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DEVELOPMENT AND INVESTIGATION OF PETROLEUM BITUMEN WITH ENHANCED PERFORMANCE PROPERTIES FOR ROAD CONSTRUCTION

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Annotation

Development of Scientific Foundations and Technological Principles for the Production and Efficient Operation of a Modern Manufacturing-Technology Complex for Producing Bituminous Materials with Enhanced Performance Properties for Road Construction, Based on the Application of Modification Technologies Utilizing Various Hard-to-Process Wastes, By-Products, and Secondary Industrial Resources.

Keywords

Bitumen, Asphalt Concrete, Waterproofing, Modification, Structural-Mechanical Properties, Oxidation, Photoelectrometric Method.

INTRODUCTION

Petroleum-derived bitumen is a fundamental material in contemporary road construction, offering the capacity to form long-lasting, water- and frost-resistant pavement layers. However, under conditions of intensive traffic loads and fluctuating climatic factors, conventional bitumen often falls short of providing the desired performance, leading to premature degradation of road surfaces. Consequently, the design and study of bitumen with enhanced operational properties, tailored to specific environmental and service conditions, remain a critical objective in pavement engineering research.

Recent advances in modified petroleum bitumen focus on incorporating polymers, copolymers, mineral fillers, and other chemical modifiers that enhance essential properties, including plasticity, viscosity, thermal stability, and crack resistance. Beyond production, a thorough assessment of physical and chemical characteristics is essential, employing advanced analytical techniques such as dynamic rheology, thermogravimetric analysis, and microstructural examination.

Therefore, the investigation of petroleum bitumen with superior operational characteristics holds significant relevance both scientifically and practically, aiming to extend pavement longevity, reduce maintenance costs, and improve overall road safety. This study is dedicated to developing methods for producing modified bitumen and conducting a comprehensive evaluation of its properties, providing insight into the effectiveness of various strategies for enhancing the performance of road construction materials.

It is well known that petroleum bitumen ranks among the most widely used binding materials in road construction. The development of road infrastructure represents a key factor in the socio-economic growth of a country. In the Republic of Uzbekistan, substantial quantities of bituminous composite binders are consumed annually for the construction of new highways, as well as for the reconstruction and repair of existing asphalt concrete pavements.

LITERATURE REVIEW AND METHODOLOGY

However, an analysis of the current condition of road networks indicates that a significant portion of pavements fails to meet established regulatory standards. Findings from independent applied studies demonstrate that, under moderate climatic conditions, road bituminous materials lose a substantial part of their initial operational properties within 2.0–2.5 years of service. Among the affected characteristics is their capacity to provide reliable waterproofing of the pavement structure, which is critical for maintaining long-term durability and preventing premature degradation.

In this study, bitumen samples were prepared using a laboratory-scale batch installation (Fig. 1), consisting of an oxidation column, an air supply and control system for the reactor, and a gas purification system. The purification system included a series of absorption flasks (6a, 6b, 6c), two of which were designed to absorb hydrogen sulfide and sulfur-containing compounds (6b, 6c), while the third flask served to condense water vapor and organic substances released during the oxidation process. This experimental setup allowed precise control of oxidation conditions and ensured reproducible production of bitumen samples with targeted properties for subsequent testing.

