The effect of modification of asphalt concrete mixtures of different grain sizes with "Ric-Polycell" (Ukraine) and "Duroflex®-SMA" thermoplastic polymers (Germany), which were added directly to the asphalt mixer during their preparation, on the properties of asphalt concrete was studied. It is confirmed that it is more expedient to use stone mastic asphalt concretes with a larger size of mineral crushed stone grains on high-traffic roads, as they are more rutting-resistant compared to asphalt concretes with smaller size and content of crushed stone grains.

The effect of the temperature of preparation and thermostating of asphalt concrete mixtures modified with the investigated thermoplastics on the compressive strength of asphalt concrete at a temperature of 50 °C, which were made of the studied mixtures, was investigated. It was found that the maximum possible temperatures of preparation and thermostating of asphalt concrete mixes provide a more complete modification.

The effect of the content of thermoplastic polymers in the composition of asphalt concrete mixtures on the properties and rutting resistance of fine-grained asphalt concrete, as well as stone mastic asphalt concrete, was studied. It was found that adding the "Ric-Polycell" polymer in the amount of 1.5 % and 3 % by weight of bitumen in the composition of the studied asphalt mixtures in the asphalt mixer during their preparation increases the rutting resistance of asphalt concrete under the studied conditions by 2.52–3.86 times. Modification of asphalt concrete mixtures with the "Duroflex®-SMA" additive in the amount of 0.3 % and 0.6 % by weight of the aggregate by a similar technology also allows increasing the rutting resistance of the obtained asphalt concrete by 1.86–3.16 times. Using these modifiers in the future will have a positive effect on the service life of the entire pavement structure

Keywords: fine-grained asphalt concrete, stone mastic asphalt concrete, bitumen, asphalt concrete mixture, thermoplastic polymer, asphalt mixer, plastic deformations, rutting resistance

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AN INVESTIGATION OF THE EFFECT OF THERMOPLASTIC ADDITIVES IN ASPHALT CONCRETE MIXTURES ON THE PROPERTIES OF DIFFERENT TYPES OF ASPHALT CONCRETE

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1. Introduction

The increase of the lifetime of pavement structures under the influence of heavy vehicles, the density of which has increased significantly in the last decade, can be achieved through the use of road construction materials of increased durability and innovative construction technologies. As a material for flexible pavements, different types of asphalt concrete mixtures are used. One of the most common ways to improve asphalt concrete pavements is the preparation and application of asphalt concrete mixtures based on polymer-modified bitumens.

For the modification of petroleum road bitumens, the following most common classes of polymers are used: elastomers (rubbers); various latexes (divinylstyrene, divinylnitrile); thermosetting polymers (epoxy and phenol-formaldehyde resins); thermoplastic (polyethylene, ethylene-vinyl acetate); thermoelastoplastic (styrene-butadiene-styrene). All of them are designed to improve the physical and mechanical properties of bitumen and asphalt concrete based on them. The most widespread in road construction are thermoplastic and thermoelastoplastic polymers.

Improving the asphalt concrete properties is a crucial practical task, the solution of which will affect the durability of asphalt concrete pavements.

2. Literature review and problem statement

Increasing the asphalt concrete durability is usually carried out by improving the properties of petroleum road bitumen as the main component of asphalt concrete by introducing surfactants, polymers and other modifiers.

In [1], the achievements and problems in the polymer modification of bitumens for road construction for the last 40 years are considered. It is shown that polymers improve certain properties of bitumen but there are limitations as for the future of this technology. Constraining factors for using polymer-modified bitumen are high cost, low resistance to aging and poor storage stability. Many scientists have tried to solve this problem but at this stage, it is quite difficult to eliminate these shortcomings and obtain a binder with ideal properties. In [2], the joint modification of bitumen with sulfur and SBS polymers was investigated. It was found that although this composition provides a more stable binder during storage, its properties deteriorate significantly after aging due to significant degradation of the SBS polymer and leveling of the modifying effect, so further research in this direction is impractical.

In [3], a new type of polymer-modified bitumen is proposed, which considers the use of thermoplastic polyurethane as an alternative to styrene-butadiene-styrene (SBS) polymers. The authors found that this additive has poor compatibility with bitumen. According to the studied physical and mechanical properties of the obtained binders, the optimal content of this polymer is 13 %. Obviously, this is a too high concentration of polymer compared to SBS polymers, which are introduced into bitumen in an amount of 3–3.5 %. This will negatively affect the cost of modified bitumen and will constrain its use as a modifier of bitumen intended for asphalt concrete mixtures.

Also, natural bitumens can be used as modifiers. The results of [4] show that asphalt concretes modified with the Gilsonite additive are characterized by the increased modulus of elasticity, rutting resistance and shear resistance. But this additive has a negative effect on flexibility, which in turn impairs the low-temperature properties of asphalt concrete.

In [5], the influence of polyethylene terephthalate (PET) on the properties of stone mastic asphalt concretes was investigated. The authors note that the addition of PET to the mixture has a positive effect on the properties of stone mastic asphalt concrete and promotes the reuse of industrial waste. However, using such modifiers impairs the low-temperature properties of asphalt concrete, which can further adversely affect the durability of pavements made of such material in operating conditions. In [6], it was found that the modification of bitumen with polished rubber crumb, spent PET and adhesive additives also has a positive effect on the properties of bitumen and stone mastic asphalt concrete. But it should be noted that rubber crumb and spent PET are secondary raw materials produced in different countries, by different manufacturers and by different technologies, which can not guarantee the stability of the properties of these components and, accordingly, the quality of modification with this composition. In [7], it was found that the combined action of SBS polymer and rubber crumb in the modified bitumen improves the properties of the initial bitumen. The studied binders also have good storage stability. It is noted that in this combination, a significant effect is exerted by the rubber crumb, which can be obtained from unstable raw materials, so the effect of modification cannot be stable in industrial production conditions. Also, at the moment there are no results of integrated research on the impact of the proposed binder on asphalt concrete properties.

