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Stone mastic asphalt modified with stabilizing additives of multifunctional action

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Abstract. The paper presents the results of studies of the physicomechanical properties of stone mastic asphalt (SMA) with the use of stabilizing additives of multifunctional action aimed at increasing the strength characteristics of SMA, resistance to plastic deformations, increase in shear stability of asphalt concrete, as well as reduction of the negative impact of technological temperatures on oil bitumen contributing to its oxidation and premature aging in the production of asphalt mixes. The structure of bitumen modified with composite thermoplastic elastomer was studied by nuclear magnetic resonance. For experimental verification of the effectiveness of additives in the composition of SMA, standard methods used for all types of asphalt concrete were applied and the following indicators of physical and mechanical properties were studied: compressive strength, water saturation, shear resistance, abrasion, resistance to plastic deformation. The results of studies of physical and mechanical properties of SMA grades 10 and 15 containing additives of the Viatop Plus CT40 and Viatop Plus FEP series showed that the values of compressive strength at 20 and 50 °C exceed similar indicators of properties of SMAs with the use of a stabilizing additive Viatop 66 considered as control compositions.

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1. Introduction

During the last 17 years, stone mastic asphalt have been widely used in Russia when arranging pavements with high load-bearing stresses, considering their high transport and operational performance (roughness), and resistance to external influences (water resistance, shear resistance) [1, 2]. The experience of using stone mastic asphalt in the Republic of Tatarstan in Russia is more than 15 years. Fig. 1 shows the kinetic dependence of the output volumes of the main types of asphalt concrete mixtures in the Republic of Tatarstan: SMA, type B grade II, produced in accordance with Russian State Standard 9128, as well as other types of asphalt concrete.

An analysis of the above dependence shows that SMA production is relatively high and averages 90.5 thousand tons per year.

Currently, road manufacturing enterprises are developing the release of SMA according to new standards. So, in 2017, the Volgadorstroy LLC asphalt concrete plant organized the production of SMA-19 asphalt concrete designed in accordance with PNST (preliminary national standard) 127-2016. When developing the composition of SMA-19, they use bituminous binders that take into account the temperature range of operation of the road surface and the characteristics of traffic loads for each particular construction project or repair. SMA-19 was used in the repair of the transport interchange of the M-7 Volga highway in

Zelenodolsky district of the Republic of Tatarstan, as well as in the repair of the roadway section of Kulakhmetov Street in Kazan, Russian Federation. Also on the main streets in the cities of the Republic of Tatarstan and the supporting network of regional roads carried out repair work with the application in the top coat of asphalt mix SMA-20 on polymer-bitumen binder, which improves their durability.

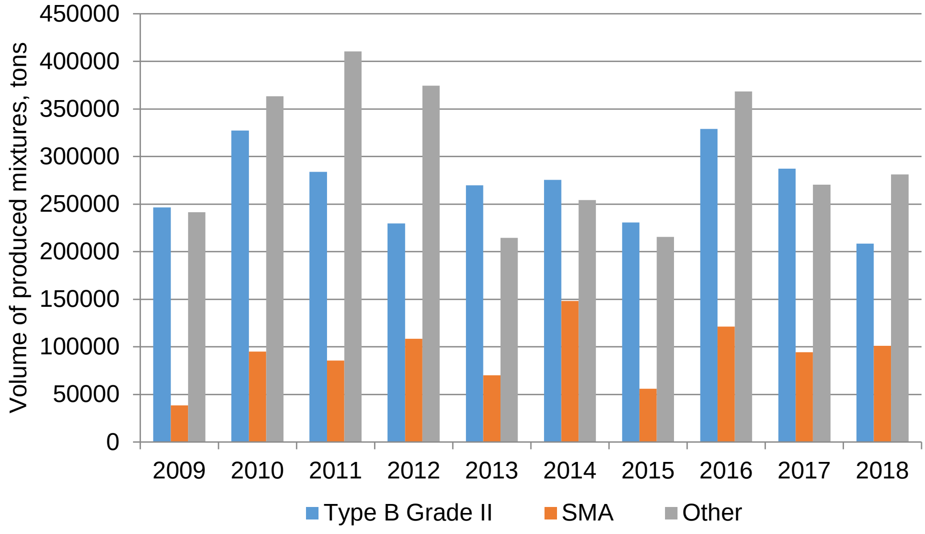

Figure 1. Kinetic dependence of the output of asphalt mixtures.

