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Physical and mechanical properties of bitumen modified with energy-saving additives based on surface-active substances

Abstract. The article examines the influence of modern energy-saving additives based on surface-active agents available on the Ukrainian market on the physico-mechanical and performance properties of BND 70/100 paving-grade road bitumen. The relevance of the study is обусловлена the need to reduce the production and laying temperatures of asphalt concrete mixtures, which allows for lower energy consumption, reduced harmful emissions into the atmosphere, and improved technological efficiency of road construction without deterioration of pavement quality.

The study analyzes the effect of various contents of energy-saving additives on the main quality indicators of bitumen. The relationships between changes in bitumen properties and additive concentration are presented, enabling the determination of optimal dosages from the perspective of ensuring the required performance characteristics of the bituminous binder.

Special attention is paid to the investigation of adhesion properties of bitumen, in particular its adhesion to the surface of mineral aggregates and to glass, which serve as indicators of binder-aggregate interaction. The obtained results demonstrate a significant effect of surface-active additives on improving adhesion and enhancing bitumen resistance to stripping.

Based on a comparative analysis of experimental data, it was established that, considering the overall set of investigated properties, the EN3 additive is the most effective energy-saving additive. Its application provides an optimal combination of improved bitumen properties and enhanced adhesion characteristics, confirming the feasibility of its use in warm mix asphalt production technologies.

Keywords: petroleum road bitumen, modification, energy-saving additive, adhesion to surface

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Introduction. At present, three of the most widely used technologies for producing so-called warm mix asphalt and asphalt concrete can be identified. These include the use of additives based on waxes or surface-active agents (surfactants), foaming of bitumen by injecting water into hot bitumen, and foaming of bitumen through the use of additives containing water.

In Ukraine, energy-saving additives have become the most widely applied approach for the production of asphalt concrete mixtures.

Energy-saving additives are materials produced on the basis of waxes, surface-active agents, and/or other components that enable a reduction in the technological temperatures of production, laying, and compaction of

hot asphalt concrete mixtures, as well as the execution of works at low ambient temperatures. To be classified as an energy-saving additive, the reduction in these temperatures should be at least 15 °C. The use of such additives allows energy savings while simultaneously reducing emissions of harmful substances into the environment. The extent of temperature reduction during production and paving of asphalt concrete mixtures with energy-saving additives depends on the type of additive, bitumen viscosity, mixture composition, and ambient temperature conditions.

Energy-saving additives act as inhibitors of both technological thermal aging and long-term service aging of bitumen, since exposure to high temperatures during asphalt mixture production and to solar radiation during extended pavement service leads to changes in the group-chemical composition of the binder. The use of energy-saving additives makes it possible to produce so-called warm mix asphalt. In recent years, new warm mix asphalt technologies have been developed in Europe and the United States, allowing a reduction in asphalt mixture production temperatures without deterioration of pavement strength characteristics compared to conventional hot mix asphalt. This effect is achieved through physico-chemical mechanisms that reduce the shear resistance of the asphalt mixture during production, laying, and compaction.

The typical production temperature range for such mixtures is approximately 105 °C to 125 °C. Their application enables reduced energy consumption, lower atmospheric pollutant emissions, decreased binder aging intensity, increased hauling distances of the finished mixture, and an extended construction season. In addition, they provide the required deformability at

low temperatures and resistance to permanent deformation caused by heavy vehicle loads at high summer temperatures.

Surface-active energy-saving additives simultaneously act as effective adhesion agents for bitumens and asphalt concretes. Under current market conditions, manufacturers offer surfactant-based additives that combine both energy-saving and adhesive properties. The dosage of these additives depends on the type of asphalt concrete used and its production and laying temperatures, transportation time, required degree of compaction, binder grade in the asphalt mixture, and the use of reclaimed asphalt pavement (RAP) within the mixture composition [1–15].