The study [8] found that bitumen modification with sulfur and polyethylene wax can improve the properties of bitumens and asphalt concrete based on them. According to the proposed option, it is possible to achieve a fairly high-quality modification of bitumen and improve its heat resistance, but the paper does not provide information about the low-temperature characteristics of the studied binders. Also, at the moment there are no results of experimental studies on the effect of a combination of these additives on the properties of asphalt concrete, which can affect pavement durability.

It is known that both thermoplastics and thermoelastoplastics are used as bitumen modifiers that can be introduced directly into the asphalt mixer [9]. Preparation of mixtures by this technology has both certain advantages and disadvantages in contrast to the classical technology of asphalt mixtures based on polymer-modified bitumen. The main disadvantage of this technology is a rather short period of bitumen interaction with the polymer, which may lead to an incomplete effect of the modifier. However, the main advantage is the possibility to prepare asphalt concrete mixtures without additional equipment. In [10], the modification of sand asphalt concrete mixtures with SBS polymers by introducing them into the asphalt mixer at the stage of preparation was considered. It was found that if the polymer matures for at least two hours, it is possible to achieve the greatest effect from the modification and obtain asphalt concretes with the properties close to asphalt concretes prepared directly using bitumens modified with this type of polymer. The paper considers the modification of only sand asphalt concrete mixtures, which are commonly used as a layer of pavement, and also there are no studies of modification with polymers of other classes by this technology.

The effect of road bitumen modification with thermoelastoplastic polymers on the properties and rutting resistance of different types of asphalt concretes is covered in previous works [11, 12]. In these works, there are no investigations concerning the use of thermoplastic polymers, and only the effect of bitumen modification using classical technology is considered.

After studying the works [1–12], it was found that the modification of bitumens with both known and new modifiers and their compositions can change the properties of binders. However, it should be noted that today the best option for modifying viscous road bitumens are thermoelastoplastic and thermoplastic polymers, which have long proven themselves in the world markets of road bitumen modifiers.

Usually, bitumens are modified using classical technology, in special equipment, then used for asphalt concrete mixes. Due to the fact that the technology of bitumen modification with thermoplastic polymers by introducing them directly into the asphalt mixer (at the stage of preparing a hot asphalt concrete mixture) has not become widely used, these asphalt concretes remain less studied today. All this gives grounds to assert that it is expedient to study the effect of modification of hot asphalt concrete mixtures with thermoplastic polymers at the stage of their preparation on the physical and mechanical properties and rutting resistance of asphalt concrete.

3. The aim and objectives of the study

The aim of the study is to determine the effect of modification of hot asphalt concrete mixtures with thermoplastic polymers at the stage of their preparation on the properties of asphalt concrete. This will allow obtaining modified asphalt concretes with improved properties, which are intended for the arrangement of constructive layers of pavements by the simplified technology.

To achieve the aim, the following objectives were set:

– to investigate the effect of preparation and thermostatting temperature of asphalt concrete mixtures on the compressive strength index at a temperature of 50 °C;

– to study the physical and mechanical properties and rutting resistance of type A dense fine-grained asphalt concrete, as well as SMA-10 and SMA-20 stone mastic asphalt concrete with "Ric-Polycell" and "Duroflex®-SMA" polymer additives.

4. Research materials and methods

4. 1. Materials for research of the effect of thermoplastic additives on asphalt concrete properties

Cube-shaped granite crushed stone and crushed screenings produced by Gaivoronsky Granite Quarry LLC (Ukraine), limestone mineral powder, TOPCEL (Germany) stabilizing fibrous additive and BND 70 oil road bitumen were used for the preparation of stone mastic asphalt concrete mixtures.

"Ric-Polycell" (Ukraine) and "Duroflex®-SMA" (Germany) thermoplastic polymers were used as modifiers. Thermoplastic additives accepted for the research on the recommendation of manufacturers are added directly to the asphalt mixer during the production of asphalt concrete mixes. The "Ric-Polycell" additive can be used for the modification of both fine-grained asphalt concrete mixes and stone mastic asphalt concrete mixes, on the condition of adding the stabilizing fibrous additive. The "Duroflex®-SMA" additive is intended for stone mastic asphalt concrete mixes modification without the stabilizing fibrous additive.

The granulometric composition of SMA-10 stone mastic asphalt concrete accepted for research is given in Fig. 1, SMA-20 stone mastic asphalt concrete in Fig. 2, and type A hot dense fine-grained asphalt concrete in Fig. 3.

The petroleum road bitumen accepted for research met the requirements of the national standard and belongs to the BND 70/100 brand. The results of studies of bitumen properties in terms of needle penetration depth at a temperature of 25 °C, ring and ball softening point and ductility at a temperature of 25 °C are given in Table 1.

