Studying fatigue life of macadam and mastic asphalt concrete with various binders

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Abstract. The article shows the results of fatigue life tests of macadam and mastic asphalt concrete made with use of a bituminous binder of various PG marks. The optimal compositions of the samples of macadam and mastic asphalt concrete characterized by close residual porosity to exclude its effect on the physical and mechanical properties and indicators of fatigue life are selected. A Cooper CRT-SA4PT-BB-16 testing machine was used to evaluate the fatigue life of macadam and mastic asphalt concrete, testing beam specimens for four-point bending. The following test protocol was used in the work: a loading frequency of 10 Hz, a test temperature of +20 °C, a decrease in the rigidity of the samples to 50% of the initial value and the number of cycles was recorded. Based on the analysis of the obtained dependences: strength indicators, mixture stiffness and fatigue life, it is shown that there is no linear relationship between the mark of bitumen binder and the fatigue life of a road composite made on its basis, therefore, focus on PG mark of bitumen to design the composites of durable asphalt concrete with predetermined properties is not enough.

Key words: bituminous binder, macadam and mastic asphalt concrete, fatigue life, four-point bending.

1 Introduction

Modern trends in the design of asphalt concrete are based on increasing the accuracy of predicting the durability of materials in road surfaces depending on specific operating conditions. The more accurately the working conditions of the asphalt concrete in the pavement are taken into account, the more reliable the asphalt concrete can be designed.

The existing traffic intensity and an increase in axial loads significantly affect the road surface and the structure as a whole which in turn leads to various defects including those associated with a decrease in the fatigue life of asphalt concrete in the pavement.

Repeating traffic loads cause damage to the asphalt layers, which leads to their fatigue cracking [1]. Therefore, the fatigue of asphalt concrete can be considered as the accumulation of damage under repeating loads.

The fatigue life of an asphalt pavement depends on many factors:
- pavement structures (thin pavements or pavements that do not have strong underlays will be affected to fatigue cracking to a greater extent);
- transport and axial loads;
- age of the pavement and materials used in its construction, etc.

The bending fatigue test allows us to evaluate the durability of asphalt concrete pavements at various operating temperatures under conditions of repeating transport load [2]. In laboratory
conditions, these characteristics of asphalt concrete are determined by cyclic loading of a bent beam. Two loading modes are used: controlled stress and controlled deformation. Controlled deformation is the most commonly used mode.

The result of laboratory fatigue tests is recorded as the number of load cycles before failure depending on the initial tensile strain. Typically, the data are presented as fatigue curves and the period of stress relieving is called unloading or “relaxation”.

It is known [3-9] that asphalt concrete is restored after a loading cycle as a result of stress relaxation. It is obvious that the dynamics of the processes of asphalt concrete relaxation will significantly depend on the bitumen binder used in its composition.

Over the past four decades, various researchers have studied the importance of relaxation time between load applications during fatigue testing of asphalt pavements. Various results are presented in the literature [10-16], demonstrating a diverse opinion on the influence of the relaxation period. Some researchers believe that the rest period leads only to a temporary restoration of the dynamic module, without increasing the fatigue life of asphalt concrete [14], while others [15, 16] found that the restoration of the dynamic module of the composite increased its fatigue life. These various findings were based on a large selection of asphalt mixtures, laboratory tests and research approaches [17-22].

At present, with the introduction of PG bitumen binders classification taking into account the real temperature working range of the material in the coating there is reason to believe that this will become an effective tool in the struggle to increase the fatigue life of asphalt concrete [23-24].

Thus, the aim of the research was to study the effect of bitumen binders on the fatigue life of macadam and mastic asphalt concrete.

2 Materials and methods

2.1 Objects and methods

Currently, asphalt concrete fatigue testing facilities differ in the following ways:

- industrial or individual manufacture;
- pneumatic or hydraulic;
- frequency range 0-10 Hz or 0 - 60 Hz;
- by the method of fixing the beam;
- methods for determining beam deflections;
- method of data processing.

In this work, we used the Cooper Technology installation – Cooper CRT-SA4PT-BB-16 for testing for 4-point bending. The main advantage of the Cooper installation is the number of data points output per cycle, including 200 points, regardless of the load frequency. Moreover, if the number of cycles is less than 100, then the results for each cycle are displayed. Between the 100th and 1000th cycles results are generated for each 100th cycle with the number of cycles over 1000, respectively, for each 1000th cycle. Sequential data sampling is used for processing the results.

