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Effectiveness of wax additives in cast asphalt concrete mixtures

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Abstract. The use of cast asphalt concrete mixtures makes it possible to produce road surfaces with very high wear resistance and water resistance. One of the problems of using cast asphalt concrete mixtures is the need for high temperature of their preparation. This significantly increases energy costs, worsens the labour conditions of workers and negatively affects the environment. Therefore, it is very important to search for effective methods to reduce the temperature of production of cast asphalt concrete mixtures without deterioration of their performance characteristics. One of the promising solutions to this problem is the use of synthetic waxes as additives that change the rheological properties of bituminous binder. Besides, the use of additives based on synthetic waxes makes it possible to improve the resistance of asphalt concretes to plastic deformations, which is very important for cast asphalt concrete pavements. In this paper, changes in the physical and chemical properties of bitumen binder modified with a new complex additive Viskodor PV-2 are investigated. In order to evaluate the effectiveness of this additive, these changes were compared with those observed when the well-known wax modifiers Licomont BS-100 and Sasobit were introduced into bitumen. The effect of these additives on the properties of cast asphalt concrete was also studied. It has been established that the introduction of 2.5 % of the investigated additives allows reducing the temperature of paving of cast asphalt concrete by at least 30 °C without reducing its strength characteristics. It is revealed that the use of Viscodor PV-2 in the composition of cast asphalt concrete contributes to the increase in the value of workability with a simultaneous decrease in the index of the die indentation depth. It is established that the efficiency of Viscodor PV-2, used as an additive to reduce the temperature of preparation of cast asphalt concrete mixtures, is not inferior to the known waxes Licomont BS-100 and Sasobit.

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1. *Introduction*

The requirements for the strength characteristics of road surfaces are constantly increasing due to the increasing loads and traffic on motorways. In this regard, materials with improved performance are becoming more and more common. Cast asphalt concrete mixtures are one of them. Cast asphalt concrete mixtures differ from traditional asphalt concrete mixtures by the increased content of bitumen (7.5–10 %)

and mineral powder (20–30 %). In this regard, the main factors determining its strength characteristics are the rheological properties of bitumen binder and asphalt concrete microstructure [1].

Due to the high binder content and increased paving temperature, cast asphalt concrete mixtures have high mobility and do not require compaction. After cooling, a durable waterproof and crack-resistant pavement is formed, with residual porosity not exceeding 2 % [2]. The advantages of cast asphalt concrete are its high density, wear resistance, and corrosion resistance [3]. The use of cast asphalt concrete can significantly increase the service life of the road surface up to 15–20 years [4]. The main disadvantages of cast asphalt concrete mixtures are the need for high energy costs and the use of special transport equipment that provides constant mixing and heating of the mixture to maintain the temperature within 220–230 °C. Due to the high content of mineral powder and bituminous binder, the cost of such mixtures is higher than traditional asphalt concrete [5]. In addition, pavements made of cast asphalt concrete based on bitumen without the use of polymer modifiers have low shear stability, which leads to the formation of plastic deformations [6]. To improve the ability of cast asphalt concrete mixtures to resist plastic deformations, the binder is modified with polymers. Thus, the results of studies [7–10] confirm that the use of polymer-modified bitumen binders significantly improves the strength characteristics of cast asphalt concrete mixtures, increasing their resistance to mechanical loads and seasonal temperature fluctuations. According to [7] introduction of 4 % SBS increased viscosity of bitumen at 165 °C from 0.14 to 0.95 Pa*s, i.e. 6.8 times. As a result, in order to maintain the required mobility, there is a need for higher temperatures of preparation and placement, increasing the binder content. All this combined with the high cost of polymers leads to a significant increase in the cost of technology.

To solve this problem, additives are used to improve the mobility of the mixture. In Russia, additives based on surfactants that reduce bitumen viscosity in the range of process temperatures and are used in the production of warm asphalt concrete mixtures are widely used as temperature-lowering additives [11]. However, the introduction of these additives can reduce the resistance of cast asphalt concrete to plastic deformations. In European countries, organic additives based on waxes, such as Licomont BS-100, Sasobit, etc., are widely used to improve the technological properties of asphalt concrete mixtures. [12].

The introduction of wax-based modifiers reduces the viscosity of the bituminous binder at temperatures above the melting point of the wax, thereby increasing the mobility of the cast asphalt mixture. At the same time, waxes have the ability to crystallise at lower temperatures, forming structures that increase the viscosity and strength properties of the bituminous binder. Due to this, the introduction of Sasobit into asphalt concrete mixes allows to ensure the necessary mobility of the mix at a lower binder content, lower temperature of preparation and paving without reducing the quality characteristics of the road surface, which is proved in [12–14]. In the study of cast asphalt concrete mixtures [3], it was found that Sasobit introduced at a concentration of 0.3 % of the binder mass increased the workability index by 20 %. Researchers [15–17] found that the introduction of 2.0–4.0 % of Licomont BS-100 modifier into bituminous binder composition reduces viscosity at the temperature of asphalt concrete mixture preparation and structures the binder at pavement operation temperatures, which is expressed in the increase of softening and penetration temperature at 25 °C, thus increasing asphalt concrete resistance to plastic deformations.

