Magazine of Civil Engineering. 2022. 115(7). Article No. 11509

Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

Research article

UDC 625.75

DOI: 10.34910/MCE.115.9

Workability of warm mix asphalt additives and mechanical property characterization of asphalt concrete

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Keywords: warm mix additives, mechanical properties, rheology, activation energy, workability

Abstract. Warm mix asphalt (WMA) technology offers a promising solution to address the ecological concern of asphalt mixtures. Warm asphalt (WA), is expected to be a sustainable paving technology that integrates energy conservation, noise reduction, and performance optimization. This study aims to characterize and compare the engineering properties of WA mixture prepared with various WMA additives. To achieve this goal, WA mixtures were prepared with seven different WMA additives, including Adgezol 3-TD, DAD-TA2, Azol 1007, Cecabase RT 945, DAD-TA, Doros-T and Amdor TS-1. Comprehensive laboratory tests were conducted to characterize their workability and engineering properties, including penetration, fragility and softening temperature of bitumen, and dynamic viscosity. According to the experimental results, WMA additives including Adgezol 3-TD, DAD-TA2, Doros-T and Azol 1007 provided a 30% reduction in dynamic viscosity of modified bitumen; however, with such WMA additives as DAD-TA, Cecabase RT 945 and Amdor TS-1 no reduction in dynamic viscosity of modified bitumen was observed. Coefficients that consider the complex of physical, mechanical, technological and economic properties, as well as a generalized criterion (Fk) for the technical and economic efficiency of chemical additives were developed. It was proposed to divide warm mix additives into two groups: additives that improve the efficiency of bitumen by 5% (Fk≥1.05) or more, as well as additives that do not improve the efficiency of bitumen by more than 5% (Fk≤1.05), that is, have no significant effect on the properties. Comprehensive laboratory tests were conducted to characterize their workability and mechanical properties, including moisture susceptibility. According to the experimental results, only with Cecabase RT 945 and DAD-TA one can achieve compliance with regulatory requirements for hot asphalt concrete. The influence of warm mix additives on the structure of bitumen was studied. Using the Arrhenius equation, the change in the activation energy required to overcome the potential (kinetic) barrier of the bitumen with the surfactants had been calculated. The workability of warm mix additives was investigated, on the basis of which their classification was proposed.

Citation: Obukhova, S.Yu., Korolev, E.V., Novikov, A.N., Shevtsova, A.G. Workability of warm mix asphalt additives and mechanical property characterization of asphalt concrete. Magazine of Civil Engineering. 2022. 115(7). Article No. 11509. DOI: 10.34910/MCE.115.9

1. Introduction

The use of technologies of warm asphalt concrete, based on an initially lower preparation temperature, allows you to ensure both the achievement of an economic effect and the reduction of environmental pressure in the process of manufacturing the road surface [1]. Thus, French researchers have found that the use of warm asphalt-concrete mixtures can reduce greenhouse gas emissions by 12 % and flue gas emissions by 25 % [2]. Modern technology for the production of warm asphalt concrete is based on the use of technological, physical and chemical methods that ensure the achievement of the required viscosity of bitumen at low temperatures for the production of road asphalt pavement [2, 3].

There are several possible options for producing warm asphalt concrete mixtures: bitumen foaming by means of foaming additives (zeolites) or mechanical foaming systems; organic plasticizing additives containing wax and / or paraffin; chemical additives (surfactants); combined technologies, including the simultaneous use of several of the above methods [4–12].

Bitumen foaming technologies that use water as the foaming component are currently considered cost-effective. However, they are associated with high initial equipment costs and are limited by the lower operating temperature due to the condensation temperature of water vapor. In addition, residual moisture may enter the asphalt concrete to be laid, which will contribute to the destruction of the road surface [4, 5].

The use of organic additives or waxes leads to a decrease in the melting point of bitumen, which allows the production of mixtures at lower temperatures [6, 7]. However, the use of wax in the composition of bitumen reduces the crack resistance of both the binder and asphalt concrete based on it, and may not be effective in areas with low temperatures [8].