SMA was developed in Germany in 1966, and since 1970 it has been widely used in the upper layers of road surfaces with high traffic density and is an independent type of asphalt concrete [3–6].

SMA is characterized by an increased content of gravel and bitumen (up to 80 % and 7.5 % by weight, respectively) and residual porosity of up to 1%. Studies show that the coefficient of internal friction tg α largely depends on the grain composition of the mixture. When designing the composition of SMA, it should be borne in mind that a greater effect in the fight against rutting is provided by a stable gravel frame rather than the increased viscosity of the bitumen used [7]. To keep free bitumen on the gravel surface, at the stage of road construction, it is necessary to introduce fibrous stabilizing additives into the mixture [8]. So, in the SMA production practice, additives of the brands Viatop, TOPCEL and others, which are granular material containing cellulose fiber and organic components, have most widely proven themselves [9–12]. The stabilizing additives based on fibrous industrial waste have been widely studied as well [13–16].

The results of research [17] showed that the introduction of 20 mm long fibers in the amount of 0.2 % of the mass of bitumen increases the cracking resistance of the bitumen, increases its structural strength and fatigue life.

In [18], the influence of various additives from the class of mineral fibers, cellulose fiber, styrene-butadiene-styrene (SBS) on the properties of SMA was studied, including an increase in the service life of asphalt concrete coatings, as well as a possible reduction in the thickness of coating layers. It was found that the service life of the modified mixture coating is 1.07, 1.081 and 1.243 times longer than that of the unmodified mixture, respectively.

In [19], it was shown that the introduction of nanoscale SiO_2 and nano TiO_2 particles in the amount of 1.2 % and 0.9 % of the bitumen mass, respectively, into the SMA mixture increases the strength of the SMA and fatigue life.

In [20] it was found that the introduction of polyethylene terephthalate (PET) as an additive in asphalt, in the amount of 4 %, 6 %, 8 % and 10 % by weight of the content of bitumen, increases the resistance of the latter to aging.

The influence of various types of aggregates (large and small basalt, large and small limestone, large basalt and small limestone) on the low-temperature characteristics and resistance to cracking of the lime is studied [21].

It was found [22] that the introduction of polyvinyl chloride waste and electric arc furnace dust into the SMA reduces the sensitivity of the SMA to moisture and increases the resistance to aging of asphalt binders, improves their tensile strength, water permeability and resistance to destruction of asphalt concrete mixtures.

A comparative analysis in [23] showed that the use of polymer-bitumen binder in the composition of SMA as well as fibers of natural origin (banana fibers) has a positive effect on the properties of the binder and asphalt concrete. Thus, the introduction of natural fibers increases the binder's resistance to aging and water and the fatigue strength SMA. At the same time, the mixtures modified with polymer additives require less energy for their compaction in comparison with the natural fiber SMA. Also, the effectiveness of using leather industry waste [24] and plastic bottles [25] as stabilizing additives in the composition of SMA has been established.

The purpose of this work was to study the indicators of physical and mechanical and operational and technical properties of stone mastic asphalt grade SMA-10 and 15, containing stabilizing additives multifunctional action brand Viatop series Plus, as well as the establishment of optimal technological factors for the preparation of new SMA.

To achieve this goal, the following tasks were adopted:

1. To make the comparative analysis of indicators of properties of SMA-10 and 15 containing additives Viatop Plus FEP and Viatop 66 defining their resistance to formation of plastic and shear deformations;

2. To make the comparative analysis of indicators of properties of SMA-10 and 15 containing the Viatop Plus CT40 additive and prepared at different temperature conditions (140 and 170 °C) and similar asphalt concretes containing the Viatop 66 additive.

2. Methods

Samples of gravel and mastic asphalt concrete were investigated in accordance with current regulatory documents. Conclusions on their quality are made in accordance with the requirements of current standards, as well as on the basis of construction codes.

For a comparative assessment of the physicomechanical properties of SMA grades 10 and 15 containing additives of the Viatop Plus CT40 and Viatop Plus FEP series, we used SMA of similar grades containing the Viatop 66 additive as control compositions.