Until recently, the Russian market has exclusively used expensive imported additives based on synthetic waxes, such as Licomont BS-100 and Sasobit, which significantly increased the cost, created difficulties with delivery and, as a consequence, limited the use of such modifiers in asphalt concrete. Thus, the task of development of the Russian modifier on the basis of waxes, not inferior in efficiency to imported additives, was actual. In this connection, Selena LLC together with the Department of Automobile and Railway Roads A.M. Gridchin of Belgorod State Technological University named after V.G. Shukhov developed the additive Viskodor PV-2, which is a complex composition including a mixture of waxes, plant-based plasticisers, and nitrogen-containing cationic surfactants. According to [18, 19], Viscodor PV-2 reduces the temperature of preparation of asphalt concrete mixtures and has structuring properties that increase the temperature range of plasticity of the binder. In this regard, studies on the use of Viscodor PV-2 in the composition of cast asphalt concrete mixtures are promising.

The subject of the study is the influence of these additives on the physicochemical properties of the binder and qualitative indicators of cast asphalt concrete mixtures. The aim of the research was: to study the influence of modifiers based on synthetic waxes on the properties of bitumen binder; to select the most effective dosage of the studied additives in binder for cast asphalt concrete mixtures; to evaluate the effectiveness of the new additive Viskodor PV-2 in cast asphalt concrete mixtures in comparison with imported wax additives Licomont BS-100 and Sasobit. The object of the study is bituminous binder samples with Viskodor PV-2, Licomont BS-100, and Sasobit additives and cast asphalt concrete mixtures prepared with the use of binder modified in this way.

2. Materials and Methods

In this study, the effect of the complex additive Viscodor PV-2 (produced by Selena, Russia) on the properties of bituminous binder and cast asphalt mixture was investigated. For comparative purposes, the additives Sasobit (polyethylene wax produced by Fischer-Tropsch synthesis, manufactured by SasolWax, South Africa) and Licomont BS-100 (amide wax, manufactured by Clariant, Switzerland) were also tested and selected as the most widely used additives. For preparation of tested samples of binder and cast asphalt concrete mixtures, the bitumen of BND 70/100 grade produced by JSC Gazpromneft-MNPZ was used, which corresponds to Russian State Standard GOST 33133-2014 in its physical and chemical properties.

For preparation of cast asphalt concrete mixtures on the basis of bitumen BND 70/100 modified by investigated additives, crushed stone of fractions 8–16 and 4–8 mm and crushed sand of fractions 0–4 mm produced by Pavlovsk Nerud JSC and mineral powder MP-2 of Tsentr-Izvestnyak LLC were used. In order to study the effect of additives Viskodor PV-2, Sasobit, and Licomont BS-100 on bitumen properties and selection of rational concentration for testing in cast asphalt concrete mixtures, based on the experience of earlier studies [19], a number of bitumen binder samples were prepared with the introduction of each of the additives in different concentrations in the range from 2.0 to 3.5 % with a step increase – 0.5 %. Preparation of the modified binder was carried out using a laboratory stirrer, by mixing bitumen with the studied organic additives for 60 minutes at 150 °C.

The prepared samples of bituminous binder were tested for physical and chemical properties. Softening temperature of the ring and ball was determined in accordance with GOST 32054-2013, needle penetration depth at temperatures of 0 and 25 °C – according to GOST 33136-2014, ductility and maximum tensile force at temperatures of 0 and 25 °C – according to GOST 33138-2014, brittleness temperature – according to GOST 11507-78, adhesion of the binder to the mineral material was evaluated according to the method described in GOST 11508 with the use of granite sift of 0–4 mm fraction as a mineral material. Granulometric compositions of mineral materials used in the study were determined by dividing into fractions by sieving a sample of material through a set of appropriate sieves and determining the total residues on each sieve according to GOST 33029-2014. On the basis of grain compositions of mineral materials, the optimal composition of mineral part for cast asphalt concrete mixture LA 16 Vn was selected in accordance with GOST 54401-2020. Using initial bitumen and bitumen modified with investigated additives, as well as optimally selected mineral part, the compositions of cast asphalt concrete mixtures were prepared.

Further, according to GOST R 54400-2020, test specimens were made. The maximum density of the tested mixtures was determined in accordance with GOST R 58401.16; the bulk density of the tested samples was determined in accordance with GOST R 58401.8; the depth of stamp indentation was determined in accordance with GOST R 54400-2020 p. 11.4. The paving ability of the mixture was identified in accordance with GOST R 54400-2020 p. 11.9 and assessed by the value of the cone slump index. Each mixture was tested at temperatures of 185, 200, and 215 °C to determine the temperature-reducing effect of the investigated additives.

3. Results and Discussion

The results of tests of bitumen BND 70/100 modified by investigated additives are reflected in Tables 1, 2 and Figs. 1–4. The obtained data show that the introduction of all the studied additives is characterised by a decrease in penetration at 25 °C, an increase in the softening point, an increase in the plasticity interval, a decrease in ductility at temperatures of 25 and 0 °C, and an improvement in the adhesion properties of bitumen binder.

Table 1. Penetration of bitumen modified with investigated additives.