Emergence of warm-mix additives has alleviated the high demand for heat energy in asphalt plant producer or in the paving process itself. Given this development, several studies have reported that warm mix asphalt (WMA) additives in asphalt mixture could reduce the required temperatures for mixing and compaction of asphalt mixtures by up to 20–40 °C through a reduction in binder viscosity and chemical interaction between WMA additives and neat asphalt binder [13, 14]. The use of chemical additives does not require additional costs for upgrading the equipment, and as a rule the additives had mixes with bitumen in the tanks of the mixing plant or are introduced by means of existing automatic equipment for the introduction of conventional adhesive additives [15–22]. This determines the prevalence of such a technological solution in the global construction industry, which is confirmed by foreign researches. The method of preparation of the asphalt concrete sample depends on the type of tests. Nevertheless, it is worth noting that better performance of warm asphalt concrete is achieved with rotational compaction on the gyrator [15, 16], because this method simulates the impact of the roller during compaction in real operating conditions. The authors of [18] studied the influence of chemical additives on the tensile strength coefficient (TSR) which is an indicator that characterizes the effect of moisture on the properties of asphalt concrete. The authors in [19] considered whether all types of asphalt concrete mixtures are suitable for the preparation of warm asphalt concrete mixtures. It has been found that asphalt mixes with a high binder content, such as AR-AC-13, are not suitable for the preparation of warm asphalt mixes. In [20] the influence of the compaction temperature on the bulk properties of asphalt concrete was studied. It is established that in the temperature range of 122–135 °C, an improvement in the bulk properties of asphalt concrete is observed. The authors in [21, 22] investigated the effect of chemical additives on the physical and mechanical properties of asphalt concrete containing recycled asphalt pavement (RAP). It was found that additives for warm asphalt concrete, which is containing RAP, do not allow improving the moisture resistance (TSR). The authors of [23, 24] indicated that the use of binder's viscosity is not sufficient to quantify the production temperatures or the overall workability, specifically for modified asphalt binders and RAPM containing asphalt mixtures. Eventually, direct evaluation of production temperature based on workability should be used for WMA. Several factors, including additive type and dosage, the grade of asphalt binder, and aggregate gradation affect the strength characteristics WMA [25–27].

Moreover, insufficient data for the computation of mixing and compaction temperature with the utilization of workability devices entails rigorous research to form a concrete conclusion. The analysis of the available scientific literature shows that the works are mainly aimed at studying the influence of chemical additives on the properties of warm asphalt concrete mixtures, and there are no research articles aimed at studying their influence on the properties and structure of bitumen, the main structure-forming component of asphalt concrete that determines its properties. However, it is worth noting that the occurrence of fatigue defects and low-temperature cracking of asphalt concrete by 60–90 % depend on bitumen, and the formation of plastic track by 40 % [29–31]. Therefore, the study of the effect of warm additives on the properties of bitumen will make it possible to predict the properties of asphalt concrete at the early stages of the study. This makes this study relevant. Therefore, the main purpose of the study is to establish the workability of chemical warm-mix additives. To do this, it is necessary to solve the problems of determining the influence of various chemical warm-mix additives on the properties and structure of bitumen 70/100.

This study is expected to provide extensive information for the established workability of chemical warm additives, which will allow predicting the mechanical properties of asphalt concrete modified with warm mix additives at an early stage.

2. Materials and Methods

The study of the effect of chemical additives on bitumen was carried out on chemical additives presented on the Russian market and recommended for the production of warm asphalt concrete mixtures:

- Adgezol 3-TD which is an organic composition obtained on the basis of the products of the interaction of tall oil with polyalkyl polyamine compounds, production by LLC "Basis";
- Azol 1007 which is a surfactant of the ampholytic type with a complex of plasticizing additives, production by LLC "Kotlas Chemical Plant";
- Cecabase RT 945, the information about the composition is not available in the public domain, production by Arkema (France);
- DAD-TA which is a highly active liquid composition of surfactants based on polyamines, production by Selena LLC;
- DAD-TA2 which is a specially modified amphoteric surfactant, production by Selena LLC;
- Doros-T, the information about the composition is not available in the public domain, production by Doros LLC,
- Amdor TS-1 that is a mixture of cationic surfactants, production by Uralkhimplast-Amdor LLC.

As a binder, bitumen of the BND 70/100 brand, production by Lukoil LLC, was considered. The properties of BND 70/100 are presented in Table 1.

Table 1. Physical and mechanical properties of BND 70/100.

Indicator name	Requirement of Russian State Standard GOST 33133	Actual value
The depth of penetration of the needle at a temperature of 25 °C, mm $^{-1}$	71–100	72
The depth of penetration of the needle at a temperature of 0 °C, mm $^{-1}$, no less than	21	24
Ring and ball softening temperature, °C, no less than	+ 47	+ 50
Fraass fragility temperature, °C, no more than	– 18	– 19

Mineral powder MP-1 (an inactive carbonate rock dolomite), crushed granite of 5–20 mm size and stone mineral (crushed granite screenings of 0–5 mm size) were used as mineral materials for the preparation of asphalt concrete type B according to Russian State Standard GOST 9128.