Problem statement. The aim of the study is to determine the changes in the physico-mechanical properties of bitumen when modified with energy-saving additives based on surfactants. The main objectives of the study are to carry out bitumen modification using energy-saving surfactant-based additives and to evaluate the quality indicators of the bitumen.

Main material and results. "For the purpose of testing new modifying additives and studying their effect on the properties of the binder, a domestic oxidized road petroleum bitumen of grade BND 70/100, produced by PJSC 'Ukratnafta' (Kremenchuk, Ukraine), was selected as the model bitumen. The main physico-mechanical properties of BND 70/100 bitumen, produced by PJSC 'Ukratnafta', according to DSTU 4044:2019 [16], are presented in Table 1.

Table 1 – Properties of BND 70/100 Bitumen, produced by PJSC 'Ukratnafta'

Property	Actual Value	Requirements for BND 70/100 Bitumen according to DSTU 4044:2019 [16]
Needle penetration at 25 °C, 0.1 mm	75	71-100
Softening point, °C	48,8	45-51
Fraass brittleness temperature, °C	-13	≤-13
Ductility at 25 °C, cm	>150	≥60
Adhesion to glass surface, %	31,2	≥18
Flash point in open cup, °C	295	≥ 230
Solubility in organic solvent, %	99,96	≥99,0
Penetration index	-0,50	від -2,0 до 1,0

Based on the main property indicators, the selected bitumen as the model material meets the requirements of DSTU 4044:2019 [16]. To determine the adhesion of bitumen to mineral material, dense granite crushed stone from natural igneous rocks, fraction 20–40 mm, sampled at LLC «Mokryansky Quarry No. 3», was used. For the study, surfactant-based additives, presented in Table 2, were employed.

For the modification of BND 70/100 bitumen (produced by PJSC 'Ukratnafta') with energy-saving surfactant-based additives, the following modification parameters were selected:

- additive content of 0.1, 0.2, 0.3, 0.4, and 0.5 wt.%;

- temperature for combining and mixing bitumen with additives: 150 °C (mixing was carried out using a mechanical four-blade paddle mixer at 400 rpm);

- modification time: 1.0 hour.

Bitumens modified with energy-saving surfactant-based additives were compared with the requirements of DSTU 4044 [16] and SOU 45.2-00018112-067:2011 [17]. The energy-saving effect of the used additives is planned to be studied during the design of asphalt concrete mixtures in future research.

The changes in the physico-mechanical properties of bitumen after modification are presented in Table 3 and illustrated in Figure 1.

Table 2 – Energy-saving additives selected for the study

Sample No	Source	Characteristics	Designation and Comparative Cost
1	Ukraine	Viscous brown liquid	EN1 (lowest)
2	Sweden	Amber-colored liquid	EN2 2 (medium)
3			EN3 (highest)

Table 3 – Changes in the properties of the base bitumen after modification with energy-saving additives based on surface-active agents

No.	Indicator	Additive content, wt.% of bitumen"										Requirements for BND-A 70/100
		BND 70/100	EN1			EN2			EN3			
			0,1	0,3	0,5	0,1	0,3	0,5	0,1	0,3	0,5	
1	Needle penetration at 25 °C, 0.1 mm	75	70	63	64	79	79	77	80	79	75	71-100
2	Softening point, °C	48,8	49,4	50,2	50,4	48,8	49,2	49,4	49,6	50,0	50,2	45-51
3	Fraass brittleness temperature, °C	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	≤-13
4	Ductility at 25 °C, cm	>150										≥60
5	Adhesion to crushed stone surface, points	2,5	3,5	3,5	4,0	4,0	4,5	5,0	4,0	4,5	5,0	not less than 5,0
6	Penetration index	-0,5	-0,5	-0,6	-0,5	-0,4	-0,3	-0,3	-0,1	0,0	-0,1	-2.0 to 1.0
7	Plasticity index	61,8	62,4	63,2	63,4	61,8	62,2	62,4	62,6	63	63,2	-