Binder composition number	1	2	3	4	5	6	7	8	9	10	11	12	13
Name of additive	Without additive	Viscodor PV-2				Licomont BS-100				Sasobit			
Additive concentration, %	0	2.0	2.5	3.0	3.5	2.0	2.5	3.0	3.5	2.0	2.5	3.0	3.5
Depth of needle penetration at 25 °C, 0.1 mm	81	72	70	63	55	68	63	61	54	54	52	50	48
Depth of needle penetration at 0 °C, 0.1 mm	28	32	31	28	27	30	29	27	25	25	25	24	23

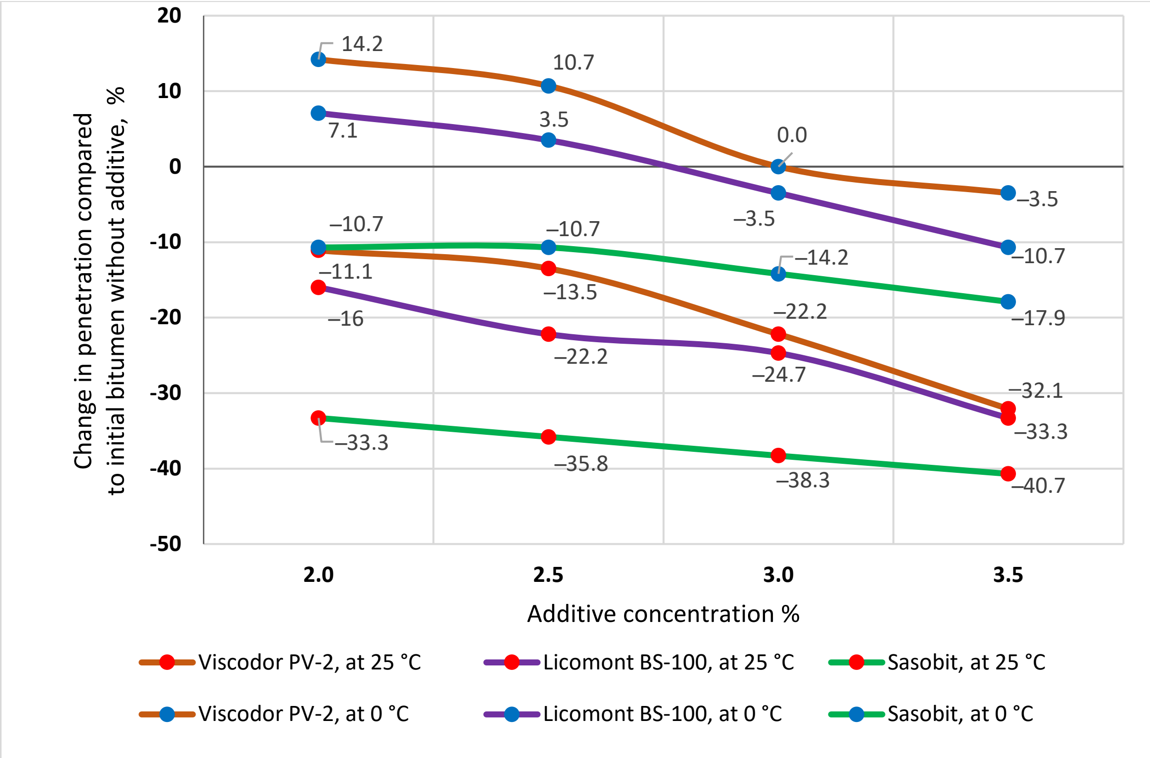

Figure 1. Change in penetration when bitumen is modified with additives.

Table 1 and Fig. 1 demonstrate the effect of the investigated additives on the change in needle penetration depth at temperatures of 25 and 0 °C.

According to the obtained data, all investigated additives when introduced reduce the needle penetration depth at 25 °C. With increasing concentration of additives, penetration index at 25 °C decreases, which is due to the ability of waxes to structure bituminous binder. The greatest decrease in needle penetration depth is observed at introduction of Sasobit additive. So, already at introduction of 2 % Sasobit, penetration of bitumen at temperature 25 °C decreases by 33.3 %, while introduction of the same amount of Licomont BS-100 gives a decrease in penetration depth by 16.0 %. Similar results of penetration reduction when comparing the effect of Licomont BS-100 and Sasobit on bitumen binder were obtained both by Russian and Western European researchers [17, 20–22] The lowest penetration reduction at all tested concentrations is observed when Viscodor PV-2 is added. Introduction of 3 % of this additive reduces penetration at 25 °C by 11.1 %. This is due to the presence of plasticising components in the composition of this additive. It should be noted that the intensity of penetration reduction when adding Viscodor PV-2 significantly increases at concentrations above 2.5 %. Thus, further increase in concentration leads to more intensive reduction of plastic properties of bitumen. It is revealed that in contrast to the additive Sasobit, the introduction of which even at 2 % reduces the penetration of bitumen BND 70/100 at 0 °C by 10.7 %, modifiers Viskodor PV-2 and Licomont BS-100 at a concentration of up to 2.5 % slightly increase this indicator, which will contribute to increasing the resistance of cast asphalt concrete to low temperatures of the winter period, and thus increase the service life of the roadway. Introduction of Viscodor PV-2 and Licomont BS-100 in concentration of 3 % and more causes a decrease in the depth of needle penetration at 0 °C in comparison with the indicator of the original bitumen, which indicates a deterioration of plastic properties of the binder and therefore may be inappropriate for use in pavements operated in conditions of seasonal temperature change.