For this type of asphalt concrete, samples must be formed in according with Russian State Standard GOST 12801. However, this method is based on the formation of asphalt concrete sample under constant vertical load from a hydraulic press. Whereas in real conditions of road construction in the process of compaction of asphalt concrete pavement, the load from the roller is rotational and variable. The main property that characterizes the processability of a warm asphalt concrete mixture at low temperatures is its ability to achieve the required density with minimal effort during the compaction process. The method of compaction of asphalt concrete mixture (ACM) samples using the device of rotational (gyration) compaction, which is achieved by combining the shear force during rotation and the vertical resulting force, allows simulating to the process of compaction of asphalt concrete mixtures in the road surface in the laboratory as close to the real conditions as possible. The device "Laboratory gyratory compactor Cooper CRT-GYR" (hereinafter – gyrator) provides a record of the number of rotations (revolutions) required to achieve a given density of asphalt concrete. Therefore, this method was chosen for scientific research.

The studies considered asphalt concrete of type B with a given density of 2380 ± 10 kg/m^3, the consumption of chemical additives corresponded to the manufacturers' recommendations. The asphalt concrete mixture was prepared at a temperature of 150 °C; then, the mixture was kept in a drying cabinet at a temperature of 110 °C for 2 hours to stabilize the temperature of the mixture by volume. Compaction of mixtures with various chemical additives was carried out at a temperature of 110 °C until the specified density of asphalt concrete was reached. At the same time, for ACM containing the chemical additive under study, the number of the gyrator revolutions required to achieve the given density of asphalt concrete at a sample height of 115 mm was recorded.

When evaluating the effectiveness of the chemical additives used, their influence on the physical, mechanical and technological properties of the bitumen binder, as the main structure-forming component of asphalt concrete, was evaluated according to the following properties:

- The depth of penetration of the needle, at a temperature of 25 °C and 0 °C, according to Russian State Standard GOST 33136;
- Ring and ball softening temperature, °C, according to Russian State Standard GOST 33142;
- Fraass fragility temperature, °C, according to Russian State Standard GOST 33143;
- Dynamic viscosity at a shear rate of 100 s^{-1} according with Russian State Standard GOST 33137, on the Anton Paar Modular Compact Rheometer Physical MCR 101.

Three samples were prepared for each investigated chemical additive. No less than three measurements were made for each test method according to the requirements of Russian State Standard. The results are presented as an average value.

Based on the multi criteria optimization method [32], quality and efficiency criteria were developed. The effectiveness of the surfactant was evaluated according to the generalized criterion of technical and economic efficiency $\left(F_k\right)$, which takes into account both the set of operational properties and economic indicators, calculated by the formula:

$$F_k = K_q \cdot K_{ec}. \tag{1}$$

The coefficient of economic efficiency $\left(K_{ec}\right)$ was determined by the formula:

$$K_{ec} = 1 \Big/ 1 + P_{cd} \cdot \frac{C_{hd}}{C_b}, \tag{2}$$

where P_{cd} and C_{hd} are consumption, kg/t, and cost, rub/t, of the chemical surfactant, respectively; C_b is the cost of oil bitumen, rub/t.

Operational properties were evaluated by a generalized quality coefficient $\left(K_q\right)$, which takes into account the complex of physical, mechanical and technological properties of bitumen and asphalt concrete mixture:

$$K_q = \sqrt[6]{k_{compaction} \cdot k_{P_{25}} \cdot k_{P_0} \cdot k_{T_{fr}} \cdot k_{T_{softening}} \cdot k_{\eta}}, \tag{3}$$

where $k_{compaction} = \dfrac{N_{compaction}}{N'_{compaction}}$ is a criterion that takes into account the effect of a chemical additive on the compaction of an asphalt concrete mixture equal to the ratio of the number of revolutions required for compacting an asphalt concrete mixture without a chemical additive to the number of revolutions required for compacting an asphalt concrete mixture with a chemical additive;

$k_{P_{25}} = \dfrac{P_{25}}{P'_{25}}$ is a criterion that takes into account the effect of a chemical additive on the conditional viscosity equal to the ratio of the depth of penetration of the needle at 25 °C into bitumen without a chemical additive to the depth of penetration of the needle at 25 °C into bitumen with a chemical additive;