The preparation of asphalt mixtures was carried out at various temperature conditions. So, mixtures with the addition of Viatop Plus FEP were prepared at a traditional temperature of 160–170 °C. Mixtures with the Viatop Plus CT40 additive were prepared both at a temperature of 160–170 °C and at 140 °C (by the warm method) in order to establish the effectiveness of the components included in the Viatop Plus CT40 additive and to obtain SMA-15 samples with the properties corresponding to the regulatory requirements.

Technical characteristics used to evaluate the quality of asphalt concrete were determined according to Russian State Standard 12801-98, Russian State Standard 31015-2002, PNST 181-2016, PNST 180-2016 test methods. To determine the physical and mechanical properties of SMA we used the necessary complex of standard equipment. The tests were carried out in the laboratory for testing road-building materials of the Test road scientific-production center of the Institute of Transport Constructions of Kazan State University of Architecture and Civil Engineering.

To determine the strength of the gravel mineral grains, we used: a hydraulic press P-50 according to Russian State Standard 9753-88 with a maximum load of 500 kN, with a force meter providing an error of not more than 2 % of the measured load, steel cylinders with a removable bottom and a plunger with an inner diameter of 75 and 150 mm, laboratory balance with measuring limits of 0.5 and 1 kg of the 4th accuracy class, a set of standard sieves with a diameter of 1.25; 2.5; 5.0; 10; 20 and 40 mm.

To determine the grain composition of mineral materials, we used: laboratory scales with measuring limits of 0.5 and 1 kg of the 4th accuracy class, a set of standard sieves with diameters from 0.14 to 40 mm.

To determine the bulk density of mineral materials we used laboratory scales according to Russian State Standard 24104, 4th accuracy class and vessels with a capacity of 3.0, 5.0 and 10.0 liters.

For the manufacture of SMA cylinder samples in accordance with Russian State Standard 12801-98, we used: a drying cabinet (SHSS – 80P), with a heating temperature of up to +200 °C, a vibrating platform, a hydraulic press P-50 according to Russian State Standard 9753-88 with an ultimate load of up to 500 kN with a force meter providing an error of not more than 2 % of the measured load, a press-out device for extracting asphalt concrete samples from cylindrical forms and other auxiliary equipment.

To determine the compressive strength of SMA samples, we used: an MGM 100 A test electronic machine with a measurement limit of up to 100 kN with a force meter providing an error of not more than 2 % of the measured load, mercury thermometers and vessels with a capacity of 3.0 to 10.0 liters, thermostat (TVB –18).

To determine the average density of SMA samples, laboratory scales were used according to Russian State Standard 24104 of the 3rd accuracy class with a device for hydrostatic weighing (BP 3100S).

To determine the water saturation and average density of SMA samples, we used: a vacuum unit (SHSV 45K), laboratory balance in accordance with Russian State Standard 24104, 3rd accuracy class with a device for hydrostatic weighing (BP 3100S), chemical mercury thermometers with a division value of 10 °C according to Russian State Standard 400, vessels with a capacity of 3.0; 5.0 and 10.0 liters.

To determine the abrasion of asphalt concrete samples, we used the VTI's Prall installation – a system that imitates wear of asphalt concrete pavement with studded tires. During testing, the abrasive effect on a cylindrical SMA specimen is reproduced by 40 steel spheres within 15 minutes.

To determine the resistance of asphalt concrete to plastic deformation, we used the Lintel L KNK-20 installation, which provides for the simultaneous testing of two samples and simulates the process of pavement deformation under the influence of multiple vehicle loads.

The material composition of the Viatop Plus FEP additive includes a polymer additive from the class of elastomers, therefore, the study of the structural and dynamic changes of bitumen in the presence of a polymer was of scientific interest. For comparative analysis, as an additive in this experiment, we used mixed thermoplastic elastomer (TEP) – a material from the class of elastomers that includes polymers: polyethylene, ethylene-propylene rubber and isoprene rubber. The dosage of the TEP additive in bitumen was 2.5–4 %. To study the structure of bitumen modified by TEP, the pulsed method of nuclear magnetic resonance (NMR) was used. The transverse relaxation times were measured by spin-spin relaxation methods on laboratory nuclear magnetic resonance spectrometers. The proton resonance frequency was 20.0 and 19.5 MHz. The duration of the $\pi/2$ radio frequency pulse was 3 μs. The settings were controlled by a computer; during measurements, digital signal accumulation was used.