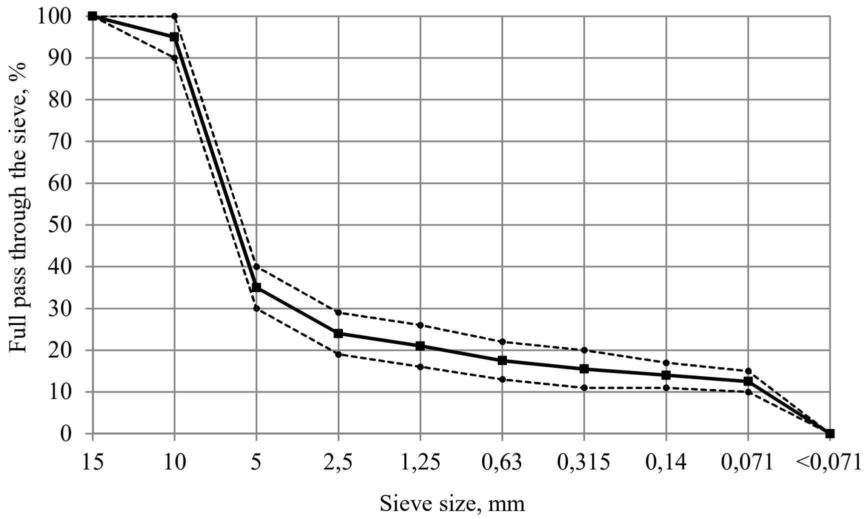

Fig. 1. Granulometric composition of SMA-10 stone mastic asphalt concrete

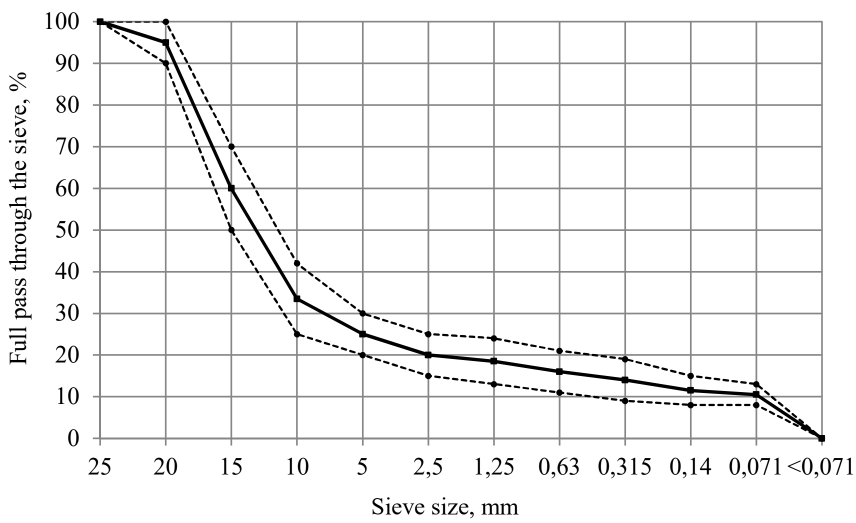

Fig. 2. Granulometric composition of SMA-20 stone mastic asphalt concrete

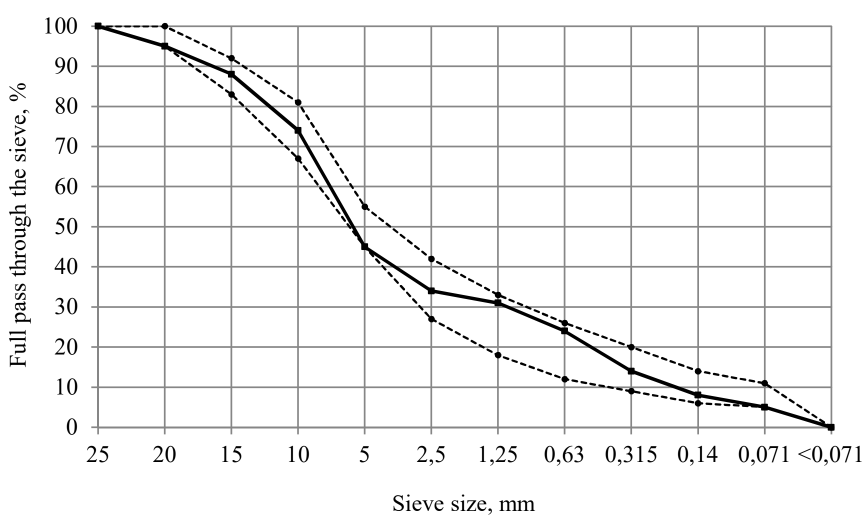

Fig. 3. Granulometric composition of type A dense fine-grained asphalt concrete

Table 1

Properties of BND 70/100 petroleum road bitumen accepted for the preparation of asphalt concrete mixtures

Properties	BND 100/70 bitumen
Needle penetration depth, mm^{-1}, at 25 °C	78
Ring and ball softening point, °C	49
Ductility at 25 °C, cm	>100

The results of the selection of granulometric composition and the properties of initial materials indicate that the initial materials meet the requirements of the national standards. They can also be used for the preparation of asphalt mixtures and studies of the properties of asphalt concretes based on them.

4. 2. Methods and equipment adopted for research

To solve the problems, standard methods and devices in Ukraine were used to determine the physical and mechanical properties of mineral materials, bituminous binders and asphalt concrete in laboratory conditions. The results are presented as the arithmetic mean of tests of three asphalt concrete samples for each given index. For investigation of asphalt concrete rutting resistance, the test bench designed in the research laboratory of the Department of Road Building and Maintenance of the Kharkiv National Automobile and Highway University (Ukraine) was used (Fig. 4) [13].

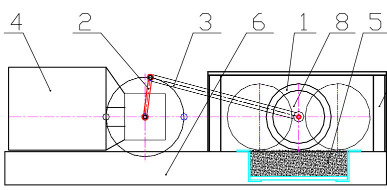

Fig. 4. Scheme of the test bench [13]: 1 – rubber; 2 – carrier; 3 – link; 4 – gear motor; 5 – asphalt concrete sample; 6 – frame; 7 – case; 8 – metal disk

The test bench is designed to assess the resistance of asphalt concrete to the accumulation of residual deformations in the form of a rut at different temperatures and load levels on the wheel moving on the sample surface. The test temperature is controlled and maintained by a temperature controller and during testing was 65 °C. The wheel pressure on the sample was 0.8 MPa. Prism samples with dimensions of 300 mm in length, 150 mm in width and 70 mm in height prepared in the laboratory were tested.

The tests were performed by cyclic rolling of the loaded wheel on the surface of the prepared asphalt concrete samples at a given temperature with periodic measurement of rut depth as a criterion of asphalt concrete resistance to the accumulation of residual plastic deformations. For studies of rutting resistance of one type of asphalt concrete, a series of tests was performed from three samples, after which the arithmetic mean value of rut depth was calculated with the appropriate number of passes of the test bench wheel, standard deviation and confidence interval.