$k_{P_0} = \dfrac{P'_0}{P_0}$ is a criterion that takes into account the effect of a chemical additive on the conditional viscosity equal to the ratio of the depth of penetration of the needle at 0 °C in bitumen with a chemical additive to the depth of penetration of the needle at 0 °C in bitumen without a chemical additive;

$k_{T_{fr}} = \frac{T'_{fr}}{T_{fr}}$ is a criterion that takes into account the effect of a chemical additive on the crack resistance of bitumen equal to the ratio of the fragility temperature of bitumen with a chemical additive to the fragility temperature of bitumen without a chemical additive;

$k_{T_{softening}} = \frac{T_{softening}}{T'_{softening}}$ is a criterion that takes into account the effect of a chemical additive on the heat resistance of bitumen equal to the ratio of the softening temperature of bitumen without a chemical additive to the softening temperature of bitumen with a chemical additive;

$k_{\eta} = \frac{\eta'}{\eta}$ is a criterion that takes into account the effect of a chemical additive on the initial dynamic viscosity of bitumen at a temperature of 70 °C, at a shear rate of 100 s^{-1} equal to the ratio of the dynamic viscosity of bitumen with a chemical additive to the dynamic viscosity of bitumen without a chemical additive.

At the stage of studying the effect of chemical additives on the properties of bitumen and the compaction of asphalt concrete mixture, the most rational additives are selected for further study of their effect on the properties of asphalt concrete, which were evaluated according to the following properties:

- average density, kg/m^3, not rated;
- water saturation, %, according with Russian State Standard GOST 9128;
- compressive strength, MPa, at 20 and 50 °C, according with Russian State Standard GOST 9128;
- water resistance, according with Russian State Standard GOST 9128;
- water resistance under long-term water saturation, according with Russian State Standard GOST 9128.

No less than three measurements were made for each test method according to the requirements of Russian State Standard GOST 9128. The results are presented as an average value.

The influence of temperature on the viscosity of the system "bitumen/bitumen with surfactant" under study was evaluated using the parameters a and U of the dependence $\eta = f(T)$ described by the Arrhenius equation [33]:

$$\eta = a \cdot e^{\frac{-U}{(RT)}}, \tag{4}$$

where η is bitumen viscosity, Pa*s; a is a constant whose unit of measurement is similar to the unit of viscosity measurement; U is activation energy of the flow process, J/mol; R is a universal gas constant (R = 8.314 J/(mol·K)); T is the absolute temperature, K.

The activation energy U is an important parameter equal to the amount of energy that must be brought from the outside to start the flow, that is, to overcome the physical barrier that characterizes the parameters of the melt structure for the systems under consideration. Thus, U characterizes the excess energy in relation to the average energy of the particles at a given temperature. Obviously, the change in U during the introduction of additives will characterize the structural changes that occurred as a result of their introduction.

The physical meaning of the constant a becomes apparent only when:

$$e^{\frac{-U}{(RT)}} = 1.$$

This equality holds when $T \to \infty$:

$$\eta(\infty) = \lim_{T \to \infty} a \cdot e^{\frac{-U}{(RT)}} = a.$$

Thus, the constant a is also a structural parameter that characterizes the effect of additives (surfactants) on the absence of temperature influence.

3. Results and Discussion

To establish the effectiveness of chemical additives at the first stage, their effect on the manufacturability (compacting) of a warm asphalt concrete mixture (WACM) compacted at a low temperature of 110 °C was studied, the results are presented in Table 2.

Table 2. The effect of various additives on the compaction of WACM.

Name of warm-mix additive	Additive consumption, % by weight of bitumen	Compaction temperature, °C	Number of revolutions of the gyrator, units
without warm-mix additive	–	150	53
		110	110
Adgezol 3-TD	1.0	110	65
DAD-TA2	1.0	110	66
Azol 1007	1.0	110	65
Cecabase RT 945	0.3	110	50
DAD-TA	0.3	110	50
Doros-T	0.6	110	69
Amdor TS-1	0.3	110	62

The analysis of the results presented in Table 2 allowed us to establish that all the considered additives reduce the required number of gyrator revolutions by 38... 55 % in order to achieve a given density of asphalt concrete at a reduced temperature. The use of the additive Cecabase RT 945 and DAD-TA allows you to reduce the compaction temperature of the asphalt concrete mixture by 40 °C without compromising its manufacturability, obtained under standard conditions – the compaction temperature of 150 °C.