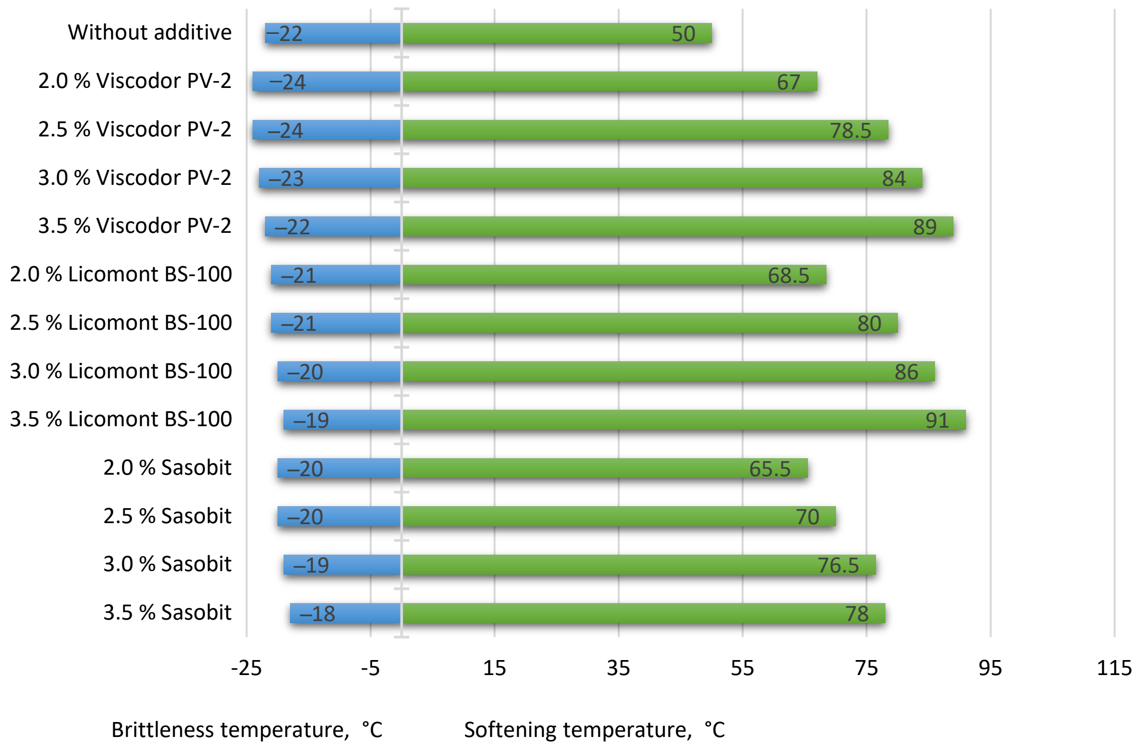

Figure 2. Change of plasticity interval of BND 70/100 after modification.

Temperature range of plasticity of modified bituminous binder in comparison with initial bitumen BND 70/100 without additives increases for all investigated additives due to a significant increase in softening temperature (Fig. 2). This is explained by the property of waxes to structure bituminous binder and will contribute to the decrease in the index of die indentation depth and resistance to plastic deformation of cast asphalt concrete mixtures. Common for the investigated wax additives is the dependence of the softening temperature increase and temperature interval of plasticity on the amount of the introduced additive. Thus, the plasticity interval for the initial bitumen – 77 °C, while the plasticity interval of bitumen modified with 2.0 and 3.5 % Viscodor PV-2 – 91 and 111 °C, with 2.0 and 3.5 % Licomont BS-100 – 89.5 and 110 °C, with 2.0 and 3.5 % Sasobit – 85.5 and 96 °C, respectively. The greatest increase in softening temperature is observed with the addition of Licomont BS-100 (2.5 % increase in softening temperature by 60 %), and the lowest for Sasobit (2.5 % increase in softening temperature by 40 %). However, both of these additives slightly increase the binder's brittleness temperature, which may adversely affect the low-temperature resistance of cast asphalt concrete. The greatest increase in the brittleness temperature is observed with the addition of Sasobit: 2 % of the additive increases this index by 2 °C, and further increase correlates with increasing concentration. The obtained results of temperature interval change at introduction of Licomont BS-100 and Sasobit additives correlate with literature data [14, 17, 21, 22]. Viscodor PV-2 at a concentration of up to 3 % reduces the brittleness temperature of bituminous binder due to the presence of plasticising agents in its composition. Further increase of Viscodor PV-2 input up to 3.5 % leads to increase of brittleness temperature up to the index of initial bitumen. Thus, the brittleness temperature of bitumen at the addition of 2–2.5 % Viscodor PV-2 decreases from –22 to –24 °C, while this indicator for the binder with 3.5 % of the additive is equal to –22 °C.

Table 2. Ductility of bituminous binder modified with investigated additives.

