Comparative assessment of the technological properties of mastic and sulfur-mastic asphalt concrete mixtures

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Abstract. The technological properties of mastic and sulfur-mastic asphalt concrete mixtures have been evaluated. The hypothesis has been confirmed that the compositions of mastic asphalt concrete mixtures with crystallization-coagulation structure have increased fracture resistance. Optimal technological modes of producing and paving are recommended.

1. Introduction
Mastic asphalt is road-building material, a type of asphalt concrete formed after cooling in the road surface of the mastic asphalt concrete mixture.

According to GOST R 54401-2011 “Hot road mastic asphalt concrete. Technical requirements” mixture of mastic asphalt concrete is a moving mixture, with minimal residual porosity, consisting of the mineral part (crush, sand and mineral powder) and viscous oil road bitumen (with polymer or other additives (or without them) as an astringent. The mastic mix is laid at a mixture temperature of at least 190 degrees Celsius without being sealed. Depending on the temperature, size and time of the load application, the mastic asphalt concrete at operating temperatures shows elastic-elastic and viscous-plastic properties [1].

Mastic asphalt concrete differs from traditional asphalt concretes by the increased to 7.5–10 % (by mass) content of bitumen and increased to 20–30 % shares of mineral powder. Thus, the content of asphalt astringent (AA), consisting of mineral powder and bitumen, increases to 28 % and above. The content of the rubble (grains larger than 5 mm) is from 0 to 50 % of the mass, which at this concentration causes the formation of a half-framed and frameless structure of asphalt concrete. The main feature of mastic asphalt concretes is that the strength and deformational properties of the material are determined by the rheological properties of the asphalt astringent substance or its microstructure [2, 3].

2. Setting a problem
In traditional compacted asphalt concretes, the so-called macrostructure (the content and shape of rubble and sand) [2] plays a much larger role in the formation of the physical and mechanical properties of materials. Increased content of AA causes the fluidity of mastic mixtures, which, with the right selection of rational composition, allows you to stack them without sealing.

This explains the main transport and operational properties of the mastic asphalt concrete – waterproofness, high grip with the underlying structural scraps of road clothes (bridge canvas), fatigue
Fracture resistance and the ability to extinguish (damp) oscillations at sign-shifting transport loads in a wide range of frequencies and amplitude of oscillations on road artificial structures throughout the life cycle of the construction layer [4]. The material shows high resistance to corrosion, antibacterial resistance, resistance to anti-ice reagents, is environmentally friendly.

Compared to traditional compacted, the main advantages of mastic asphalt concretes are high water resistance and fatigue durability.

The disadvantages of mastic asphalt concrete include poor resistance to plastic rut formation, the need to use special equipment and equipment in the delivery and laying of the material, low crack resistance in winter when used in it composition of road bitumen of increased viscosity (with a penetration of less than 50). Technological difficulties of laying the mixture if necessary to control the design longitudinal and cross slopes. All this significantly limits the scope of the use of mastic blends.

Wider use of mastic asphalt concretes found in road and bridge construction, on city streets in the tramway zone, on sidewalks.

Mastic mixtures are actively used in pit repair especially in winter, as they do not require a seal during which traditional hot mixtures are quickly cooled.

During the years of the use of mastic asphalt concrete in our country and abroad, numerous attempts have been made to optimize the compositions and properties of the material, however, at the end of the 20th century, principled materials, technological and constructive solutions no one was found [5, 6].

3. Materials and methods

Asphalt concrete and asphalt concrete mixtures, including mastic, are polymineral highly concentrated dispersal systems [7, 8], allowing the use of modern ideas about structural formation using basic positions of physical-chemical mechanics and contact interaction theory in highly concentrated dispersal systems and theoretical prerequisites for the management of these processes in asphalt concretes.