Bending fatigue tests are performed for asphalt concrete beams with repeating four-point load with a set level of deformation. The beam is held in place by four clamps during the test. A repeating (sinusoidal) load is applied to the two inner clamps. The load frequency usually varies from 1 to 10 Hz, creating a constant bending moment in the middle of the beam. Deflections caused by the load are measured in the center of the sample. The number of load cycles before the destruction of the beam allows you to evaluate the fatigue life of a particular asphalt concrete mixture.

The decision to terminate the test depends on the mode and purpose of the test. The study used the protocol in the constant deformation mode, the limiting state of the sample was determined as the point at which the stiffness reached a predetermined value of 50% of the initial reading.

The beams made of asphalt concrete mixture with dimensions of 380×50×63 mm were placed in a 4-point testing machine and subjected to load during the experiment. The test time depended on the strain level selected for the experiment.
The object of the research was macadam and mastic asphalt concrete MMAC-20. Compaction of the asphalt mix was carried out by sector compactor INFRATEST 20-4031.

Macadam from an igneous rock – gabbro-diabase was used as a mineral aggregate. Physical and mechanical characteristics of macadam are presented in table 1.

Table 1. Physical and mechanical characteristics of macadam.

| Characteristic name                                      | Units | Requirements GOST 8267-93, GOST 31015-2002, GOST 9128-2013 | Factual data |
|---------------------------------------------------------|-------|---------------------------------------------------------------|--------------|
| Content of dust and clay particles                       | %     | Not more than 1.0                                            | 1.0          |
| Clay content in lumps                                    | %     | Not more than 0.25                                           | 0.0          |
| Content of lamellar (flaky) and needle-shaped grains     | %     | Not more than 10                                             | 5.40         |
| True density                                            | kg/m³ | Not standardized                                             | 3.01         |
| Mass loss after crushing test                           | %     | Not more than 16                                             | 2            |
| Crushability mark                                       |       | Not less than 1200                                           | 1400         |
| Mass loss after abrasion test                           | %     | Not more than 25                                             | 5.25         |
| Abrasion mark                                           |       | I1                                                            | I1           |

For the manufacture of samples of macadam and mastic asphalt concrete, bituminous binders marked by PG were used. The properties of binders are presented in table 2.

Table 2. Properties of PG binders.

| PG binder     | Dynamic viscosity, Pa·s | Integrated shear modulus before aging, MPa | Mass change, % | Comprehensive shear modulus after aging at RTFOT°C | Rigidity on a bending beam rheometer (BBR) | BBR rigidity | Integrated shear modulus after aging at RTFOT°C |
|---------------|-------------------------|---------------------------------------------|----------------|-----------------------------------------------------|-------------------------------------------|--------------|-------------------------------------------------|
|               | 135°C | 165°C | % | 12°C | 18°C | rigidity | creep | rigidity | creep | rigidity | creep | rigidity | creep |
| 58-28 (1)      | 0.389 | 0.106 | 65.1 | 0.38 | - | - | 166.45 | 0.304 | 1.02 | 0.82 |
| 58-28 (2)      | 0.410 | 0.113 | 66.2 | 0.35 | - | - | 166.94 | 0.306 | 1.03 | 0.82 |
| 76-28 (3)      | 1.817 | 0.474 | 80.5 | 0.26 | 78.6 | - | - | 124.63 | 0.323 | 1.21 | 1.03 |
| 76-28 (4)      | 1.866 | 0.423 | 81.2 | 0.30 | 80.4 | - | - | 125.49 | 0.327 | 1.21 | 1.06 |
| 70-28 (5)      | 1.653 | 0.391 | 77.1 | 0.81 | 73.1 | - | - | 116.85 | 0.302 | 1.01 | 0.96 |
| 70-22 (6)      | 2.798 | 0.878 | 86.8 | 0.24 | 71.4 | 148.18 | 0.339 | 133.50 | 0.289 | 0.95 | 0.94 |
| 76-34 (7)      | 1.96  | 0.467 | 108.0 | - | - | - | - | 1.12 |
The selected granulometric composition of the macadam and mastic asphalt concrete mixture is shown in figure 1.