Binder composition number	1	2	3	4	5	6	7	8	9	10	11	12	13
Name of additive	Without additive	Viscodor PV-2				Licomont BS-100				Sasobit			
Additive concentration, %	0	2.0	2.5	3.0	3.5	2.0	2.5	3.0	3.5	2.0	2.5	3.0	3.5
Ductility at 0 °C, cm	4.2	3.7	3.6	3.0	2.4	3.4	3.2	2.6	1.8	2.1	2.0	1.9	1.7
Maximum tensile strength at 0 °C, N	115	159	160	171	172	135	150	160	168	175	177	178	180
Ductility at 0 °C, cm	130	64	61	52	49	62	58	49	46	61	55	51	45
Maximum tensile strength at 25 °C, N	1.0	5.1	5.8	6.0	7.1	5.5	6.0	6.5	6.8	5.1	5.9	7.7	8.2

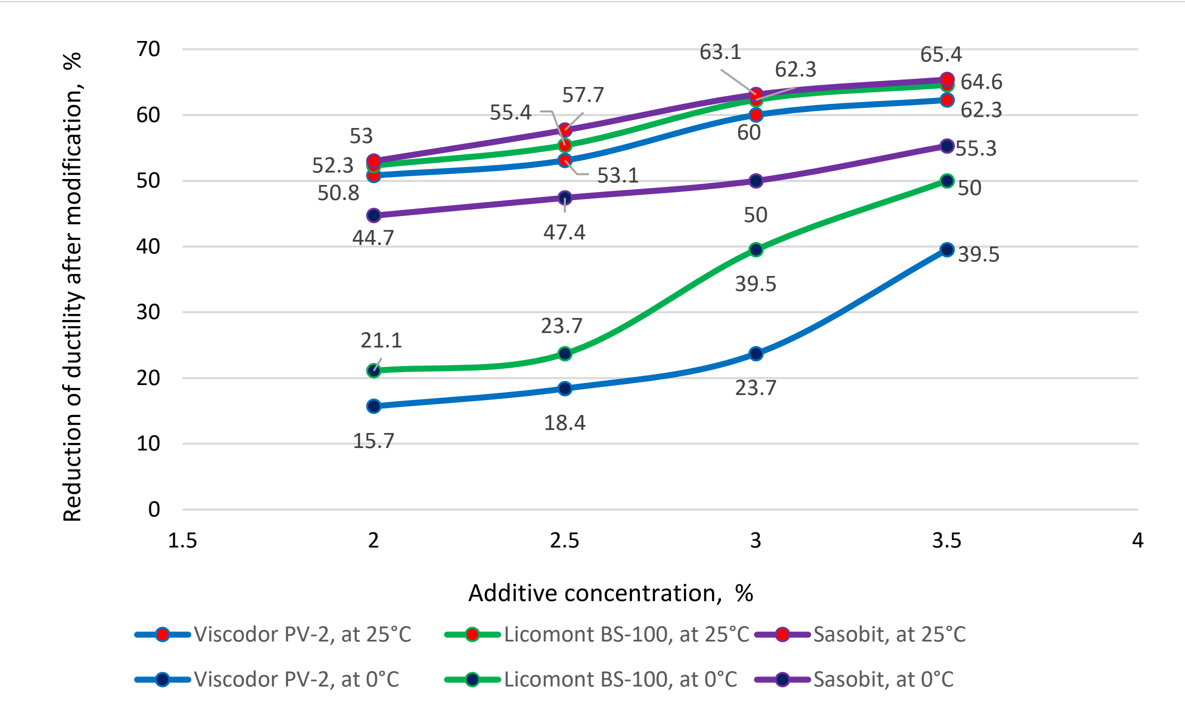

Figure 3. Reduction of bitumen ductility after modification.

Change of ductility of binder samples modified by the investigated additives is presented in Table 2 and Fig. 3. According to the results obtained, the studied organic additives reduce the ductility of bitumen both at 25 and 0 °C. The intensity of ductility reduction increases with increasing concentration of additives input, which is confirmed by the results of the study [22]. The decrease in ductility of the binder indicates an increase in its structuring as a result of increasing the content of synthetic waxes in bitumen. The most significant decrease in ductility both at 25 and 0 °C is caused by the introduction of Sasobit additive (purple lines in Fig. 3). The least significant reduction of ductility at 25 and 0 °C is observed at introduction of additive Viskodor PV-2 (blue lines in Fig. 3), which is due to the presence in the composition of surfactants and plasticising components. The maximum tensile strength recorded both at 25 and 0 °C indicates an increase in the cohesive strength of the binder, proportional to the increase in the concentration of the studied wax modifiers. Thus, the maximum tensile strength at 25 °C through modification of bitumen 2 % additives Viskodor PV-2, Licomont BS-100, and Sasobit increases by 410, 450, and 410 %, and the introduction of these additives in a concentration of 3.5 % increases this index by 610, 580, and 720 %, respectively. The maximum tensile force at 0 °C at the introduction of 2 % additives Viskodor PV-2, Licomont BS-100, and Sasobit increases by 38.3, 17.4, and 52.2 %, and with 3.5 % additives – by 43.0, 46.1, and 32.0 %, respectively. The increase in cohesive strength of the binder will contribute to the strength of the cast asphalt pavement.