4. 3. Technology of preparation of asphalt concrete mixtures

To study the effect of temperature, preparation and thermostating of the mixture were performed using type A asphalt concrete mixtures modified with the "Ric-Polycell" polymer in the amount of 3 % by weight of bitumen and mixtures modified with the "Duroflex®-SMA" polymer in the amount of 0.6 % by weight of stone material. Preparation and thermostating of mixtures in the laboratory were performed according to the following method:

– heating of stone materials to 150–155 °C, 160–165 °C, 170–175 °C, 180–185 °C;

– introduction of the polymer into the aggregate in a given amount;

– mixing of the aggregate with the polymer;

– introduction of aggregate filler and bitumen into the mixture;

– mixing of asphalt concrete mixture to a homogeneous state;

– termostatting of the asphalt concrete mixtures in the oven at 155 °C, 165 °C, 175 °C and 185 °C for 30 minutes.

By the thermostatting of the mixture before the formation of asphalt concrete samples, a certain duration of mixture transport to the object was modeled.

After that, cylindrical laboratory samples were formed.

The "Ric-Polycell" additive was introduced in the heated aggregate of asphalt concrete mixtures (180–185 °C) in an amount of 1.5 % and 3 % by weight of bitumen. During the preparation of stone mastic asphalt concrete mixtures, the "TOPCEL" stabilizing fibrous additive in the amount of 0.4 % by weight of the aggregate (before polymer introduction) was additionally introduced into their composition. After that, the asphalt concrete mixture was mixed (dry mixing) until the components were evenly distributed and the optimal amount of bitumen was introduced. Bitumen was introduced in the amount of 5.5 % for type A fine-grained asphalt concrete mixture, 5.3 % for SMA-20 stone mastic asphalt concrete mixture, 6.1 % for SMA-10 stone mastic asphalt concrete mixture by weight of stone materials. After that, mixing was continued until homogeneous mixtures were obtained. The ready asphalt concrete mixtures were thermostated for 30 minutes in the oven at a temperature of 185 °C. After the thermostatting was completed, laboratory samples were prepared from the asphalt concrete mixtures further subjected to testing.

To study the properties of asphalt concrete from the mixtures modified with the "Duroflex®-SMA" polymer additive, the modifier was introduced into the heated aggregate of asphalt concrete mixtures (180–185 °C) in an amount of 0.3 % and 0.6 % by weight of stone material. Then asphalt concrete mixtures were prepared according to the same procedure as when using the "Ric-Polycell" additive.

5. Results of experimental studies of the effect of thermoplastic additives in asphalt concrete mixtures on asphalt concrete properties

5. 1. Investigation of the effect of preparation temperature of modified asphalt concrete mixtures on asphalt concrete properties

The effect of the preparation temperature of modified asphalt concrete mixtures was studied by the compressive strength index at a temperature of 50 °C, as it is more sensitive to modification than the normalized values. The results of studies of the compressive strength at a temperature of 50 °C are shown in Fig. 5.

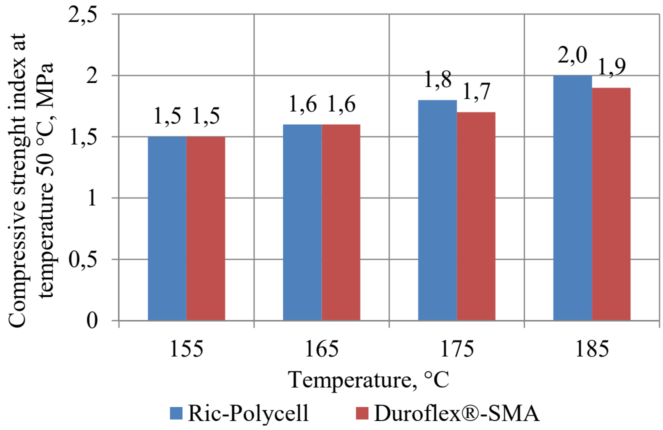

Fig. 5. Relationship between compressive strength at 50 °C and thermostatting temperature

The research results show that an increase in the preparation and thermostatting temperature of asphalt concrete mixtures leads to an increase in the compressive strength index. This indicates the increase in the modifying efficiency of the studied polymers with the increase of possible preparation temperatures of mixtures.

5. 2. Investigation of the properties of asphalt concretes obtained from mixtures modified with the "Ric-Polycell" polymer additive

The results of studies of the physical and mechanical properties of type A fine-grained asphalt concrete are given in Table 2.

Table 2

Physical and mechanical properties of type A fine-graded asphalt concrete modified with the "Ric-Polycell" polymer additive

Index	Type A BND 70/100	Type A BND 70/100+1.5 % Ric-Polycell	Type A BND 70/100+3.0 % Ric-Polycell
Porosity of the aggregate, % by volume	15.7	15.7	15.7
Average density, kg/m^3	2,404	2,403	2,410
Residual porosity, % by volume	3.3	3.8	3.7
Water saturation, % by volume	2.6	2.6	2.7
Compressive strength, MPa, at			
0 °C	6.7	8.0	8.1
20 °C	3.2	4.0	4.3
50 °C	1.3	1.8	2.0
Water resistance under long-term water saturation	0.88	0.91	0.92

Analysis of the research results indicates that the introduction of the "Ric-Polycell" polymer into the mixture significantly increases the compressive strength of type A asphalt concrete at all temperatures. The introduction of the 'Ric-Polycell" additive in the amount of 1.5 % and 3.0 % by weight of bitumen in the composition of the mixture compared to asphalt concrete without the additive helps to increase the strength. As a result, the compressive strength index at 50 °C increased by 38.5 % and 53.8 % respectively, at 20 °C by 25 % and 34.3 %, and at 0 °C by 19.4 % and 20.8 %. Water resistance under long-term water saturation of the studied asphalt concretes increases by 3.4 % and 4.5 %.