![Grain composition of MMAC-20.](image)

Figure 1. Grain composition of MMAC-20.

From the rationally selected ratio of mineral materials and bituminous binders, cylinder samples were prepared to evaluate the physical and mechanical parameters of macadam and mastic asphalt concrete. Also, beam samples 50×63×380 mm in size were prepared for fatigue resistance to bending by sawing. After sawing, the samples were dried at room temperature to constant weight, then thermostated for 2 hours before loading at the indicated temperature. Then they were loaded until the stiffness decreased to 50% of the initial value. The loading frequency was 10 Hz, the test temperature + 20 °C.

3 Results and discussions
Fatigue cracking is the result of repeating loads caused by rolling stock often with an increased axle load combined with the thermal effect on the asphalt pavement of roads. Very often the moment when the fatigue failure of the pavement becomes apparent corresponds to the end of its service life. The physical meaning of fatigue cracking in asphalt concrete layers is based on the bending of the paving slab. In this case, maximum tensile strains are observed in the lower layer of asphalt concrete, while the upper parts undergo compressive strains. The crack appears in the lower part of the plate, propagating upward with continued loading due to the non-uniformity of deformations.

The intensity of the accumulation of fatigue deformations on the road surface can occur due to various reasons, including flaws in the granular composition of asphalt concrete mixtures, their low water resistance and the tendency to aging of both bituminous binders in the composition of the mixtures and the mixtures themselves. An important role in the occurrence of such destructive processes is played by the quality of the support of the asphalt concrete slab on the underlying layers [25].

Cylinder samples were prepared and their physical and mechanical properties were studied in order to exclude the estimation of the contribution of the bitumen binder to the fatigue life of the macadam and mastic asphalt concrete mixture and the lack of strength indicators. The results are presented in table 3.

Obviously, the indicators of the porosity of the mineral part and the residual porosity of the samples of macadam and mastic asphalt concrete contribute significantly to the properties of the composite. In this regard, when selecting the composition of the samples the variability of the residual porosity was leveled out by the content of bitumen. Based on the data presented all samples comply with the requirements of regulatory documentation.
Table 3. The influence of a bitumen binder on the physical and mechanical parameters of macadam and mastic asphalt concrete.

| Parameter name                           | Requirements GOST 31015 | Bituminous binder |
|------------------------------------------|-------------------------|-------------------|
|                                          | PG 58-28 (1)            | PG 58-28 (2)      |
|                                          | PG 76-28 (3)            | PG 76-28 (4)      |
|                                          | PG 70-28 (5)            | PG 70-22 (6)      |
|                                          | PG 76-34 (7)            |                   |
| Binder content, % by weight over 100% of the mineral part | -                       | 5.7 5.8 5.8 5.8 5.3 5.3 5.2 |
| Average density, kg / m³                 | -                       | 2380 2370 2380 2370 2380 2385 2370 |
| Mineral part porosity, %                 | 15-19                   | 15.5 16 16 16 15.7 15.7 16 |
| Residual porosity, %                     | 1.5-4.5                 | 2.8 3.0 2.5 2.5 3.3 3.3 2.5 |
| Water saturation, %                      | 1.0-4.0                 | 1.87 2.01 1.90 2.35 2.29 2.97 2.49 |
| Binder drainage, %                       | 0.20, not more than 0.11 | 0.12 0.17 0.14 0.12 0.11 0.14 |
| Compressive strength at 50 °C, MPa       | 0.65 not less than 0.73     | 0.76 1.76 2.0 1.20 1.06 1.78 |
| Tensile strength at compression at 20 °C, MPa | 2.2 not less than 4.25   | 3.25 3.35 4.65 4.5 3.45 3.33 4.7 |
| Crack resistance, MPa, at 0°C            | 2.5-6.0                 | 4.93 4.22 4.05 4.9 3.0 2.80 2.7 |
| Uniaxial Shear Stability: coefficient of internal friction shear adhesion at 50 °C, MPa | 0.93 not less than 0.98 | 0.98 0.92 0.94 0.94 0.94 0.97 |
|                                          | 0.18 not less than 0.21 | 0.22 0.32 0.36 0.49 0.36 0.26 |

At the next stage beam samples were made for testing fatigue life on the basis of the tested mixtures. One of the fundamental indicators in the study of fatigue life is stiffness, which acts as a criterion for predicting cracking and possible rutting. This parameter also serves as an indicator of tension and strain arising in the composite structure under actual (simulated in the laboratory) loading conditions.