It is important to note that when increasing the concentration of Viscodor PV-2 and Licomont BS-100 over 2.5 %, there is a more dramatic decrease in the ductility of bitumen at 0 °C, which in turn will lead to a decrease in the frost resistance of cast asphalt concrete.

Taking into account the above-mentioned, the concentration of Viscodor PV-2 and Licomont BS-100 – 2.5 % as the most rational and not leading to a significant decrease in low-temperature characteristics was chosen for the preparation of the investigated samples of cast asphalt concrete based on modified bitumen binder. In [21], when justifying the selection of Licomont BS-100 modifier dosage in bituminous binder BND 60/90 for cast asphalt concrete, it was also noted that the increase of modifier dosage more than 3 % is not reasonable and can adversely affect the strength of the road surface in winter.

In order to ensure comparability of the study results, a concentration of 2.5 % by weight of bitumen in the cast asphalt mix samples was also selected for the Sasobit additive.

a) b) c) d)

Figure 4. Appearance of granite sift covered with bituminous binder after boiling:

a) without additives; b) 2.5 % Viscodor PV-2; c) 2.5 % Licomont BS-100; d) 2.5 % Sasobit.

Fig. 4 shows the results of adhesion assessment of the initial bitumen and modified by the investigated additives at a concentration of 2.5 % to the mineral material according to GOST 11508. As a mineral material was used granite sifting 0–4 mm, as it is this material was further used for the preparation of experimental compositions of cast asphalt concrete mixtures. It is obvious that the introduction of the investigated additives gives an increase in the index of adhesion with the mineral material. So, the coverage of mineral material with initial unmodified bitumen after boiling was less than ¾ of the surface, which according to GOST 11508 corresponds to the sample No. 3, binder modified with Licomont BS-100 and Sasobit additives after boiling covers more than ¾ of the surface, and corresponds to the sample No. 2. Bitumen modified Viskodor PV-2 after boiling completely covers the surface of mineral material and corresponds to the sample No. 1. The greatest efficiency in improving the adhesion properties showed the additive Viskodor PV-2 as this additive contains in its composition cationic surfactants. The increase in adhesion of bituminous binder with the introduction of wax additives was noted earlier studies [17, 23, 24]. Increase of adhesion will improve such properties of road pavement as water resistance, frost resistance, wear resistance and increase the service life of road pavement.

Granulometric compositions of mineral materials used for preparation of the investigated cast asphalt concrete mixtures (mineral powder MP-2 produced by Tsentr-Izvestnyak LLC, crushed stone of fractions 8–16 and 4–8 mm, and crushed sand of fractions 0–4 mm produced by Pavlovsk Nerud JSC), determined by sieving on sieves according to GOST 33029-2014, are presented in Table 3.

Table 3. Grain composition of mineral materials.

No. n/a	Material name	Content of grains finer than this size, (mm) in % by weight								
		22.4	16.0	11.2	8.0	4.0	2.0	0.5	0.125	0.063
1	Crushed stone of fractions 8–16 mm	100.0	94.5	41.0	23.5	1.2	0.0	0.0	0.0	0.0
2	Crushed stone of fractions 4–8 mm	100.0	100.0	100.0	97.5	24.5	3.2	0.0	0.0	0.0
3	Sand of fractions 0–4 mm	100.0	100.0	100.0	100.0	97.7	71.1	30.1	9.2	4.7
4	Mineral powder	100.0	100.0	100.0	100.0	100.0	100.0	100.0	92.2	84.9

The optimal composition of the mineral part of the cast asphalt concrete mixture LA 16 Vn, selected on the basis of grain compositions in accordance with GOST 54401-2020, is shown in Table 4 and the graph of grain size distribution in Fig. 5.

Table 4. Selection of grain composition of the mineral part of the mixture.

No. n/a	Material name	Content, %	Content of grains finer than this size, (mm) in % by weight						
			22.4	16.0	8.0	4.0	2.0	0.5	0.063
1	Crushed stone of fractions 8–16 mm	39.0	39.0	36.9	9.2	0.5	0	0	0
2	Crushed stone of fractions 4–8 mm	11.0	11.0	11.0	10.7	2,7	0,4	0	0
3	Sand of fractions 0–4 mm	28.0	28.0	28.0	28.0	27.4	19.9	8.4	1.3
4	Mineral powder	22.0	22.0	22.0	22.0	22.0	22.0	22.0	18.7
Grain composition of the mineral part			100.0	97.9	69.9	52.5	42.3	30.4	20.0
Requirements of GOST R 54401-2020 for cast asphalt concrete mix LA 16 Vn		min	100	90	62	43	35	24	19
		max	100	100	78	61	50	41	28