In such systems, in the process of technological reworking, spatial structures arise, the properties of which are largely determined by superficial phenomena at the boundaries of the phase section. The type of these structures is represented in the rice according to [9, 10] in figure 1 and is determined by the type of contact between the particles of the dispersal phases:

- reversible coagulation contacts formed through the thickness-equal layer of liquid dispersion medium;
- irreversibly collapsing true phase contacts or interweaving contacts;
- strong true contacts that are formed as a result of chemical and phase transformations in the process, and after the completion of reactions polymerization of liquid astringent, crystallization, cooling of melts, plastic deformation of dispersed particles, interweaving fibers and bonding them, and other.

In various real-world building composites there are also mixed types of contact structures, for example, coagulation-crystallization. The properties and strength of such dispersal systems are determined by the ratio of these types of contact interactions. Depending on the task at which the technological operations are carried out, as noted above, it is its mobility, which reduces the energy costs when stirring the mastic asphalt concrete mixture, and does not require sealing mechanisms during its styling and sealing. This is achieved by heating up to high technological temperatures and basal macrostructure of a mixture with a high content of asphalt astringent substance (AV).

However, the operational requirements for shifting resistance of asphalt concrete coatings force the use of high viscous road bitumen when designing mastic mixtures, which, as noted, significantly reduce crack resistance in winter. It is not always possible to achieve an optimal balance of these contradictory requirements.

The task of materials has been successfully solved by the addition of a modified sulfur mixture in the composition of the asphalt concrete mixture [11, 12], which has a phase transition temperature in the presence of bitumen in the range of 113–120 °C in the amount of up to 30 %.
As a working hypothesis of the study it is accepted that in the mastic compositions with the addition of sulfur this possibility is realized by the creation of dispersal systems with a mixed micro-contact structure. At the technological stage at high temperatures (above 120 degrees), only coagulation contacts are formed in the mixture, which ensures its mobility. After the completion of all technological operations in the process of structural formation when cooling, part of the contacts due to the phase transition of the sulfur component forms a more complex coagulation-crystallization structure. In the resulting dispersal system, crystallizing contacts at positive summer temperatures provide a shift resistance of the material in a constructive layer, and coagulation – crack resistance in winter.

Figure 1. The main types of contact between solid dispersal phase particles in concentrated dispersal systems (by P.A. Rebinder [9, 13]): 1 – atomic contact; 2 – coagulation contact; 3 – phase contact.

Academician P.A. Rebinder [9, 13] considered the processes of structural formation in dispersal systems. Given there is additiveness of the strength of elementary contacts:

\[ P_m = k_1 \cdot F_c \cdot n^{\frac{2}{3}} = k_2 \cdot F_c \cdot \varphi \cdot S_{sp}^2 = k_3 \cdot F_c \cdot \varphi \cdot d_i^{-2} \]  (1)

where: \( P_m \) – limit the voltage of the shift; \( F_c \) – average grip strength in contact between particles; \( n \) – average number of contacts; \( \varphi \) – relative density of structure; \( S_{sp} \), specific surface of the particles of the dispersal phase of the highly concentrated dispersal system; \( d_i \) – the characteristic size of these particles.

Comparative assessment of the quality of the initial effects on the asphalt concrete mixture and the elementary contacts formed in the asphalt concrete were made by the magnitude of the average grip force in contact between \( F_c \) particles. Professor E.D. Yakhnin proposed to define it by known experimentally defined values of the limit voltage shift \( P_m \) and the geometric parameters of the researched dispersal system [14]:

\[ F_c = P_m \cdot d \cdot \rho \cdot \frac{(V_s - V_m) \cdot (V_{sm} - V_m)}{V_{s0} - V_s} \]  (2)

where \( P_m \) – limit the voltage of the shift; \( d \) – characteristic size of dispersal phase particles; \( \rho \) – dispersal phase density; \( V_s \) – the specific volume, i.e. the volume attributed to the unit of the mass of the structure; \( V_m \) – the specific volume, i.e. the volume attributed to the unit of the mass of the structure; \( V_{s0} \) – critical specific volume of the system, above which the structure is not formed and \( P_m = 0 \) when \( V_s = V_{s0} \), but and \( P_m = 0 \) when \( V_s < V_{s0} \).
Processes of formation of bitumen film on mineral materials began to be studied in the 60s at the Department of Road-Building Materials HADI under the direction of Professor M.I. Volkov. Thus, I.M. Borsch with the help of chromatographic and fluorescent analyses found that as a result of interaction on the surface of mineral particles formed adsorption-salt layers of associated bitumen.