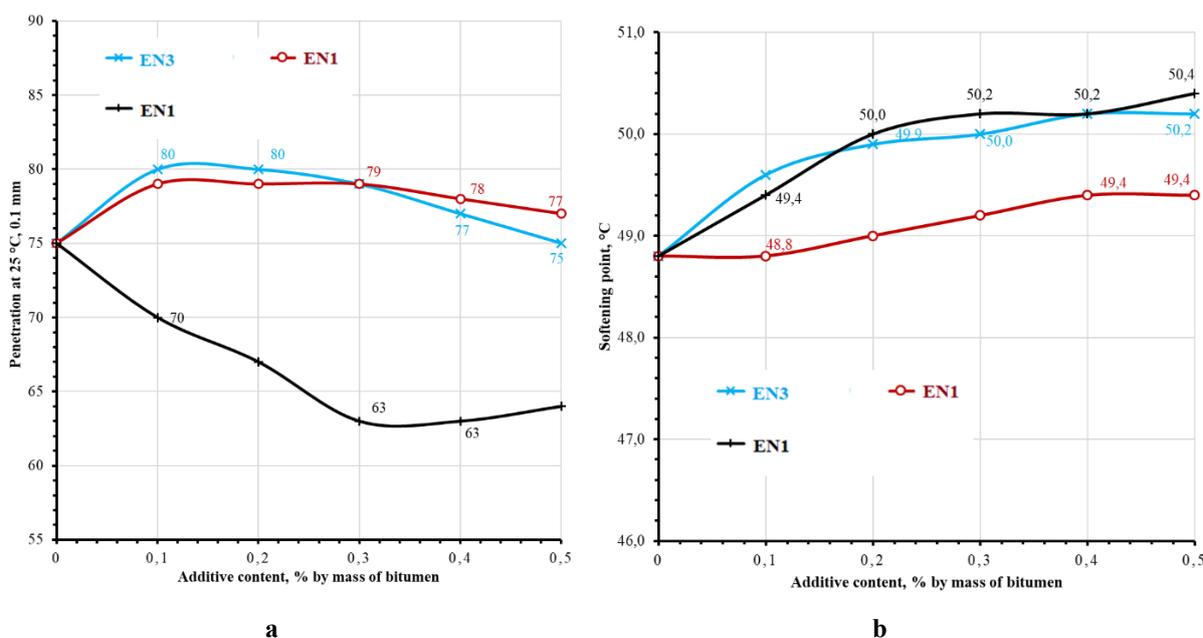


Figure 1 – Changes in bitumen properties at different dosages of energy-saving surfactant-based additives: (a) penetration at 25 °C; (b) softening point

Analysis of Table 3 indicates that the surfactants used only slightly affect the main physico-mechanical properties of the base bitumen (all modified bitumens retain their grade according to penetration compared to the original bitumen), except for adhesion to the crushed stone surface. The requirements for BND-A 70/100 bitumen according to SOU 45.2-00018112-067:2011 [17] for adhesion to the crushed stone surface are not less than 5.0 points, and according to DSTU 9187 [18], not less than 4.5 points.

Bitumens modified with surfactants do not demonstrate the required adhesion to Mokryansky crushed stone at a dosage of 0.3 wt.% of bitumen according to SOU 45.2-00018112-067:2011 [17]. Only

foreign additives at a dosage of 0.3 wt.% meet the adhesion requirements according to DSTU 9187 [18], and at a content of 0.5 wt.% of bitumen, they provide the necessary adhesion to the crushed stone surface according to SOU 45.2-00018112-067:2011 [17].

For better comparison of results, it was decided to determine adhesion to a glass surface for energy-saving additives at a dosage of 0.5 wt.%. These surfactant dosages in bitumen for the study of adhesion to the glass surface were selected based on the adhesion results with Mokryansky crushed stone. Comparative tests using the adhesion to glass surface indicator are presented in Table 4.