At the second step of evaluating the effectiveness of the studied chemical additives (surfactants), their effect on the physical, mechanical and technological properties of bitumen was studied. The main indicators that reflect their behavior under operating conditions are: the conditional viscosity characteristics which are the depth of penetration of the needle (penetration at 25 °C and 0 °C) and the plasticity interval (softening temperature and brittleness temperature). The dynamic viscosity is an indicator that determines the technological characteristics of the binder. The results of the determination of physical, mechanical and technological properties are presented in Table 3 and in Fig. 1 and 2.

Table 3. The effect of various additives on the penetration of BND 70/100.

Name of warm-mix additive	Additive consumption, % by weight of bitumen	The depth of penetration of the needle, mm $^{-1}$, at a temperature of, °C	
		0	25
without warm-mix additive	–	24	72
Adgezol 3-TD	1.0	26	82
DAD-TA2	1.0	28	80
Azol 1007	1.0	28	89
Cecabase RT 945	0.3	29	76
DAD-TA	0.3	28	76
Doros-T	0.6	28	81
Amdor TS-1	0.3	28	73

As can be seen from Table 3, all the studied additives have a plasticizing effect on bitumen, but do not change its mark, in accordance with Russian State Standard GOST 33133. The modified bitumen is in the conditional viscosity range of 70/100 mm^{-1}. It should be noted that the greatest plasticizing-diluting effect is observed in additives with a recommended concentration of 0.6–1 %, which is 20 % on average, while in additives with a concentration of 0.3 %, the plasticizing effect is 0.3–6 % on average.

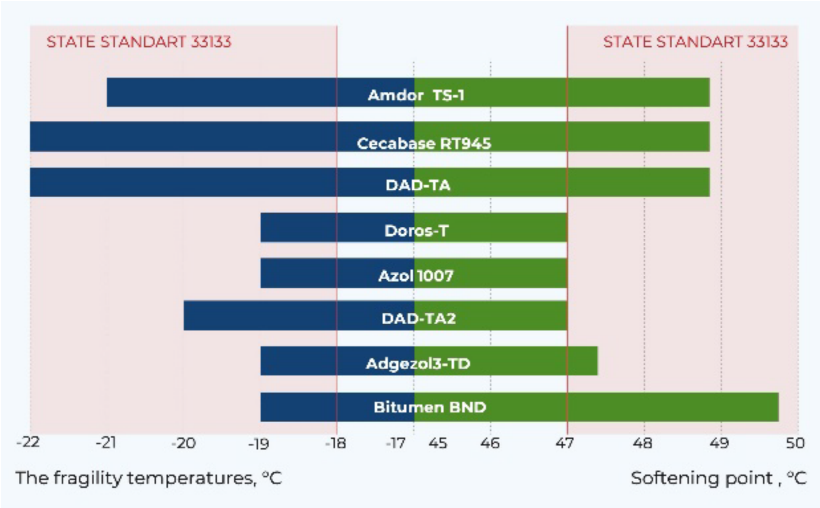

Figure 1. The effect of additives (surfactants) on the fragility and softening temperature of bitumen.

During the study of the effect of additives on the range of plasticity of bitumen (the combination of softening temperature and fragility) as shown in Fig. 1, it was found that the additives Doros TS-1, Azol 1007 and DAD-TA2 with a concentration of 0.6–1 % did not pass the tests for the softening temperature of binders, the obtained indicators are at the tolerance limit. It is also important to note that the additives Azol 1007 and Adgezol 3-TD did not affect the fragility temperature. At the same time, all additives with a recommended consumption of 0.3 % (Cecabase RT 945, DAD-TA and Amdor TS-1) showed results close to bitumen in terms of softening temperature, which indicates the absence of a plasticizing effect in bitumen in the operating temperature range. At the same time, bitumen with additives has improved low-temperature characteristics: additives Cecabase RT945 and DAD-TA showed an improvement of up to 16 %.