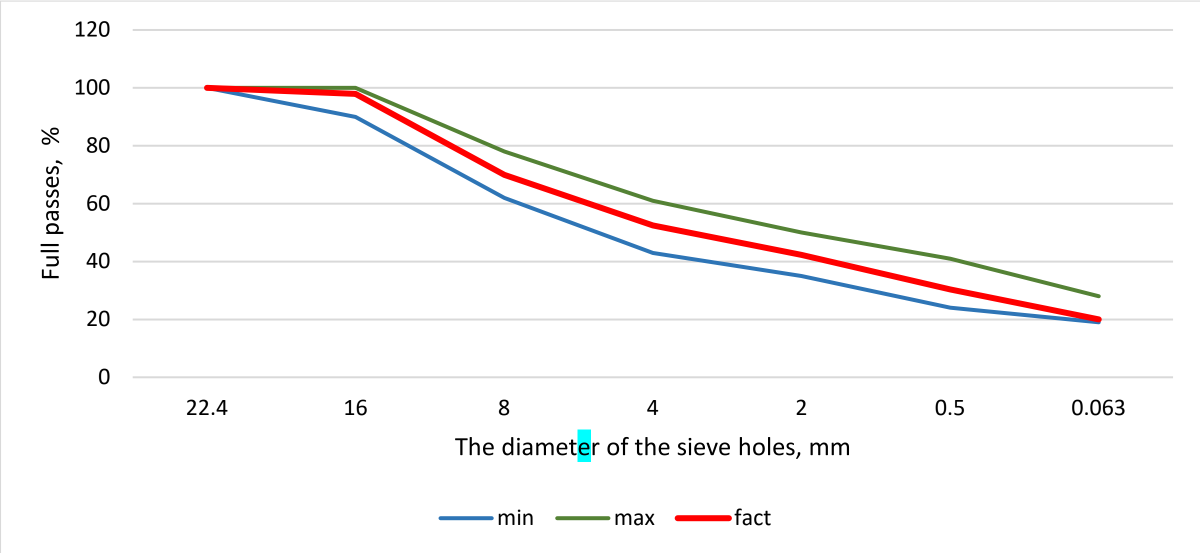

Figure 5. Granulometric composition curve.

On the basis of initial bitumen BND 70/100 without additives and bitumen modified with 2.5 % of investigated additives, as well as optimally selected composition of the mineral part of the mixture, LA 16 Vn asphalt concrete mixtures were prepared, the compositions of which are presented in Table 5.

Table 5. Compositions of cast asphalt concrete mixtures.

Components of bitumen binder composition in the mixture	Number of cast asphalt concrete mix					
	1	2	3	4	5	6
	Content, %, (over 100 % mineral content)					
Bitumen	9	9.5	10	8.775	8.775	8.775
Viscodor PV-2				0.225		
Sasobit					0.225	
Licomont BS-100						0.225
Total quantity of bitumen binder	9	9.5	10	9	9	9

The results of the study of physical and mechanical characteristics of the samples of cast asphalt concrete mixtures based on the original bitumen BND 70/100 and modified binders are presented in Table 6.

Table 6. Physical and mechanical properties of cast asphalt concrete mixtures.

Name of property		Requirements of GOST R 54401-2020 for cast asphalt concrete mixLA 16 Vn	Number of cast asphalt concrete mix					
			1	2	3	4	5	6
Maximum density of the mixture, g/cm^3		not regulated	2.4098	2.3977	2.3984	2.3981	2.3937	2.4031
Bulk density, g/cm^3		not regulated	2.3931	2.3834	2.3844	2.3852	2.3795	2.3902
Air void content, %		no more than 1.5	0.69	0.60	0.58	0.54	0.59	0.54
Paving ability, mm, not less, at temperature:	185 °C	not regulated	10	17	19	33	35	31
	200 °C	not regulated	17	25	28	39	42	36
	215 °C	not less than 30	26	35	40	49	55	43
Depth of stamp indentation, at 40 °C, mm		1.0–4.0	2.73	3.31	4.48	2.45	3.11	2.38
Increase of depth of stamp indentation after 30 min, mm		no more than 0.6	0.15	0.49	0.51	0.35	0.4	0.32

The analysis of the obtained data (Table 6) allows us to state that the control asphalt-concrete mixtures without additives (Nos. 1 and 3) with the binder content of 10 and 9 %, respectively, did not meet the requirements of GOST R 54401-2020. Thus, composition No. 1 containing 9 % bitumen at 215 °C had a paving ability of 26 mm, which is below the norm – not less than 30 mm, and composition No. 3 containing 10 % unmodified bitumen, with a satisfying the normative requirement paving ability of 40 mm at 215 °C, had depth of stamp indentation – 4.48 mm, which is above the required normative value – from 1 to 4 mm. Composition No. 2 containing 9.5 % of binder meets the requirements of GOST R 54401-2020 (paving ability of this mixture at 215 °C – 35 mm, depth of stamp indentation – 3.31 mm).

The introduction of the studied additives allowed to obtain mixtures with a lower content of bituminous binder – 9 %, meeting the normative requirements both in terms of paving ability and depth of stamp indentation.

The obtained results show that the quality of compaction, characterised by the index of air voids content, in samples Nos. 4, 5, and 6 using bitumen modified with the studied additives, improves in comparison with both sample No. 1, containing the same amount of binder but without additives, and with sample No. 2, containing a larger amount of binder (9.5 %). The best compaction was found in the samples containing Viscodor PV-2 and Licomont BS-100 (0.54 % air voids, compared to 0.69 % in the sample with the same amount of bituminous binder without additives and 0.60 % in the sample containing 9.5 % binder). The introduction of Sasobit reduced the amount of air voids to 0.59 %. Thus, the use of the investigated additives will improve the compactibility of asphalt concrete mixture without the need to increase the paving temperature and at a lower binder content.