The results of studies of the rutting resistance of type A fine-grained asphalt concrete were obtained at a test temperature of 65 °C after 30,000 passes of the test bench wheel.

According to the results of experimental studies (Fig. 6), it was found that the rutting resistance of the studied asphalt concretes increases with an increase in "Ric-Polycell" polymer additive content. After 30,000 wheel passes on the rut at a test temperature of 65 °C, the rut depth decreases from 2.55 and 3.86 times with an increase in the polymer additive content from 1.5 % to 3 % by weight.

The results of studies of the effect of the "Ric-Polycell" additive on the physical and mechanical properties of SMA-10 and SMA-20 stone mastic asphalt concretes are given in Tables 3, 4.

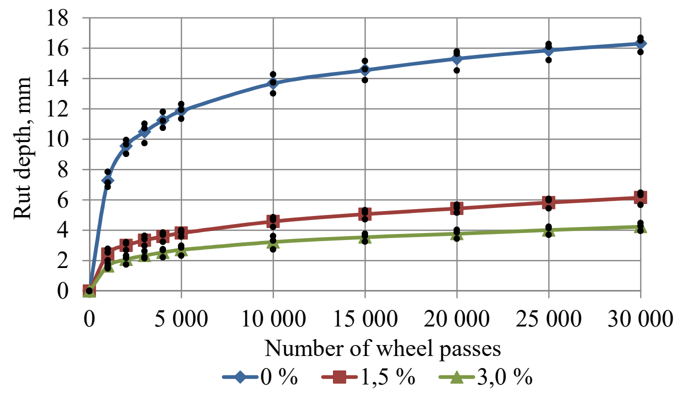

Fig. 6. Dependences of rut depth in type A fine-grained asphalt concrete with the "Ric-Polycell" additive on the number of wheel passes at 65 °C

Table 3

Physical and mechanical properties of SMA-10 stone mastic asphalt concrete with the "Ric-Polycell" polymer additive

Index	SMA-10 BND 70/100	SMA-10 BND 70/100+1.5 % Ric-Polycell	SMA-10 BND 70/100+3 % Ric-Polycell
Water saturation, % by volume	1.6	1.3	1.2
Average density, kg/m^3	2,395	2,393	2,392
Compressive strength, MPa, at:			
20 °C	3.5	4.5	5.0
50 °C	1.0	1.3	1.5
Internal friction coefficient	0.91	0.91	0.91
Water resistance under long-term water saturation	0.92	0.94	0.94
Shear adhesion at 50 °C, MPa	0.17	0.20	0.22
Splitting tensile strength at 0 °C, MPa	4.8	5.5	5.8
Binder content, %	6.1	6.1	6.1

Table 4

Physical and mechanical properties of SMA-20 stone mastic asphalt concrete with the "Ric-Polycell" polymer additive

Index	SMA-20 BND 70/100	SMA-20 BND 70/100+1.5 % Ric-Polycell	SMA-20 BND 70/100+3 % Ric-Polycell
Water saturation, % by volume	2.4	2.3	2.2
Average density, kg/m^3	2,424	2,413	2,412
Compressive strength, MPa, at:			
20 °C	2.4	3.0	3.5
50 °C	0.7	1.1	1.5
Internal friction coefficient	0.93	0.93	0.93
Water resistance under long-term water saturation	0.91	0.95	0.95
Shear adhesion at 50 °C, MPa	0.16	0.19	0.20
Splitting tensile strength at 0 °C, MPa	4.2	5.4	5.7
Binder content, %	5.3	5.3	5.3

Similar to the case of type A fine-grained asphalt concrete modification, the introduction of the "Ric-Polycell" additive in the amount of 1.5 % and 3 % helps to increase the strength characteristics of the studied stone mastic asphalt concrete.

The results of studies of the properties shown in Table 3 indicate that the "Ric-Polycell" additive in SMA-10 stone mastic asphalt concretes increases the compressive strength index at 50 °C by 30 % and 50 %, at 20 °C by 27.5 % and 42.9 %. The shear adhesion index is also increased at 50 °C by 0.03 MPa and 0.05 Mpa and the tensile strength index at 0 °C by 14.6 % and 20.8 %. At the same time, the increase of the coefficient of water resistance under long-term water saturation is quite moderate – only 2.2 %.

In SMA-20 stone mastic asphalt concretes (Table 4), the compressive strength increases at 50 °C by 1.57 and 2.14 times, at 20 °C by 1.25 and 1.46 times. Shear adhesion increases by 0.03 MPa and 0.04 MPa. The splitting tensile strength at 0 °C increases by 28.6 % and 35.7 %. The coefficient of water resistance under long-term water saturation increases by 4.4 %.

The results of studies of the "Ric-Polycell" polymer additive effect on the resistance to the accumulation of residual plastic deformations in the form of a rut in SMA-10 stone mastic asphalt concrete are shown in Fig. 7.

According to the research results, we can draw a conclusion that the "Ric-Polycell" additive increases the asphalt concrete resistance to the accumulation of plastic deformations in the form of a rut. At its content of 1.5 % by weight of bitumen in the mixture, the rut depth in SMA-10 after 30,000 wheel passes is reduced by 2.79 times compared to stone mastic asphalt concrete based on the initial bitumen BND 70/100. At the additive content of 3 % by weight of bitumen, the rut depth decreases by 3.86 times, which indicates a fairly high efficiency of the investigated polymer additive.

The results of studies of the "Ric-Polycell" polymer additive effect on the resistance to the accumulation of residual plastic deformations in the form of a rut in SMA-20 stone mastic asphalt concrete are shown in Fig. 8.

In SMA-20 stone mastic asphalt concretes when the mixture is modified with the "Ric-Polycell" additive in the amount of 1.5 % by weight of bitumen, the resistance to accumulation of plastic deformations in the form of a rut increases by 2.52 times. When the amount of modifying additive is doubled, by 3.55 times.