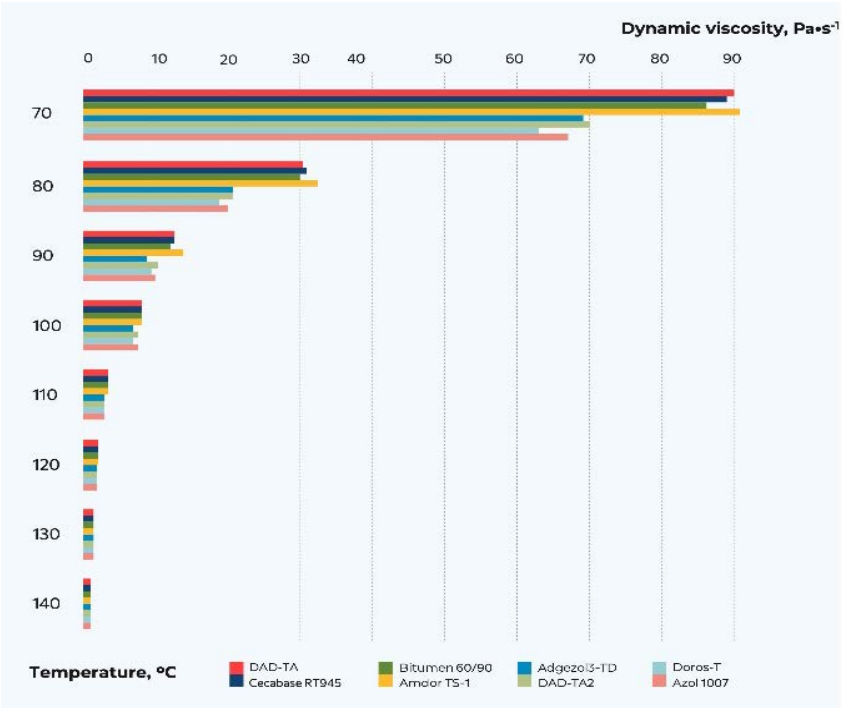

Figure 2. Dynamic viscosity of bitumen with additives (surfactants) at a shear rate of 100 s^{-1}.

Analysis of the results of the dynamic viscosity of modified bitumen (Fig. 2) shows that Adgezol 3-TD, DAD-TA2, Doros-T and Azol 1007 reduce the viscosity of bitumen by up to 30 % over the entire measured temperature range (T = 70–140 °C), which correlates with the data on the softening temperature (Fig. 1), and will have a negative impact on the deformative parameters of asphalt concrete prepared with their use. The additives DAD-TA, Cecabase RT 945 and Amdor TS-1 do not significantly affect the initial viscosity of bitumen, while maintaining the processability of the binder in the entire temperature range during the preparation of asphalt concrete mixture and, in accordance with Table 1, during its compaction.

To determine the generalized criterion of technical and economic efficiency (F_k) of the considered additives for warm asphalt concrete mixtures, the economic efficiency coefficients and operational efficiency coefficients were calculated according to the formula (2). The calculation results are presented in Table 4.

Table 4. Criteria and coefficient of economic and operational efficiency of chemical additives (surfactants).

Name of warm mix additive	Economic efficiency coefficient K_{ec}	Authors' quality criteria						Generalized quality factor K_q
		$k_{compaction}$	$k_{P_{25}}$	k_{P_0}	k_{Tfr}	$k_{T_{softening}}$	k_{η}	
Adgezol 3-TD	0.88	1.69	0.85	1.08	1.00	1.05	0.8	1.04
DAD-TA2	0.93	1.67	0.90	1.17	1.05	1.06	0.8	1.08
Azol 1007	0.93	1.69	0.79	1.17	1.00	1.06	0.8	1.04
Cecabase RT 945	0.92	2.20	0.90	1.21	1.16	0.98	1.0	1.19
DAD-TA	0.94	2.08	0.92	1.17	1.16	0.98	1.1	1.19
Doros-T	0.92	1.59	0.86	1.17	1.00	0.94	0.7	1.02
Amdor TS-1	0.94	1.77	0.96	1.17	1.11	0.98	0.7	1.08

The K_{ec} coefficient shows how much the cost of bitumen increased when a chemical additive was introduced into it taking into account its consumption. The K_q coefficient shows the contribution of the chemical additive to improving the complex of physical, mechanical and technological properties of bitumen and asphalt concrete mixture.

Based on the results obtained by calculating the coefficients of economic and operational efficiency (Table 4), a generalized criterion for the technical and economic efficiency of the use of the chemical additives in question was calculated (Fig. 3).