3. Results and Discussion

The introduction of stabilizing additives into the bitumen leads to significant changes in the slope of the free induction decay (FID) and the value of spin-spin relaxation, as well as to changes in the populations of fast and slow relaxing components. The tangent of the tilt angle of the fast and slow relaxing components of the FID differ by about 5 times. Qualitatively, we can conclude that the slowly relaxing component is determined by the mobility of low – molecular components of the system, and the rapidly relaxing component is determined by the mobility of high-molecular components.

Based on the analysis of FID, the values of spin – spin relaxation times and population of the two decay components were estimated (Figs. 2, 3).

It was found that the introduction of the TEP additive leads to a shortening of the relaxation time of the slowly relaxing T2A component (Fig. 2). This effect is especially noticeable at high temperatures, when the mobility and time of spin-spin relaxation should increase. The introduction of TEP in bitumen inhibits the development of molecular mobility of low molecular weight components. In the temperature range of 50–60 °C, a break in the temperature dependences is observed. The location of this fracture, which characterizes the defrosting of molecular mobility, turns out to be significantly higher than the similar fracture for the initial bitumen at 44 °C. This means that the introduction of the TEP additive leads to an increase in the softening temperature of the material (thawing of the translational motion modes) and, accordingly, the heat resistance of asphalt concrete.

In Fig. 3 shows the dependence characterizing the relaxation of macromolecular components in the system. From the figure, it follows that additives of the TEP series also affect high molecular weight components in bitumen.

Thus, the data obtained by the NMR method made it possible to directly confirm that the addition of mixed TEP substantially inhibits the molecular mobility of bitumen, providing a potential increase in the heat resistance of asphalt concrete. The results suggest that the polymer additive that is part of the Viatop Plus FEP additive likewise has a positive effect on bitumen and on asphalt concrete modified with this additive, in the form of an increase in its heat resistance and strength. The latter was reflected in the study of physical and mechanical properties SMAs.

Analysis of the dependences of the physical and mechanical properties of SMA-10 showed that the introduction of additives of the Viatop Plus CT40 and Viatop Plus FEP series in the composition of the mixture improves the compressive strength of SMA at 20 °C (R20) by 12–26 %. The strength index at 50 °C (R50) is increased by 5 and 55 % for mixtures containing the additive Viatop Plus FEP and Viatop Plus CT40, respectively (Fig. 4). The increase in strength characteristics at positive temperatures is consistent with the studies of bitumen with additives of stabilizing additives of the Viatop Plus CT40 and Viatop Plus FEP series by NMR.

Thus, an increase in strength characteristics with positive ones is consistent with the results of studies of bitumen with a polymer additive by NMR.

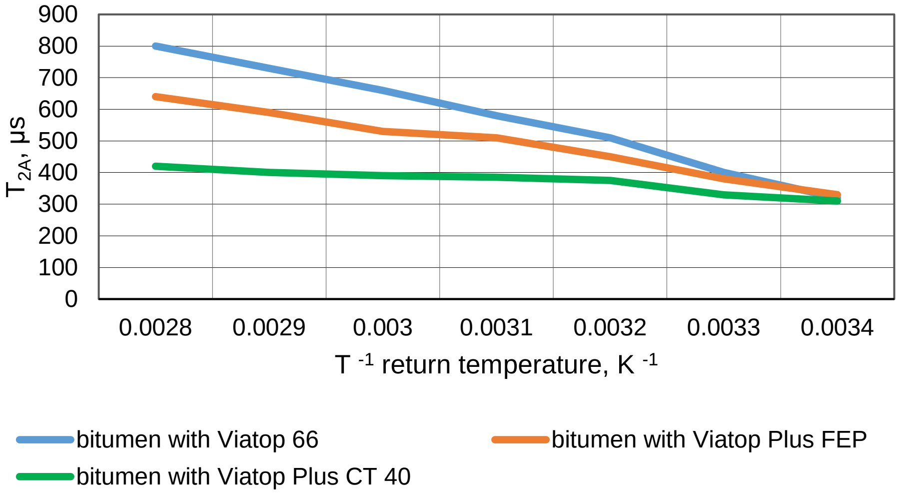

Figure 2. Dependence of the spin-spin relaxation time of the slowly relaxing T_{2A} component on temperature.