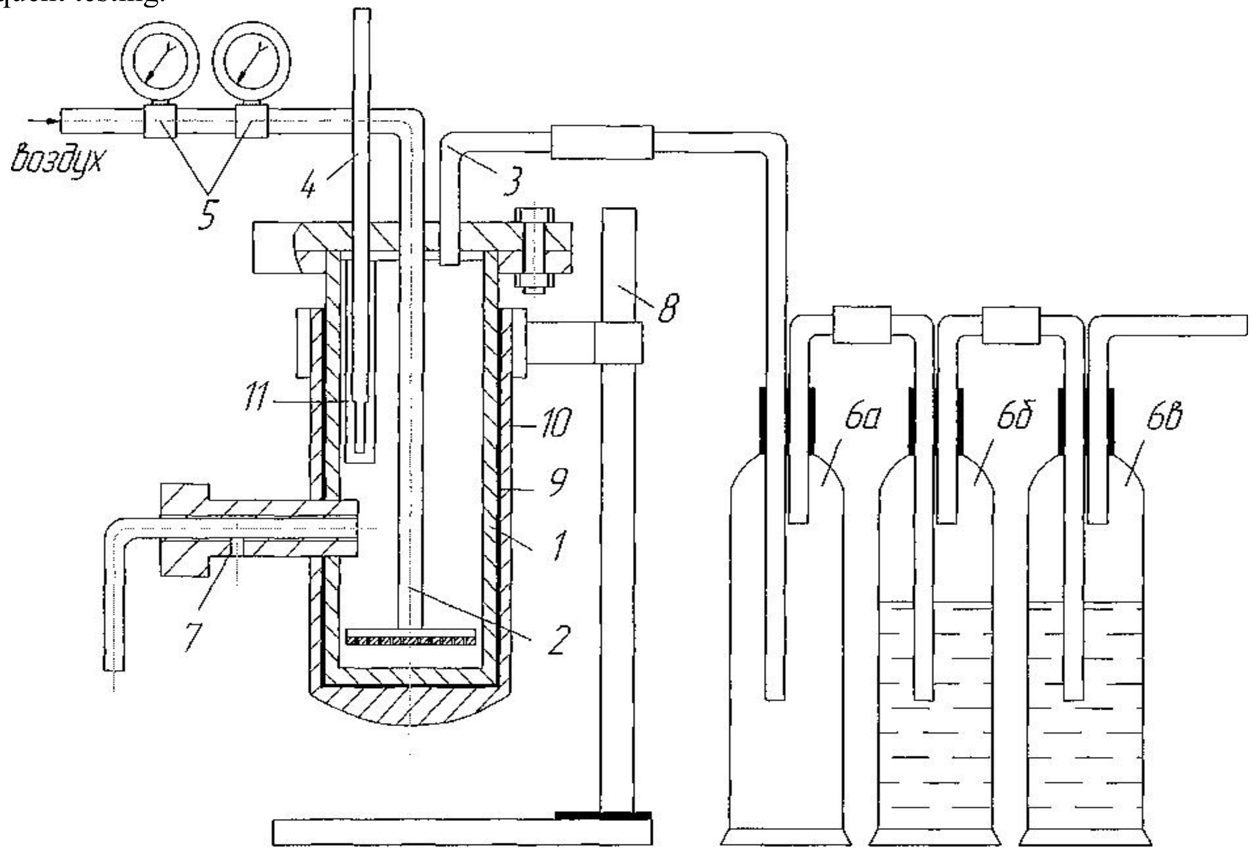

Fig. 1. Laboratory setup for the production of oxidized bitumen:
1 – Oxidation column; 2 – Sparger; 3 – Exhaust gas outlet; 4 – Thermometer; 5 – Manometers; 6a, 6b, 6c – Absorption flasks; 7 – Sampling port; 8 – Stand; 9 – Thermal insulation layer; 10 – Electric heater; T – Thermometer pocket.

This laboratory apparatus enables controlled oxidation of petroleum bitumen under reproducible conditions. The oxidation column (1) serves as the main reaction chamber, while the sparger (2) ensures uniform air distribution within the bitumen. Exhaust gases are removed via outlet (3) and pass through a series of absorption flasks (6a, 6b, 6c) for removal of hydrogen sulfide, sulfur compounds, and condensation of water vapor and organic volatiles. Temperature and pressure are monitored using a thermometer (4) and manometers (5), with the entire setup thermally insulated (9) and heated electrically (10) to maintain the desired reaction conditions. The sampling port (7) allows for periodic extraction of bitumen samples for analysis.

The oxidation column-reactor is a vertical cylindrical apparatus equipped with nozzles for air supply at the bottom of the column and for the removal of vapor and gases at the top. Temperature control within the column was achieved by adjusting the voltage applied to the column winding using a variac.

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The experimental procedure was carried out as follows: the column was filled with the feedstock and heated to the required reaction temperature. Once the desired temperature was reached, air was introduced into the column through a sparger at a volumetric flow rate of 2.5–10 L/min per kilogram of feedstock. Exhaust gases exiting the top of the column passed through a series of absorption flasks filled with 5.0% alkaline solution and mineral oil, where sulfur-containing gases were captured and condensation of liquid products (black diesel) occurred. The purified gas was then released into the atmosphere. The oxidation process was monitored by measuring the softening point of the bitumen samples.

The influence of the chemical and fractional composition of the feedstock on the oxidation rate of bitumen was studied by evaluating changes in the softening point of the samples as a function of oxidation time. Oxidation of high-molecular-weight residues from paraffinic crude oils was conducted under constant process parameters: temperature of 250 °C and an air flow rate of 5 L/min per kilogram of oxidized feedstock. Material balances of the process were calculated, accounting for the amounts of gaseous products, water, and condensate (black diesel) formed during oxidation.

RESULTS

To ensure an objective analysis of the obtained data, this section presents the results of the oxidation of residual fuel oils and tars derived from the Fergana and Surkhandarya crude oils, whose heavy residues are utilized for the production of industrial bitumen.