The results of studies of the physical and mechanical properties of type A fine-grained asphalt concrete modified with the "Duroflex®-SMA" additive are given in Table 5.

The research results indicate that the introduction of the "Duroflex®-SMA" polymer in the composition of type A fine-grained asphalt concrete mixture significantly increases the compressive strength indexes of asphalt concrete at all temperatures, as in the previous case. The introduction of the "Duroflex®-SMA" additive in the amount of 0.3 % and 0.6 % by weight of bitumen to the mixture compared to the mixture without additives leads to an increase in the asphalt concrete compressive strength at a temperature of 50 °C by 23.1 % and 46.2 % respectively. At a temperature of 20 °C by 25 % and 34.3 %, and at a temperature of 0 °C by 19.4 % and 20.8 %. Water resistance under long-term water saturation of the studied asphalt concretes increases by 3.4 % and 4.5 %.

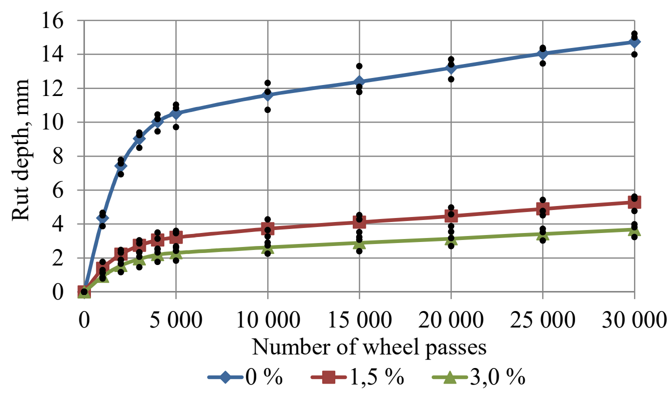

Fig. 7. Dependences of rut depth on the number of wheel passes in SMA-10 stone mastic asphalt concrete with the "Ric-Polycell" additive at 65 °C

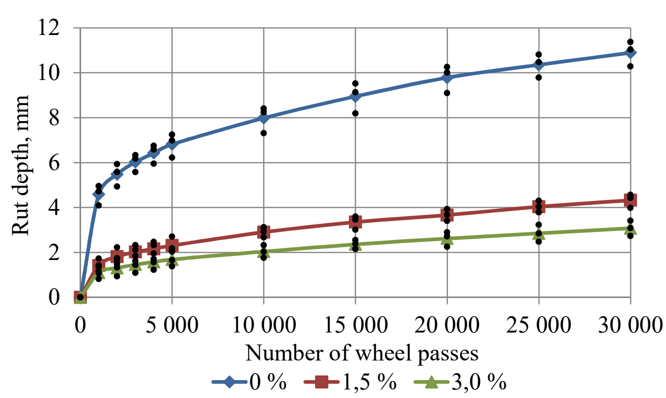

Fig. 8. Dependences of rut depth on the number of wheel passes in SMA-20 stone mastic asphalt concrete with the "Ric-Polycell" additive at 65 °C

Table 5

Physical and mechanical properties of type A fine-grained asphalt concrete with the "Duroflex®-SMA" polymer additive

Index	Type A BND 70/100	Type A BND 70/100+0.3 % Duroflex®-SMA	Type A BND 70/100+0.6 % Duroflex®-SMA
Porosity of the aggregate, % by volume	15.7	15,7	15.7
Average density, kg/m^3	2,404	2,412	2,414
Residual porosity, % by volume	3.3	3.6	3.9
Water saturation, % by volume	2.6	2.5	2.8
Compressive strength, MPa, at:			
0 °C	6.7	8.2	8.3
20 °C	3.2	3.9	4.2
50 °C	1.3	1.6	1.9
Water resistance under long-term water saturation	0.88	0.91	0.93

The results of studies of type A fine-grained asphalt concrete rutting resistance obtained at a test temperature of 65 °C after 30,000 passes of the test bench wheel are shown in Fig. 9.

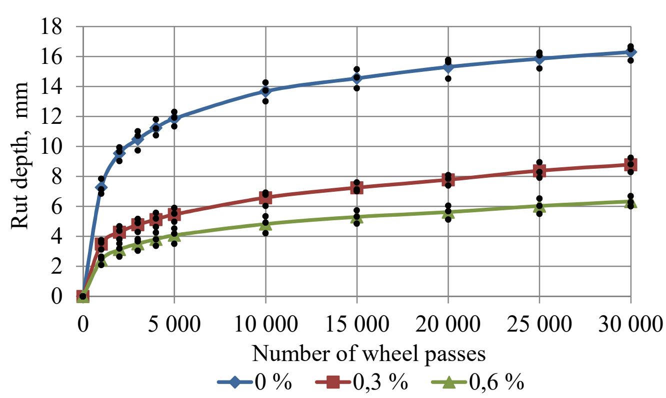

Fig. 9. Dependences of rut depth in type A fine-grained asphalt concrete with the "Duroflex®-SMA" additive on the number of wheel passes at 65 °C

As with the "Ric-Polycell" modifier, an increase in "Duroflex®-SMA" content in the composition of asphalt concrete leads to an increase in its rutting resistance. At a test temperature of 65 °C after 30,000 wheel passes on the rut with an additive content of 0.3 % and 0.6 % by weight of the aggregate, the rut depth decreases by 1.86 and 2.56 times, respectively.

The results of studies of the "Duroflex®-SMA" additive effect on the physical and mechanical properties of SMA-10 and SMA-20 stone mastic asphalt concrete are given in Tables 6, 7.