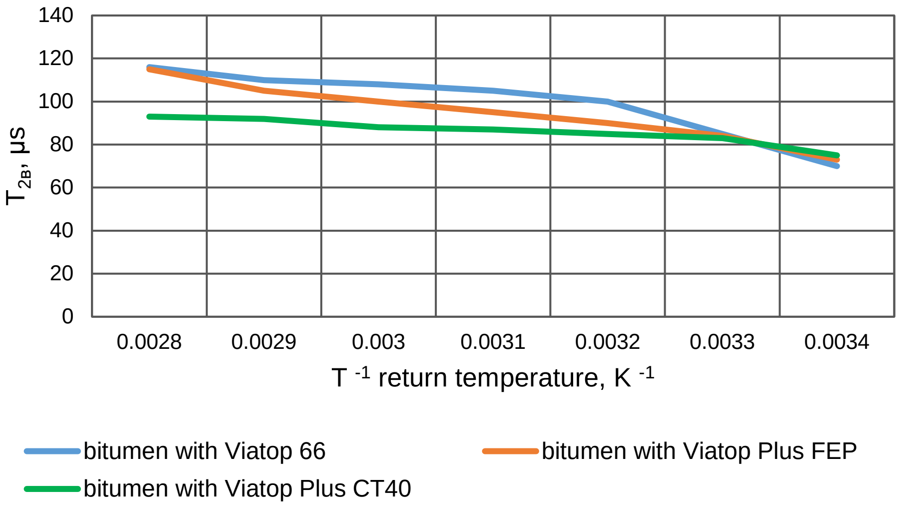

Figure 3. Dependence of the spin-spin relaxation time of the rapidly relaxing component of T_{2B} on temperature.

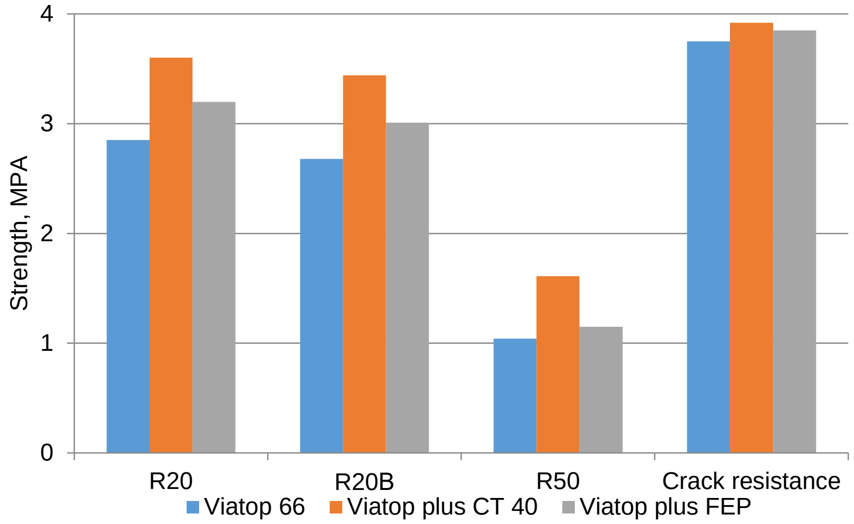

Figure 4. Physical and mechanical properties of SMA-10.

The water saturation rate of SMA-10 asphalt concrete containing the Viatop Plus CT40 additive is increased by 6 % compared with the control sample. A similar SMA with Viatop Plus FEP, on the contrary, is reduced by 5 %, which is probably due to the higher adhesive properties of the bitumen binder, which is modified by the polymer component that is part of the Viatop Plus FEP additive during the preparation of the asphalt mix.

The water resistance coefficient (K_v) of SMA-10 with the addition of Viatop Plus CT40 and Viatop Plus FEP increases slightly (by 1 %) in comparison with the control composition of SMA containing Viatop 66.