The increase in the softening point of fuel oils from different crude sources over time during oxidation is illustrated in Fig. 2. These results provide insight into the kinetics of the oxidation process and the influence of feedstock composition on the development of enhanced operational properties of the resulting bitumen.

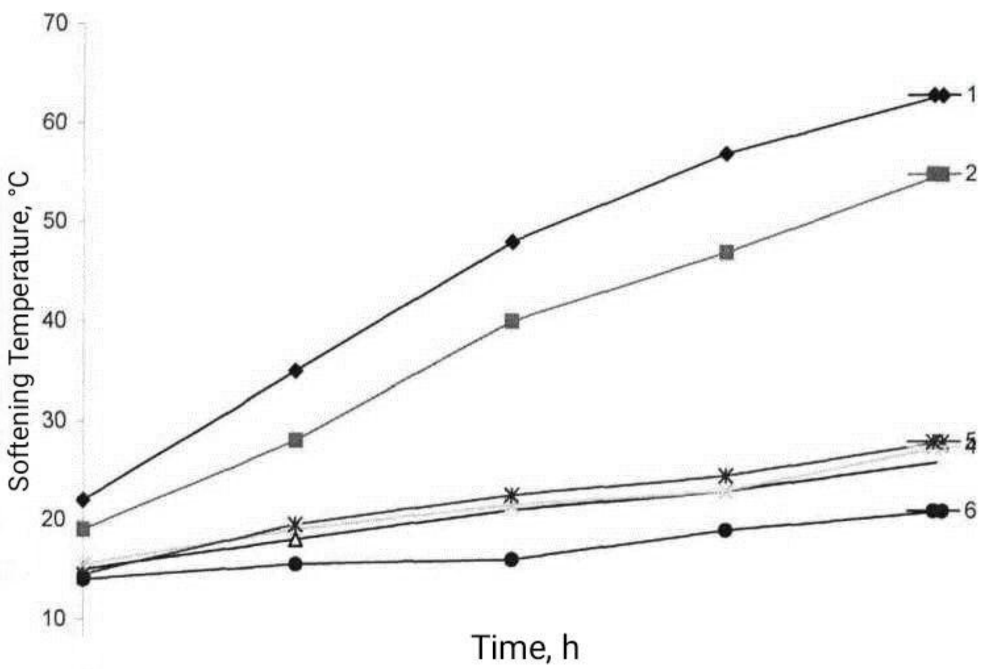

Fig. 2. Dependence of the softening point of samples on oxidation duration.

Residual fuel oils from different crude sources are denoted as follows: 1 – Afghan crude; 2 – Chinaz crude; 3 – Kyrgyz crude; 4 – Maskhar crude; 5 – Fergana crude; 6 – Residual fuel oil from the Bukhara gas-condensate field.

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This figure illustrates the progressive increase in the softening point of each feedstock as a function of oxidation time, highlighting differences in oxidation kinetics and reactivity associated with the chemical composition of the various crude residues.

As shown in Fig. 2, the nature of the crude oil significantly affects the oxidation behavior of the samples. For high-paraffinic crude oils and the Bukhara gas-condensate residue, the rate of increase in the softening point is relatively low. Over a 20-hour oxidation period, the average increase in the softening point of these samples was only 11–12 °C. Specifically, for Fergana crude fuel oil, the softening point rose by 3 °C after 5 hours, 6 °C after 10 hours, 8 °C after 15 hours, and 11 °C after 20 hours of oxidation. A similar trend was observed for other high-paraffinic feedstocks. This indicates that under the specified process parameters, the oxidation of high-paraffinic residues is limited. The observed increase in softening point can be attributed both to the oxidation of a small fraction of components present in the residual oil and to the distillation of the most volatile constituents. Consequently, the low process efficiency, coupled with the accumulation of unconverted paraffino-naphthenic hydrocarbons in the oxidized product, makes bitumen production from paraffinic feedstocks impractical.

In contrast, samples 1 (Fergana crude fuel oil) and 2 (a mixture of Surkhandarya crude fuel oils) exhibited relatively high oxidation rates throughout the entire observation period. For Fergana crude fuel oil, the softening point increased by 13 °C after 5 hours, 26 °C after 10 hours, 35 °C after 15 hours, and 41 °C after 20 hours of oxidation.