Table 6

Physical and mechanical properties of SMA-10 stone mastic asphalt concrete with the "Duroflex®-SMA" polymer additive

Index	SMA-10 BND 70/100	SMA-10 BND 70/100+0.3 % Duroflex®-SMA	SMA-10 BND 70/100+0.6 % Duroflex®-SMA
Water saturation, % by volume	1.6	1.7	1.7
Average density, kg/m^3	2,395	2,390	2,388
Compressive strength, MPa, at:			
20 °C	3.5	4.3	4.9
50 °C	1.0	1.2	1.5
Internal friction coefficient	0.91	0.91	0.91
Water resistance under long-term water saturation	0.92	0.95	0.95
Shear adhesion at 50 °C, MPa	0.17	0.19	0.21
Splitting tensile strength at 0 °C, MPa	4.8	5.4	5.8
Binder content, %	6.1	6.1	6.1
Water resistance under long-term water saturation	0.92	0.95	0.95

Table 7

Physical and mechanical properties of SMA-20 stone mastic asphalt concrete with the "Duroflex®-SMA" polymer additive

Index	SMA-20 BND 70/100	SMA-20 BND 70/100+0.3 % Duroflex®-SMA	SMA-20 BND 70/100+0.6 % Duroflex®-SMA
Water saturation, % by volume	2.4	2.3	2.2
Average density, kg/m^3	2,424	2,413	2,412
Compressive strength, MPa, at:			
20 °C	2.4	2.9	3.3
50 °C	0.7	1.0	1.4
Internal friction coefficient	0.93	0.93	0.93
Water resistance under long-term water saturation	0.91	0.93	0.93
Shear adhesion at 50 °C, MPa	0.16	0.18	0.20
Splitting tensile strength at 0 °C, MPa	4.2	5.2	5.6
Binder content, %	5.3	5.3	5.3

The introduction of "Duroflex®-SMA" in the composition of SMA-10 stone mastic asphalt concrete (Table 6) increases the compressive strength at a temperature of 50 °C by 20 % and 50 %, at a temperature of 20 °C by 22.9 % and 40 %. For the studied asphalt concrete, there is an increase in shear adhesion at 50 °C by 0.02 MPa and 0.04 MPa, increase in splitting tensile strength at 0 °C by 12.5 % and 20.8 %, increase in the coefficient of water resistance under long-term water saturation by 3.2 %.

Investigations of the properties of SMA-20 stone mastic asphalt concretes (Table 7) showed that the presence of the "Duroflex®-SMA" additive in their composition contributes to the growth of compressive strength at 50 °C by 42.9 % and 100 %, at 20 °C by 20.8 % and 37.5 %. Shear adhesion increases by 0.02 MPa and 0.04 MPa, splitting tensile strength at 0 °C increases by 23.8 % and 33.3 %, the coefficient of water resistance under long-term water saturation practically does not change.

The results of studies of the "Duroflex®-SMA" polymer effect on the resistance to the accumulation of residual plastic deformations in the form of a rut in SMA-10 stone mastic asphalt concrete are shown in Fig. 10.

The results of studies of rutting resistance show that the "Duroflex®-SMA» additive increases the resistance of stone mastic asphalt concrete to the accumulation of plastic deformations in the form of a rut. At its content of 0.3 % by weight of the aggregate in the composition of stone mastic asphalt concrete, the rut depth in SMA-10 after 30,000 wheel passes is reduced by 2.2 times compared to stone mastic asphalt concrete based on the initial bitumen BND 70/100. With an additive content of 0.6 %, the rut depth decreases by 3.16 times, which also indicates a fairly high efficiency of the studied additive.

The results of studies of the "Duroflex®-SMA" polymer effect on the resistance to the accumulation of residual plastic deformations in the form of a rut in SMA-20 stone mastic asphalt concrete are shown in Fig. 11.

In SMA-20 stone mastic asphalt concretes when modifying the mixture with the "Duroflex®-SMA» additive in the amount of 0.3 % by weight of the aggregate, the rut depth decreases by 2.05 times, and when the amount of modifier increases to 0.6 % by 2.89 times.

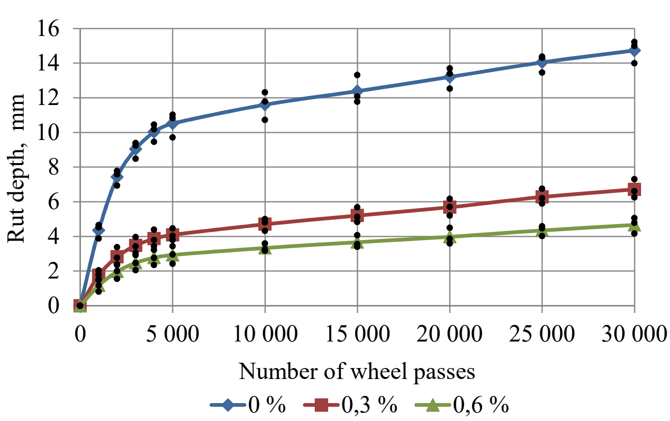

Fig. 10. Dependences of rut depth on the number of wheel passes in SMA-10 stone mastic asphalt concrete with the "Duroflex®-SMA" additive at 65 °C

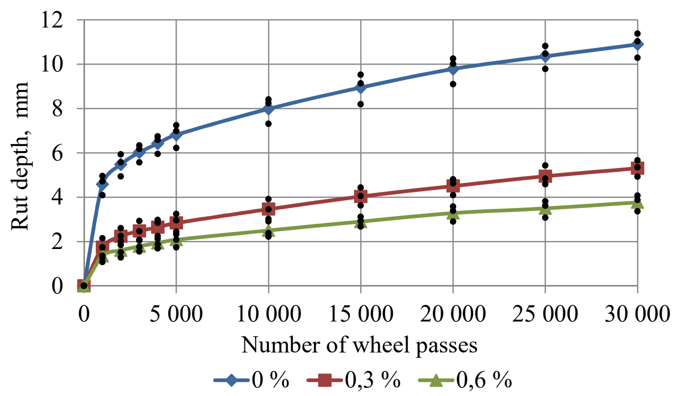

Fig. 11. Dependences of rut depth on the number of wheel passes in SMA-20 stone mastic asphalt concrete with the "Duroflex®-SMA" additive at 65 °C