The indicators of paving ability of the tested compositions at temperatures of 185, 200, and 215 °C allow to assert that the introduction of the investigated wax additives makes it possible to lower the temperature of mixture placement by 30 °C. Thus, even at 185 °C, the paving ability of the mixture with Viskodor PV-2 is 33 mm, with Sasobit – 35 mm, with Licomont BS-100 – 31 mm, which corresponds to the normative requirements for paving ability of cast asphalt concrete mixtures at 215 °C. The value of paving ability at 185 °C of the composition with Viscodor PV-2 is slightly higher than that of the composition with Licomont BS-100, which is due to the presence of surfactants and plasticisers in the composition of Viscodor PV-2. The Sasobit additive is the most effective in improving paving ability as this wax has a lower melting point. The paving ability of control mixes with bitumen without additives at temperatures of 185 and 200 °C is less than 30 mm. The possibility of reducing the temperature providing the required mobility of cast asphalt concrete mixture to 180–185 °C by introducing wax additives was revealed earlier by the studies of the Moscow Automobile and Road State Technical University (MADI) [12].

It is worth noting that the depth of stamp indentation in the compositions No. 4 with Viscodor PV-2 and No. 6 with Licomont BS-100 are 10.3 and 12.8 % lower, respectively, than in the control composition No. 1 with the same amount of unmodified binder, which is explained by the high ability of amide wax, which is part of these additives, to structure the bituminous binder. Thus, the said additives will contribute to increase the strength properties of the cast asphalt concrete and the resistance to plastic deformation. The depth of stamp indentation for mix No. 5 with Sasobit additive is 13.9 % higher than that of sample No. 1 with equal amount of binder without additive but 6 % lower than that of sample No. 2 complying with the requirements of GOST R 54401-2020, with 9.5 % unmodified bitumen. This is due to the power ability of polyethylene wax Sasobit to structure the binder in comparison with the additives Viskodor PV-2 and Licomont BS-100, which have amide waxes in their composition. The reduction of the depth of stamp indentation with the introduction of additives based on synthetic waxes is confirmed by numerous studies [21, 25, 26].

4. Conclusion

Analysis of changes in the properties of modified bitumen binder and cast asphalt concrete mixtures with the use of investigated additives allows us to draw the following conclusions.

1. Modifiers Viscodor PV-2, Licomont BS-100, and Sasobit have a structurising effect on bitumen, which is expressed in the increase of softening temperature, decrease of penetration and ductility indices at 25 °C. This will increase the strength properties of cast asphalt concrete mixtures and improve their resistance to plastic deformations. The introduction of the investigated additives improves the adhesion of bitumen with mineral aggregate, which will increase the durability of cast asphalt concrete pavement.

2. The rational concentration of Licomont BS-100 and Viscodor PV-2 is 2.5 %, as further increase in the concentration of additives, leads to a decrease in the indicators of needle penetration depth at 0 °C, ductility at 0 °C and increase in the brittleness temperature of bituminous binder, which can lead to a decrease in the binder resistance to low operating temperatures.

3. The use of the investigated additives allows to reduce the binder content necessary to achieve the required mobility of cast asphalt concrete mixtures by 0.5 % without deterioration of their qualitative characteristics. Thus, at a temperature of 215 °C, the power ability of the sample of cast asphalt concrete mixture with 9 % unmodified bitumen is 26 mm, which does not meet the regulatory requirements, while the power ability for the composition with the same amount of binder modified Viskodor PV-2 – 49 mm, Sasobit – 55 mm; Licomont BS-100 – 48 mm, which meets the requirements of GOST R 54401-2020.

4. The investigated wax additives at a concentration of 2.5 % of bitumen weight allow to improve power ability and reduce the paving temperature of cast asphalt concrete mixture by 30 °C without loss of strength characteristics. Thus, at a temperature of 185 °C, the power ability of mixtures with binder modified by Viscodor PV-2, Sasobit, and Licomont BS-100 is 33, 35, and 31 mm, respectively, which meets the normative requirements for this indicator at a temperature of 215 °C. The power ability of cast asphalt concrete mixtures without additives at temperatures of 185 and 200 °C does not reach the required value at which paving is possible.

5. Licomont BS-100 and Viscodor PV-2 additives not only effectively improve the mobility of cast asphalt concrete mixtures but also increase their resistance to mechanical loads, which is characterised by lower indices of die indentation depth (2.45 and 2.38 mm, respectively) compared to control samples without additives Nos. 1 and 2 (2.73 and 3.31 mm).

6. Viscodor PV-2 as an additive for cast asphalt concrete mixtures is not inferior in effectiveness to the well-known wax modifiers Licomont BS-100 and Sasobit. In addition, due to the presence of plasticizing and surface-active substances in the composition of Viscodor PV-2, this additive has a greater positive effect on the power ability of cast asphalt concrete mixtures than Licomont BS-100, and the presence of amide wax in the composition of Viscodor PV-2 causes a lower the depth of stamp indentation and, consequently, a higher resistance to plastic deformations than the Sasobit additive.

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