On the basis of these theoretical provisions in his doctoral work and subsequent publications, Professor I.V. Korolev used the concept of “bitumo-intensiveness” that allowed the author to propose a calculated methodology for determining the optimal content of bitumen in bitumomineral materials.

The strength of the dispersal system depends on the average number of contacts between particles \( n \).

![Figure 2](image_url)

**Figure 2.** Change in the number of contacts between globular monodisperse particles depending on their size

The average number of contacts between the particles of the highly concentrated dispersal phase, which make up the asphalt concrete mixture and asphalt concrete with a known approximation can be determined by the nomogram [15] or by empirical dependence (3):

\[
    n = 6.7373 \cdot e^{5.44 \phi} \cdot d_{eq}^{-2}
\]

where: \( \phi \) – relative density, \( d_{eq} \) – characteristic particle size.

The value of the characteristic particle size \( d_i \) is statistical in nature and depends on the quantitative ratio of particles by fractions of each material, shape and size ratios. Его можно определить по формуле (4):

\[
    d_i = \frac{\sum_{j=1}^{n} (k_f \cdot k_d \cdot a_j)}{100}
\]

where \( a_i \) – private remnants of i-faction particles, \( k_f \) – particle shape ratio, \( k_d \) – particle density ratio, \( d_i \) – fractional particle size.

To quantify the nature of bitumen interaction with the mineral surface, a medium-strength index of the grip in contact between particles can be used. According to the dependence of E.D. Yahnin (2) on
experimentally defined values of the limit voltage of the shift \( P_m \) and the geometric parameters of the researched dispersal system (characteristic size of particles of the dispersal phase \( d \), density of the dispersal phase \( \rho \), specific volume \( V_s \), volume adjustment \( V_m \) and critical unit of the dispersal system \( V_{s0} \)) [14].

Figure 3. Nomogram for determining the average number of contacts between particles [15]

After the transformations, the formula of E.D. Yahnin [15] takes the form (5). In order to assess the structure and properties of highly concentrated dispersal systems, it is advisable to use the criterion of its relative density in some cases, as it is done in the expression (1.8) proposed by P.A. Rebinder, N.V. Mikhailov and S.Y. Shalyt [17]:

At the same time \( \varphi = \frac{\rho_i}{\rho} \) and \( \varphi = \frac{\rho_{p}}{\rho} \), then
\[
F_c = \frac{P_m \cdot d^2 \cdot \rho' \cdot (1 - \varphi_i) \cdot (1 - \varphi_p)}{\rho_n \cdot (\varphi_i - \varphi_p)}
\]

(5)

where \( \varphi_p \) – relative density of loose asphalt concrete mixture; \( \varphi_i \) – relative density of compacted asphalt concrete mixture, \( P_m, d, \rho' \) same as expressions (1, 2). At the same time \( \varphi_p < \varphi_i < 1.0 \).

At the Department of Road-Building Materials MADI developed a method of calculating the optimal content of bitumen, which allowed to determine the bitumointensity of particles measuring 1 – 71 microns for various mineral materials based on results obtained experimentally [6].

The initial information used the values of bitumomy, experimentally obtained by I.V. Korolev and A.M. Gridchin by using statistical methods of mathematical forecasting.

The physical and chemical processes at the border of the phase section of the high-concentrated dispersal system will depend on the area of contact interaction.

