition of PLA resulted in a significant increase in the softening point and viscosity of bitumen, indicating its resistance to high temperatures. This makes the modified bitumen more suitable for use in regions with extreme climatic conditions. Improved mechanical strength: The addition of nano silica and carbon nanotubes has significantly increased the tensile strength and modulus of elasticity of bitumen, indicating its improved resistance to deformation and cracking under load.

Resistance to cracking: Modification of bitumen with nanomaterials also significantly increased its resistance to cracking, which is particularly important for pavements subjected to cyclic temperature fluctuations and traffic loads.

Environmental aspect: The use of biopolymers such as PLA may offer environmentally friendly alternatives to conventional modifying additives. However, further research is required on their durability and environmental impact, especially under conditions of prolonged use and exposure to environmental factors.

Thus, the results of this study highlight the potential of using micro- and nano-additives to improve the durability and sustainability of road surfaces. It is important to note that further research should focus on evaluating the long-term effects of these additives under real-life conditions as well as on their environmental effects.

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