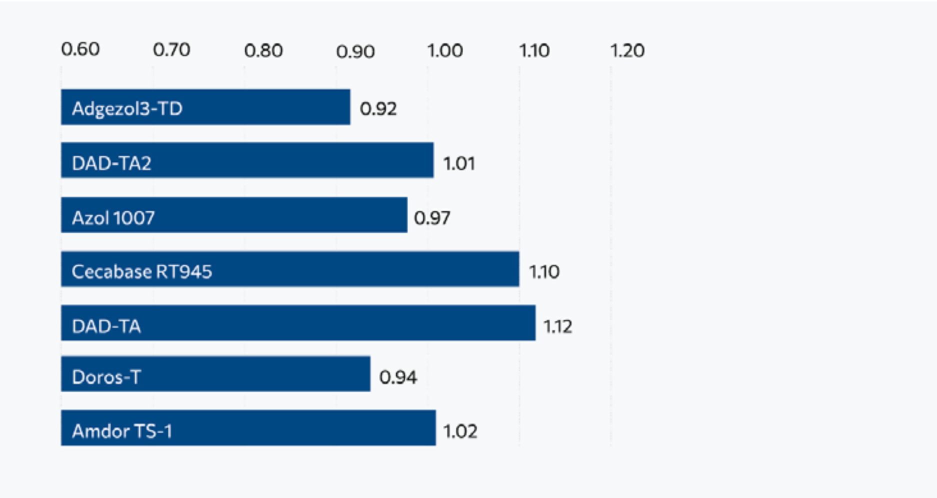

Figure 3. Generalized criterion of technical and economic efficiency of the use of chemical additives (surfactants), F_k.

The analysis of the values of the criterion for the rationality of the use of chemical additives (Fig. 3) allows us to suggest the division of the additives into two groups: additives that improve the efficiency of bitumen by 5 % (F_k ≥ 1.05) or more, as well as additives that do not improve the efficiency of bitumen by more than 5 % (F_k ≤ 1.05), that is, do not significantly change the properties.

To determine the effect of additives (surfactants) in the composition of bitumen on the properties of asphalt concrete, additives from two different groups of effectiveness were selected: DAD-TA and Cecabase RT945 from the first group, Azol 1007 and Adgezol 3-TD from the second group. The obtained results of the properties are presented in Table 5.

Table 5. Physical and mechanical properties of asphalt concrete type B compacted at a temperature of 110 °C.

Indicator name	Requirement of Russian State Standard GOST 9128-2013	Actual indicators of asphalt concrete prepared with the use of				
		without	DAD-TA	Cecabase RT945	Azol 1007	Adgezol 3-TD
Average density, g/cm ^{3}	–	2.31	2.38	2.38	2.34	2.33
Water saturation, %	1.5…4.0	3.46	1.68	1.72	2.53	2.55
Compressive strength, MPa at temperature:						
- 20 °C	no less than 2.5	3.18	4.83	4.62	4.28	4.30
- 50 °C	no less than 1.2	1.18	1.75	1.63	1.15	1.15
Water Resistance	no less than 0.9	0.80	0.98	0.97	0.80	0.80
Water resistance under long-term water saturation	no less than 0.85	0.78	0.97	0.95	0.78	0.78

The study of the physical and mechanical properties of asphalt concrete prepared on bitumen modified with additives with a recommended concentration of 0.3 % showed that they do not have a negative effect on its properties. Samples of asphalt concrete compacted at a temperature of 110 °C meet the requirements of Russian State Standard GOST 9128-2013 for traditional hot asphalt concrete mixtures, Table 5.

Asphalt concrete prepared without additives and asphalt concrete prepared using the additives Azol 1007 and Adgezol 3TD, with the recommended concentration of 1 %, is not sufficiently compacted, as evidenced by a lower average density. This naturally contributed to an increase in water saturation and an unsatisfactory value of the water resistance index of the samples <12 % than the State Standard requirements, and the compressive strength at 50 °C < 5 % than the State Standard requirements. This will negatively affect the performance of the road surface made with it. Asphalt concretes prepared using additives DAD-TA and Cecabase RT945 exceed the requirements of State Standard. Thus, the compressive strength at 20 °C is 93 % of the requirements of State Standard, the compressive strength at 50 °C is 45 % of the requirements of State Standard, and the water resistance is 9 % of the requirements of State Standard.

To explain the effect of various surfactant additives on the structure of bitumen, the authors calculated the change in the activation energy required to overcome the potential (kinetic) barrier of the bitumen binder with the studied surfactants (according to formula 4) relative to the bitumen using the Arrhenius equation, Table 6.

Table 6. Effect of additives (surfactants) on the activation energy and the viscosity constant.