Table 4 – Comparative tests of surfactants using the adhesion to glass surface indicator

BND 70/100, produced by PJSC «Ukratnafta»+ surfactants	Surfactant dosage in bitumen, wt. %	Adhesion to glass surface, %	Requirements
BND 70/100	-	35,9	≥18 for BND 70/100 according to DSTU 4044 [16]
EN 1	0,5	30,6	not less than 75 for BND-A 70/100 according to SOU 45.2-00018112-067:2011 [17]
EN 2		72,9	
EN 3		95,3	

Interpretation of results and their approval. Analysis of Table 4 indicates that, in this case, the adhesion values to the surface of Mokryansky crushed stone do not always correlate with the adhesion values to the glass surface. This is particularly evident for surfactants ES 1 and ES 2. Among the energy-saving surfactants, ES 3 provides the best adhesion performance to both glass and crushed stone.

Conclusions. The use of energy-saving surfactant-based additives for bitumen modification does not change the grade of the binder but leads to an increase in adhesion to the surface of mineral fillers. For the crushed stone selected in this study, the standardized adhesion value was achieved only with additives of foreign origin, with adhesion values of 4.5 and 5 points for additive contents of 0.3 and 0.5 wt.%, respectively.

However, the same binders, when tested for adhesion to glass plates, showed results that did not correlate with the adhesion values to crushed stone.

Thus, when evaluating the adhesive efficiency of different energy-saving additives, it is first necessary to conduct tests on adhesion to the filler that will be used in production. Following positive results and selection of the technically optimal additive, adhesion tests should be conducted with Mokryansky quarry crushed stone, which is intended specifically for comparative testing. If necessary, and as part of the final additive selection, adhesion to a glass surface should also be determined.

In the future, extended studies are planned using additional indicators of binder properties and properties of asphalt concretes prepared with the binders mentioned above.

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Фізико-механічні властивості бітумів модифікованих енергозберігаючими добавками на основі ПАР

Анотація. У статті розглянуто вплив сучасних енергозберігаючих добавок, представлених на ринку України, на основі поверхнево-активних речовин на фізико-механічні та експлуатаційні властивості дорожнього бітуму марки БНД 70/100. Актуальність дослідження зумовлена необхідністю зниження температур приготування та укладання асфальтобетонних сумішей, що дозволяє зменшити енергоспоживання, шкідливі викиди в атмосферу та підвищити технологічність дорожніх робіт без погіршення якості покриття.

У роботі проаналізовано вплив різного вмісту енергозберігаючих добавок на основні показники якості бітуму, зокрема пенетрацію, температуру розм'якшеності за методом «кільце і куля», температуру крижкості за Фраасом, розтяжність, зчеплюваність із поверхнею мінерального заповнювача, а також інтервал пластичності. Наведено залежності зміни зазначених показників від концентрації добавки, що дозволяє оцінити оптимальні дозування з позиції забезпечення необхідних експлуатаційних характеристик бітумного в'язучого.

Окрему увагу приділено дослідженню адгезійних властивостей бітуму, зокрема показнику зчеплення з поверхнею мінеральних заповнювачів та зі склом, які є індикатором взаємодії в'язучого з мінеральними матеріалами. Отримані результати свідчать про суттєвий вплив поверхнево-активних добавок на покращення адгезії та підвищення стійкості бітуму до відшарування.

На основі порівняльного аналізу експериментальних даних встановлено, що за сукупністю досліджених показників найбільш ефективною енергозберігаючою добавкою є ЕНЗ, застосування якої забезпечує оптимальне поєднання покращених властивостей бітуму та підвищених адгезійних характеристик. Це підтверджує доцільність її використання у технологіях виробництва теплих асфальтобетонних сумішей.

Ключові слова: бітум нафтовий дорожній, модифікація, енергозберігаюча добавка, зчеплюваність з поверхнею.

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