The main shear stability indicators of asphalt concrete affecting the gauge depth include the coefficient of internal friction and the coefficient of asphalt concrete adhesion during shear.

With the introduction of the additives Viatop Plus CT40 and Viatop Plus FEP in the SMA-10, the rate of shear resistance increases. The coefficient of internal friction practically remains unchanged, and the coefficient of adhesion during shear at 50 °C increases by 73 % for the mixture with the addition of Viatop plus CT40 and by 10 % for the mixture with the addition of Viatop Plus FEP. The results of SMA-10 physical and mechanical properties research are given in Table 1.

The addition of Viatop Plus CT40 and Viatop Plus FEP additives to the mixture improves the split strength. So, for example, for SMA-10 with the addition of Viatop Plus CT40, this indicator increases on average by 5 %, and for a mixture with the addition of Viatop Plus FEP by 3 % compared with the control composition on Viatop 66.

The rate of runoff of the binder in comparison with the control composition of the mixture is reduced by 0.01–0.02 %, which increases the resistance to SMA segregation during storage, transportation, loading and unloading.

Table 1. Physical-mechanical properties of SMA-10.

Mix type	Compressive strength [MPa]			Water resistance coefficient	Shear resistance		Crack resistance [MPa]	Average track depth (RD) mm	Abrasion of SMA [cm³]
	R20	R20B	R50		Internal friction coefficient [MPa]	Adhesion during shear at 50 °C [MPa]			
Mixture 1 (Viatop 66)	2.85	2.68	1.04	0.94	0.95	0.19	3.75	0.16	21.11
Mixture 2 (Viatop Plus CT40)	3.60	3.44	1.61	0.95	0.96	0.33	3.92	0.14	20.95
Mixture 3 (Viatop Plus FEP)	3.20	3.01	1.15	0.95	0.95	0.21	3.85	0.15	21.18

Along with studies of the basic physical and mechanical characteristics of SMA, regulated in Russian State Standard 31015, we carried out additional experimental studies of the resistance of asphalt concrete to rutting and to abrasive loads.

As a result of the tests, we found that the introduction of the additives Viatop Plus CT40 and Viatop Plus FEP into the SMA-10 formulations does not significantly affect the rate of their abradability, as well as the rate of gauge after 10,000 cycles of applied load. So, the values of the obtained indicators are almost comparable with the test results of SMA-10 on Viatop 66, the values are presented in Table 1.

The following are the test results of the physicomechanical properties of the investigated SMA-15 formulations, the values are presented in Table 2.

The analysis of the dependences of the physical and mechanical properties of SMA-15 showed that the introduction of additives of the Viatop Plus CT40 and Viatop Plus FEP series leads to an increase in compressive strength at 20 °C (R20) of asphalt concrete by 6–34 %; the strength at 50 °C (R50) for SMA-15 with the addition of Viatop Plus CT40 is 11 % higher in comparison with the control composition, and for

SMA with the addition of Viatop Plus FEP the value of the same indicator remains practically unchanged (Fig. 5).

The water saturation index SMA-15 with the addition of Viatop Plus CT40 and Viatop Plus FEP increases by an average of 18 %.

The water resistance coefficient of SMA-15 with Viatop Plus CT40 and Viatop Plus FEP additives remains high in the water saturation mode under vacuum and increases slightly (by 1 %) compared to the initial mixture with Viatop 66 additive.

With the introduction of the additives Viatop Plus CT40 and Viatop Plus FEP, the shear resistance of SMA-15 practically does not change.

The crack resistance of asphalt concrete is increased by 11 % with the introduction of Viatop Plus CT40, and by 4 % with the introduction of Viatop Plus FEP. The binder runoff rate for SMA-15 formulations does not change.

Table 2. Physical-mechanical properties of SMA-15.