Name of warm mix additive	Additive consumption, % by weight of bitumen	The activation energy, U		The viscosity constant, a	
		U/R	$(U/R)/(U/R)_b$	a	a/a_b
Without warm mix additive	–	11736	1.00	$9.39\cdot10^{-14}$	1.00
Adgezol 3-TD	1.0	15272	1.30	$3.14\cdot10^{-18}$	$3.3\cdot10^{-5}$
DAD-TA2	1.0	15452	1.32	$1.89\cdot10^{-18}$	$2.0\cdot10^{-5}$
Azol 1007	1.0	15745	1.34	$7.8\cdot10^{-19}$	$8.3\cdot10^{-6}$
Cecabase RT 945	0.3	12143	1.03	$3.13\cdot10^{-14}$	0.33
DAD-TA	0.3	12146	1.03	$3.08\cdot10^{-14}$	0.33
Doros-T	0.6	16609	1.42	$6.01\cdot10^{-20}$	$6.4\cdot10^{-7}$
Amdor TS-1	0.3	12098	1.03	$3.58\cdot10^{-14}$	0.38

Note: the index "b" indicates bitumen.

The data presented in Table 6 shows that all the additives used make a change in the structure of the bitumen melt. However, the studied additives can be classified into two groups:

1. Additives inducing a slight change in the parameters of the structure of the bitumen melt. For such additives, the potential barrier increases slightly, and after the termination of the structuring factor of the temperature the decrease in viscosity does not exceed 2 times.

2. Additives inducing a significant increase in the activation energy (up to 40 %) and a significant decrease in viscosity after the termination of the influence of temperature (up to 10^{+7} times).

Evaluation of the influence of the structuring factor on the behavior of bitumen modified by the presented additives requires additional research and determination of the dependence of the melt viscosity on the shear rate. By obtaining data that confirms the presented classification of additives and studying the effect of the shear rate on the viscosity of bitumen melts, it is possible to construct a structural model of the effect of additives on the rheological properties of these systems.

4. Conclusion

1. It is found that the additives (surfactants) under consideration can reduce the required number of gyrator revolutions by 38 ... 55 %, to achieve a given density of asphalt concrete at a sample height of 115 mm and a reduced temperature of 110 °C. This allows you to reduce the temperature of production and laying of asphalt concrete mix by 40 °C.

2. It is found that all the studied additives (surfactants) have a plasticizing effect on bitumen, but do not change its grade. It was found that Adgezol 3-TD, DAD-TA2, Doros-T and Azol 1007 reduce the dynamic viscosity of bitumen by up to 30 % over the entire measured temperature range (T = 70–140 °C), which correlates with the data on the softening temperature. DAD-TA, Cecabase RT 945 and Amdor TS-1 additives slightly affect the initial viscosity of bitumen, maintaining the processability of the binder in the entire temperature range during the preparation of asphalt concrete mixture, and also improve the fragility temperature of bitumen by up to 16 %.

3. To determine the complex technical and economic criterion of the effectiveness F_k of the studied additives for warm asphalt concrete mixtures, the following coefficients were developed and proposed: economic efficiency coefficient K_{ec}, which shows how much the cost of the bitumen binder increased when a chemical additive was introduced into it, taking into account its consumption; generalized quality factor K_q, which shows the contribution of the chemical additive to improving the complex of physical, mechanical and technological properties of bitumen and asphalt concrete mixture.

4. Based on the results obtained by calculating the F_k criterion, it is proposed to divide the additives into two groups: the first group includes additives Cecabase RT945, DAD-TA and Amdor TS-1, which improve the efficiency of bitumen by 5 % (F_k ≥ 1.05 and more); the second group includes additives Adgezol 3-TD, DAD-TA2, Azol 1007, Doros-T, which do not improve the efficiency of bitumen by more than 5 % (F_k ≤ 1.05), that is, do not make any significant change in the properties. It is established that the use of additives of the second group in the composition of warm asphalt concrete leads to an increased water saturation value and an unsatisfactory value for water resistance and long-term water resistance of asphalt concrete samples. This is 12 % lower than stated in the requirements of State Standard for the ultimate compressive strength at 50 °C, which is 5 % lower than the values in the requirements of State Standard. The use of additives of the first group in the composition of asphalt concrete compacted at a reduced temperature of 110 °C causes an increase in the compressive strength at 20 °C, the compressive strength at 50 °C, water resistance by 93 %, 45 %, and 9 % of the requirements of State Standard, respectively.

5. It is established that all the additives used make a change in the structure of the bitumen melt. However, the studied additives can be classified into two groups: 1. Additives leading to a slight change in the parameters of the structure of the bitumen melt; the potential barrier increases slightly, and after the termination of the structuring factor of the temperature the decrease in viscosity does not exceed 2 times. 2. Additives leading to a significant increase in the activation energy (up to 40 %) and a significant decrease in viscosity after the termination of the influence of the temperature (up to 10+7 times).

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Received 08.06.2021. Approved after reviewing 05.04.2022. Accepted 05.04.2022.