Figure 3 presents the dependence of the softening point increase of heavy residues (tars) on oxidation time under the same process conditions. As seen in Fig. 3, the oxidation behavior of tars is analogous to that of the corresponding residual fuel oils shown in Fig. 2. The highest oxidation rates were also observed for samples 1 and 2, corresponding to the Fergana and Surkhandarya tars. For example, after 2 hours of oxidation, the softening point increased by 32 °C for sample 1 and 35 °C for sample 2. It is notable that the oxidation intensity of the Fergana and Surkhandarya tars decreases slightly once the softening point reaches approximately 45 °C. These observations are in good agreement with literature data, which report the two-stage nature of bitumen oxidation.

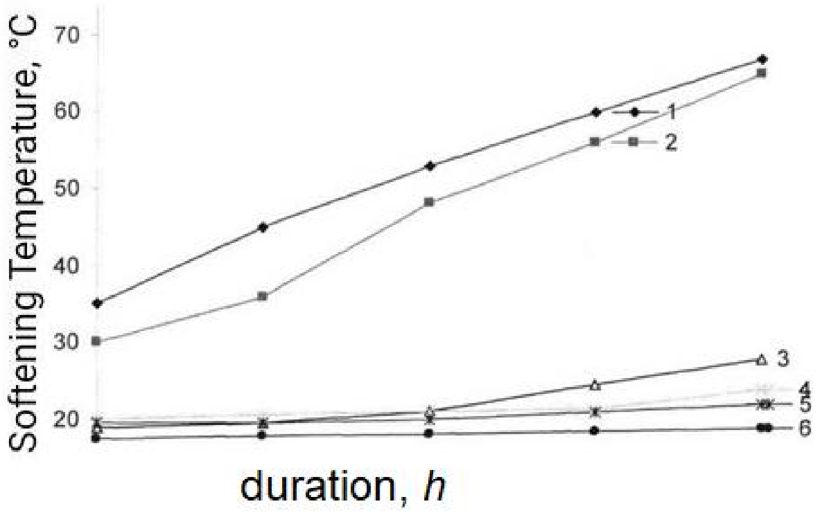

Fig. 3. Dependence of the softening point of tars on oxidation duration.
Residual fuel oils (feedstocks) are designated as follows:
1 – Afghan crude;
2 – Chinaz crude;
3 – Kyrgyz crude;

4 – Maskhar crude;
5 – Fergana crude;
6 – Residual fuel oil from the Bukhara gas-condensate field.

This figure illustrates the increase in the softening point of tars over the course of oxidation under the same process conditions as applied to the corresponding residual fuel oils. The data demonstrate similar trends to those observed in Fig. 2, with the highest oxidation rates occurring in samples 1 and 2 (Fergana and Surkhandarya residues). This comparison highlights the influence of crude oil composition on the oxidation kinetics of heavy petroleum residues.

The softening point of samples 3, 4, 5, and 6 exhibited only minor changes over the course of oxidation. This behavior can be attributed to the high content of solid paraffins and paraffino-naphthenic hydrocarbons in the feedstock, which are inherently resistant to oxidation under the given process conditions. The lowest oxidation rate was observed for the tar derived from the Bukhara gas-condensate residue.

Table 1. Physicochemical Characteristics of Tars

Parameter	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Sample 6**
Density at 20 °C, kg/m³	1035	945	937	948	942	935
Apparent Viscosity, VUdo	28.6	27.5	18.6	21.1	19.2	28.5
Solid Paraffin Content, wt.%	3.1	1.5	5.2	3.1	4.8	20.0
Sulfur Content, wt.%	4.2	2.6	0.28	0.38	0.26	2.8
Pour Point, °C	36	29	38	43	36	41
Component Composition, wt.%:						
- Oils	46.7	51.9	73.0	77.3	72.1	78.8
- Resins	31.8	38.3	19.2	17.2	21.7	14.5
- Asphaltenes	17.0	9.8	7.8	5.5	6.2	6.7

Residual fuel oils (feedstocks) are designated as follows:

1 – Afghan crude; 2 – Chinaz crude; 3 – Kyrgyz crude; 4 – Maskhar crude; 5 – Fergana crude; 6 – Residual fuel oil from the Bukhara gas-condensate field.

Note: The table presents key physicochemical parameters of the tars, including density, softening point, penetration, and other relevant characteristics, allowing comparison of oxidation behavior and quality of bitumen derived from different crude sources.

The softening point of the tar increased by 6.5 °C after 2 hours of oxidation. This behavior can be explained by the physicochemical characteristics of the tar samples, as presented in Table

1. As seen in Table 1, the tars from Fergana and Surkhandarya crude oils are characterized by a high content of aromatic hydrocarbons, which undergo dehydrogenation during oxidation and condense to form more complex systems, i.e., the formation of resins and asphaltenes.