Mix type	Compressive strength [MPa]			Water resistance coefficient	Shear resistance		Crack resistance [MPa]	Average track depth (RD) mm	Abrasion of SMA [cm^3]
	R20	R20B	R50		Internal friction coefficient [MPa]	Adhesion during shear at 50 °C [MPa]			
Mixture 1 (Viatop 66)	2.62	2.47	1.06	0.94	0.95	0.19	3.45	2.2	19.25
Mixture 2 (Viatop Plus CT40)	3.51	3.35	1.18	0.95	0.94	0.22	3.84	1.9	18.96
Mixture 3 (Viatop Plus FEP)	2.78	2.65	1.08	0.95	0.94	0.20	3.30	2.0	19.21

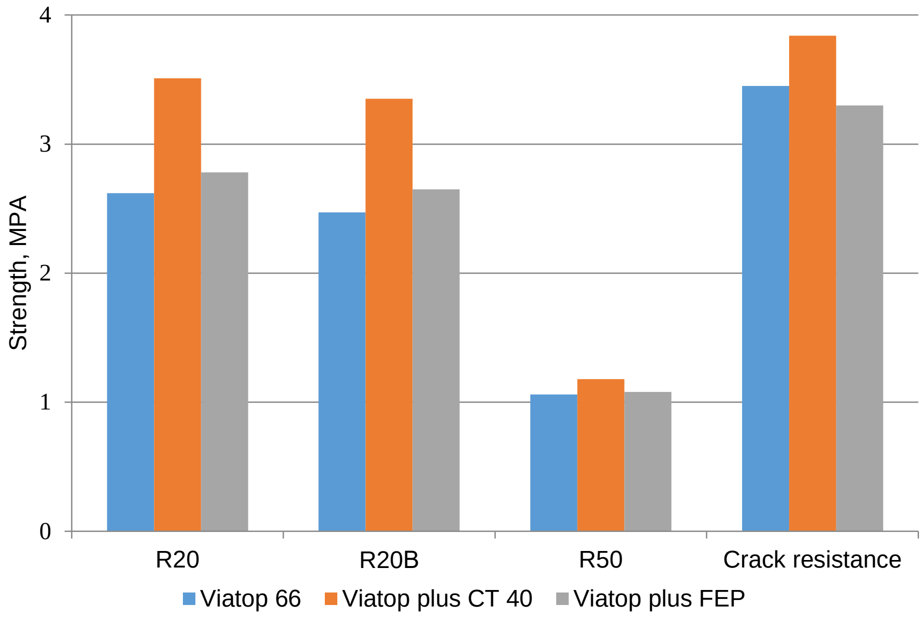

Figure 5. Indicators of physical and mechanical properties of SMA-15.

As a result of abrasion tests, we found that with the introduction of Viatop Plus CT40 and Viatop Plus FEP additives in SMA-15, this indicator slightly increases by 1–1.5 %, i.e. additives have virtually no effect on this indicator. As a result of SMA-15 tests for determining the track depth after 10,000 load cycles, we also revealed that there is a slight improvement of this indicator by 0.2–0.3 mm, the values are presented in Table 2.

4. 4. Conclusions

1. An analysis of the results allows us to conclude that the introduction of Viatop Plus CT40 and Viatop Plus FEP additives in the composition of SMA asphalt concrete grades 10 and 15 positively affects the change in the final physical and mechanical properties of the materials. Thus, the compressive strength at 20 °C of the samples under study is 26–34 % higher than the values for control samples supplemented with Viatop 66.

2. The compressive strength at 50 °C of SMA-10 containing Viatop Plus FEP is 55 % higher than that of the control sample, which characterizes its high resistance to plastic deformation.

3. The molecular mobility of bitumen with the addition of mixed TEP by the NMR method was studied. It was found that the introduction of the additive significantly inhibits the molecular mobility of bitumen, providing an increase in heat resistance and strength of crushed stone-mastic asphalt concrete.

4. We found that the physical and mechanical properties of SMA-10 and 15 asphalt concrete containing Viatop Plus CT40 and prepared by the warm method meet the requirements of GOST 31015, while the compressive strength of SMA-15 at 20 °C is 20 % higher compared to the control composition, which confirms the possibility and efficiency of the production of stone mastic asphalt mixtures at a lower temperature (140 °C) in comparison with the traditional mode of preparation (160–170 °C).

5. It was found that the addition of Viatop Plus CT40 and Viatop Plus FEP additives to the composition of SMA-15 promotes some improvement in the gauge depth index by 0.2–0.3 mm, in comparison with the control samples with the Viatop 66 additive.

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