6. Discussion of the results of experimental studies of "Ric-Polycell" and "Duroflex®-SMA" polymers effect on asphalt concrete properties

A comparative analysis of the results of experimental studies shows that with an increase in the content of the studied "Ric-Polycell" and "Duroflex®-SMA" polymers in the composition of both fine-grained asphalt concrete mixtures and stone mastic asphalt concrete mixtures, the strength of asphalt concrete from them increases significantly (Tables 2–7). Obviously, this is due to the modifying effect of the studied polymers on bitumen. Due to the dissolution of the polymer melt in bitumen, bitumen films on mineral grains have higher heat resistance, so the resistance of asphalt concrete to external loads increases.

The temperature of preparation of asphalt concrete mixtures is a factor that also affects the properties of asphalt concrete. To achieve a significant effect of the studied polymer additives in the preparation of asphalt concrete mixtures, stone materials must be heated to a temperature of 180–185 °C. The temperature of bitumen should be 165–175 °C, the temperature of the finished mixture at the outlet of the asphalt mixer should be within 175–185 °C. The specified temperature of preparation of asphalt concrete mixes at the initial stage (dry mixing cycle) ensures the softening of thermoplastic polymers. In the process of further mixing (wet cycle), there is a gradual transition of thermoplastics to the state of melt and dissolution in bitumen by mutual diffusion of molecules.

Among the studied asphalt concretes, the highest rutting resistance is inherent in SMA-20 stone mastic asphalt concrete and the least in type A dense fine-grained asphalt concrete (Fig. 6–11). These results confirm that asphalt concretes with high aggregate content have a higher coefficient of internal friction and consequently resistance of frame structure to the accumulation of plastic deformations in the form of a rut.

Modification of asphalt concrete mixtures with thermoplastics at the stage of their preparation in the mixer significantly increases the rutting resistance of asphalt concrete made of them. The studied concentrations of thermoplastic polymers increase the rutting resistance of both fine-grained and stone mastic asphalt concretes by almost two times. In this case, asphalt concrete with the "Ric-Polycell" polymer additive has a slightly higher rutting resistance compared to asphalt concrete with the "Duroflex®-SMA" polymer additive (Fig. 6–11).

The research results allow, at the stage of construction and design of flexible pavements, to assign reasonably asphalt concrete mixtures modified with thermoplastics in asphalt mixers during their preparation for pavement layers. It is obvious that on highways with high traffic intensity of heavy vehicles, based on the research results, it is more appropriate to use stone mastic asphalt concrete with a larger size of mineral grains of crushed stone. Because they are more rut-resistant compared to asphalt concrete with a smaller size and content of crushed stone grains.

Providing the implementation of the technology of asphalt concrete mixtures modification with thermoplastics directly in the asphalt mixer, the limiting factors are the limit values of the specified temperatures. Exceeding their values can lead to the partial or complete destruction of polymers and neutralize their modifying effect, as well as accelerate bitumen aging. With this technology, it is always necessary to take into account the scale factor (one-time volume of the mixture) when using different asphalt mixers, by specifying the duration of dry and wet mixing cycles. An important step in further research is to determine a criterion to predict with high probability the completeness and homogeneity of the polymer dissolution in bitumen during the preparation of asphalt mixtures in the asphalt mixer.

7. Conclusions

1. According to the research results, it was found that the temperature of preparation of asphalt concrete mixes modified with the "Ric-Polycell" and "Duroflex®-SMA" polymer additives directly in the mixer significantly affects the strength characteristics of asphalt concrete. The efficiency of modification of asphalt concrete mixtures with thermoplastic polymers increases with increasing heating temperature of its components. The efficiency of the investigated polymer additives is quite noticeable when they are introduced into the asphalt mixer (before bitumen feeding) with mineral materials at a temperature of 180–185 °C. The temperature of bitumen before feeding into the mixer within 165 °C–175 °C can be recommended.

2. It was found that an increase in the content of the studied "Ric-Polycell" or "Duroflex®-SMA" polymer thermoplastic additives in the composition of asphalt concrete mixtures causes an increase in the compressive strength indexes of asphalt concrete at different temperatures of their determination. The largest increase of the asphalt concrete compressive strength is observed at a temperature of 50 °C, which indicates an increase in the resistance of asphalt concrete with these polymers to the influence of loads at high operating temperatures. As the temperature of this index decreases, the growth rate of the compressive strength values decreases, but in the absolute value, it remains quite significant. With an increase in the content of the studied polymer in the composition of stone mastic asphalt concretes, they are also characterized by an increase in tensile strength at 0 °C and shear adhesion index at 50 °C. The results of studies of asphalt concrete rutting resistance indicate that among the studied asphalt concretes on bitumen without modifying additives, SMA-20 stone mastic asphalt concrete has the maximum rutting resistance. The lowest rutting resistance is inherent in type A dense fine-grained asphalt concrete based on pure bitumen without any additives. In this case, the greatest rutting resistance of stone mastic asphalt concrete is provided by the frame structure of the aggregate, which is created by a large number of grains in its composition. These results are in good agreement with the known data that asphalt concretes with a high content of crushed stone grains have a higher internal friction coefficient and, accordingly, rutting resistance of the frame structure compared to asphalt concretes with low crushed stone content. Modification of asphalt concrete mixtures with a minimum content of "Ric-Polycell" or "Duroflex®-SMA" polymer additives in the studied range of their concentration leads to an almost two-times increase in the rutting resistance of asphalt concrete. With an increase in the content of polymer additives, the rutting resistance of asphalt concrete also increases. Of the two investigated polymer additives, "Ric-Polycell" provides a slightly higher rutting resistance of asphalt concrete.

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