The total surface of all the elementary contacts of the highly concentrated dispersal system after the transformations was according to the formula of P.A. Rebinder, N.V. Mikhailov and S.Y. Shalyt (1) [17]:

\[
\sum_{i}^{m} S_i = \frac{1}{k_1} \sum_{d_{\text{max}}}^{d} \frac{1}{k_1}
\]

(6)

where \( n \) – average number of contact between particles per unit of volume, \( k_1 \) – size factor.

\[
k_1 = \left( \frac{P_m}{F_c} \right) \cdot n^{2/3}
\]

(7)

After that, the average area of a single (elementary) contact was defined as:

\[
S_i = \frac{d_{\text{max}}}{n} \sum_{d_{\text{max}}}^{d} \frac{1}{k_1} = \left( \frac{F_c}{P_m} \right) \cdot n^{-1/3}
\]

(8)

Assuming that single contacts are shaped like a circle, you can estimate their average size:

\[
\delta_i = \sqrt{\frac{4 \cdot S_i}{\pi}} = 2 \cdot \sqrt{\frac{S_i}{\pi}}
\]

(9)

An equally important characteristic of the structure of asphalt concrete is the magnitude of the average strength \( P_i \) of a single contact. It can be defined by the formula (10):

\[
P_i = \frac{F_c}{S_i} = \frac{P_m}{n^{1/3}}
\]

(10)

4. Discussion of the results

The structural and mechanical characteristics of asphalt-concrete mixtures and asphalt concrete, considered above, allowed to develop a calculated-experimental method of assessing the structural and mechanical properties of the compositional material and its structure on the different technological stages of its production and in the course of operation, including physically sound quantitative criteria of the structure and properties of the mastic asphalt concrete mixture and mastic asphalt concrete as polydisperpolysper polymineral compositional material. This makes it possible to regulate the technological parameters of mixtures in a direction, as well as to more reliably predict the behavior of the material at real operational impacts.

In the laboratory of MADI we tested compositions of mastic asphalt concrete mixtures with the addition of different amounts of sulfur.
The composition of the mineral part of the asphalt concrete mixtures fully complies with the requirements of GOST 544401. Four series of samples with modified sulphur have been tested (table 1).

| Table 1. The mastic of asphalt concrete mixture type I |
|---------------------------------------------|
| Series No | Rubble | Sand | Mineral powder | Bitumen | Modified sulfur |
|-----------|--------|------|----------------|---------|----------------|
| 1         | 40.0   | 35.0 | 25.0           | 7.79    | 0              |
| 2         | 40.0   | 35.0 | 25.0           | 7.79    | 10             |
| 3         | 40.0   | 35.0 | 25.0           | 7.79    | 20             |
| 4         | 40.0   | 35.0 | 25.0           | 7.79    | 30             |

In table 2 the results of the definition of rationed indicators of physical and mechanical properties for GOST 54401 series 1 and 3 are given.

| Table 2. Effect of temperature on standard mechanical properties mastic mixes series 1 and 3 |
|-----------------------------------------------------------------------------------------------|
| A view of mastic asphalt concrete                                                                 |
| The strength limit when compressed at temperature, °C                                           |
| The strength limit when shifting 50 °C                                                          |
| Coefficients of heat resistance, %                                                              |
| Traditional                                                                                     |
| 7,39                                                                                           |
| 2,74                                                                                           |
| 0,71                                                                                           |
| 0,95                                                                                           |
| Sulfur asphalt concrete                                                                         |
| 9,30                                                                                           |
| 4,30                                                                                           |
| 3,75                                                                                           |
| 3,45                                                                                           |
| Traditional                                                                                     |
| 2,70                                                                                           |
| 1,00                                                                                           |
| 0,26                                                                                           |
| Sulfur asphalt concrete                                                                         |
| 2,16                                                                                           |
| 1,00                                                                                           |
| 0,92                                                                                           |

The results show that the mastic asphalt concrete mixture of series 3 with 20 % sulphur content has significantly higher rates and noticeably lower temperature sensitivity compared to the composition of series 1 on pure bitumen BND 60/90.

It should be noted that at a temperature of 50 degrees Celsius, this composition has 3.63 times higher values of the maximum voltage of the shift.