The Fergana tar exhibits a high sulfur content (4.2 wt.%), which partially accounts for the reduced slope observed in the oxidation kinetics curve. This phenomenon may result from inhibition of the oxidation process by sulfur-containing compounds.

For the high-paraffinic residues of three other crude oils, a nearly identical pattern was observed—the oxidation kinetics show little dependence on duration. Consequently, it was decided to use, in further studies, mixtures of residual fuel oils and tars in a 1:1:1 ratio rather than single-source residues.

Table 2 presents the characteristics of bitumen obtained from these samples. As shown, bitumen derived from the Fergana and Surkhandarya tars passed the tests and, according to key parameters, corresponds to viscous bitumen of grade BND 40–60 (GOST 22245-90). It exhibits good adhesion to marble chips and sand.

In contrast, bitumen obtained from high-paraffinic residues and Fergana gas-condensate corresponds to viscous bitumen of grade BND 200/300. However, parameters such as softening point and brittleness, which determine the plasticity range (i.e., working interval) of the bitumen in the material, are below standard values. Moreover, these bitumens fail tensile tests at 0 °C and show poor adhesion to marble and sand, indicating low adhesive properties.

Table 2. Key Properties of Bitumen Obtained from Tars

Property	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Sample 6**	**GOST 22245-90 BND 200/300**
Needle Penetration at 25 °C, 10⁻¹ mm	42	56	220	234	218	280	201–300
Apparent Viscosity (5 mm orifice, 60 °C), cP	–	–	–	–	–	1080	–
Softening Point, °C, min	63	58	35	30	32	35	35
Brittleness Temperature, °C, max	-10	-12	-17	-18	-15	-11	-20
Flash Point, °C, min	230	235	205	210	214	207	200
Soft	65	60	43	45	42	35	–

ening Point After Heating at 160 °C, °C							
Ductility at 25 °C, cm	40	41	–	–	–	–	–
Ductility at 0 °C, cm	1.3	1.7	19	17	15	8	20
Adhesion Test (Marble or Sand)	Pass	Pass	Fail	Fail	Fail	Fail	

Residual fuel oils (feedstocks) correspond to samples as follows: 1 – Fergana crude; 2 – Surkhandarya crude; 3 – High-paraffinic Afghan crude; 4 – High-paraffinic Chinaz crude; 5 – High-paraffinic Kyrgyz crude; 6 – Fergana gas-condensate residue.

Note: The table presents the primary physicomechanical properties of the bitumen produced, including softening point, penetration, ductility, and adhesion, which are critical for assessing their suitability for road construction applications.

Thus, bitumen obtained from the tars of Fergana and Surkhandarya crude oils is characterized by low quality. Consequently, the tars from these crude oils cannot be utilized as raw materials for bitumen production using conventional technologies.

Conclusions and Recommendations

1. **Influence of Crude Oil Composition:**

The oxidation behavior and final properties of bitumen strongly depend on the chemical composition of the crude oil. Residual tars from Fergana and Surkhandarya crude oils, which are rich in aromatic hydrocarbons, show relatively high oxidation rates, resulting in increased formation of resins and asphaltenes. In contrast, high-paraffinic and Bukhara gas-condensate residues exhibit low oxidation activity due to the abundance of paraffino-naphthenic compounds.

2. **Quality Assessment of Bitumen:**

Bitumen produced from Fergana and Surkhandarya tars meets the viscosity requirements of grade BND 40–60 according to GOST 22245-90 and demonstrates good adhesion to aggregates such as marble chips and sand. However, bitumen obtained from high-paraffinic residues and Bukhara gas-condensate fails to meet key quality parameters, including softening point, ductility, and tensile performance at 0 °C, indicating low adhesion and limited practical applicability in road construction.

3. **Limitations of Conventional Processing:**

The study shows that certain crude residues, particularly from Fergana and Surkhandarya oils, cannot be effectively used in traditional bitumen production due to insufficient oxidation or accumulation of unconverted hydrocarbons. This highlights the need for alternative modification strategies or blending approaches to enhance bitumen quality.

4. **Recommendations for Industrial Application:**

- Employing mixtures of residues from different crude sources in optimized ratios (e.g., 1:1:1) can improve oxidation kinetics and achieve better bitumen characteristics.
- Further research on chemical or polymeric modification techniques is recommended to enhance low-quality residues, increasing their suitability for road construction.

- Selection of feedstock for bitumen production should consider both paraffinic and aromatic content to balance oxidation reactivity and final mechanical properties.

Overall, the findings underline the critical role of crude oil composition in determining the efficiency of oxidation processes and the performance of the resulting bitumen. Implementation of tailored processing strategies can expand the range of usable residues and improve the sustainability of industrial bitumen production.

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