Figure 4. Dependence of the strength limit when compressing mastic asphalt concrete mixtures on temperature

\[
y = 7,9164e^{-0.017x} \\
R^2 = 0.7715
\]

\[
y = 7,2312e^{-0.047x} \\
R^2 = 0.9993
\]
Using correlation allotment analysis, the correlations shown in Figure 4 of the correlations of the strength limit change at temperature compression were determined, on the basis of which a mathematical prediction of the change of this indicator as an area was made, low operating and high technological temperatures.

According to the method [6], they were identified and presented in table 3 values of the maximum voltage shift in a wide range of operational and technological temperatures.

**Table 3. Change in the estimated values of the maximum voltage shift depending on temperature, MP**

| Temperature °C | °K | Bitumen/sulfur ratios 100/0 | 90/10 | Technological criteria |
|----------------|----|-----------------------------|-------|-----------------------|
| -20            | 253| 22.18                       | 10.23 |                       |
| 0              | 273| 8.71                        | 7.27  |                       |
| 20             | 293| 3.42                        | 5.16  |                       |
| 50             | 323| 0.84                        | 3.09  |                       |
| 80             | 353| 0.21                        | 1.85  |                       |
| 100            | 373| 0.0817                      | 1.31  |                       |
| 119            | 392| 0.0336                      | 0.95  | Sulphur crystallization |
| 121            | 394| 0.0306                      | 0.92  |                      |
| 140            | 413| 0.0126                      | 0.66  | Producing the serous mixture |
| 160            | 433| 0.0050                      | 0.47  |                      |
| 180            | 453| 0.0019                      | 0.33  | Pawing a traditional mastic mix |
| 200            | 473| 0.0008                      | 0.24  |                      |

**Figure 5. Changing the technological properties of mastic blends when stirring**
Table 4. Change in the estimated values of the maximum voltage shift depending on temperature, MPa

| Temperature °C | °K | Bitumen/sulfur ratios 100/0 | 80/20 | Technological criteria |
|---------------|----|-----------------------------|-------|------------------------|
| -20           | 253| 22.18                       | 10.23 |
| 0             | 273| 8.71                        | 7.27  |
| 20            | 293| 3.42                        | 5.16  |
| 50            | 323| 0.84                        | 3.09  |
| 80            | 353| 0.21                        | 1.85  |
| 100           | 373| 0.0817                      | 1.31  |
| 115           | 388| 0.0405                      | 1.02  |
| 117           | 390| 0.0369                      | 0.98  |
| 140           | 413| 0.0126                      | 0.66  |
| 160           | 433| 0.0050                      | 0.47  |
| 180           | 453| 0.0019                      | 0.33  |
| 200           | 473| 0.0008                      | 0.24  |

Sulphur crystallization

Producing the serous mixture

Pawing a traditional mastic mix

Figure 6. Changing the technological properties of mastic blends when stirring

Table 5. Change in the estimated values of the maximum voltage shift depending on temperature, MPa

| Temperature °C | °K | Bitumen/sulfur ratios 100/0 | 70/30 | Technological criteria |
|---------------|----|-----------------------------|-------|------------------------|
| -20           | 253| 22.18                       | 10.23 |
| 0             | 273| 8.71                        | 7.27  |
| 20            | 293| 3.42                        | 5.16  |
| 50            | 323| 0.84                        | 3.09  |
| 80            | 353| 0.21                        | 1.85  |
| 100           | 373| 0.0817                      | 1.31  |
5. Conclusion
Analysis of the presented results allows us to formulate the following conclusions:

- The hypothesis has been confirmed that the compositions of mastic asphalt concrete mixtures with crystallization-coagulation structure have increased resintorence and fracture resistance, which allows them to compete successfully with traditional asphalt concrete compacted mixtures with significant technological advantages.
- The mixing and laying of serolytic asphalt concrete mixtures can be made at much lower (about 40–50 degrees) technological temperatures, while sneering lye do not lose their ability to do.
- When designing mastic asphalt concretes, it is necessary to take into account the basic provisions of physical and chemical mechanics, which allows to regulate their structure and properties in order to obtain the required indicators of technological and exploitation characteristics.

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