The data obtained on the test of samples of MMCA-20 for fatigue life are presented in table 4.

The main purpose of studying the stiffness indicators of asphalt concrete mixtures is to collect information on the properties of materials and the possibility of determining the stress-strain reactions in the structure of road asphalt pavement under the influence of the applied load. It is worth noting that stiffness is not a measure of the strength of a composite. Therefore, as can be seen when comparing the data presented in table 3 and 4 of the macadam and mastic asphalt concrete mixture with a high stiffness value does not necessarily have high strength. It can be assumed that indicators of high stiffness indicate the occurrence of stresses in the samples, which cause low deformation. Macadam and mastic asphalt concrete, the brittle properties of which are evaluated by crack resistance at 0 °C, as can be seen from table 3, the series of specimens (1) and (4) are characterized by the maximum crack resistance index, while the initial stiffness modulus for specimens (1) is maximum in the sample under consideration and is 3141 MPa, while series (4) is intermediate in terms of the initial stiffness modulus and is 1722 MPa. The situation is interesting with the number of loading cycles until the initial stiffness modulus drops by 50%; for the samples under consideration (1) and (4), they amounted to 14.17 and 835 thousand cycles, respectively. Thus, a brittle material may have a high stiffness value but low strength.
Table 4. The results of laboratory tests of fatigue life of MMCA-20.

| Used bitumen binder | Multiple load test results |  |
|--------------------|---------------------------|--|
|                    | Initial stiffness modulus, MPa | The number of loading cycles until the initial stiffness modulus drops by 50%, thousand cycles | The modulus of rigidity at the end of the test, MPa |
| PG 58-28 (1)       | 3200 | 14.8 | 1596 |
|                    | 3009 | 12.4 | 1499 |
|                    | 3214 | 15.3 | 1712 |
| Average value      | 3141 | 14.17 | 1602 |
| PG 58-28 (2)       | 3701 | 11.2 | 1839 |
|                    | 3041 | 9.6  | 1489 |
|                    | 3254 | 10.7 | 1609 |
| Average value      | 3332 | 10.5 | 1646 |
| PG 76-28 (3)       | 1740 | 790  | 870  |
|                    | 1655 | 905  | 825  |
|                    | 1702 | 921  | 849  |
| Average value      | 1699 | 872  | 848  |
| PG 76-28 (4)       | 1693 | 810  | 830  |
|                    | 1681 | 780  | 719  |
|                    | 1793 | 915  | 894  |
| Average value      | 1722 | 835  | 814  |
| PG 70-28 (5)       | 1340 | 800  | 632  |
|                    | 1355 | 730  | 670  |
|                    | 1415 | 690  | 699  |
| Average value      | 1370 | 740  | 647  |
| PG 70-22 (6)       | 1783 | 623  | 890  |
|                    | 2404 | 754  | 1195 |
|                    | 2231 | 634  | 1197 |
| Average value      | 2139 | 670  | 1094 |
| PG 76-34 (7)       | 1910 | 905  | 952  |
|                    | 2140 | 854  | 1060 |
|                    | 1860 | 977  | 928  |
| Average value      | 1970 | 912  | 980  |

It is worth noting that in the considered series of binders, there are samples that are assigned the same PG mark. This is PG 58-28, which corresponds to a series of samples (1) and (2) and PG 76-28 represented by samples (3) and (4), perhaps this is the most interesting sample for analysis, it allows us to conclude that the bitumen binder related to one brand, allows you to get excellent results from each other.

Let us consider more closely the series of samples (1) and (2): characterized by the results on strength indicators, the spread of which lies within the experimental error, they differ by more than 25% (3.67 thousand cycles) from each other. It can be assumed that materials characterized by low stiffness indicators (flexibility) in the long run will be distinguished by the long-term performance of the asphalt concrete slab on the road surface.

At the same time, it is necessary to understand what is the reason for the stiffness of the mixture: compaction of the mixture in the layer (it can be assumed, if it is not a matter of re-compaction of the
mixture, that the resistance of the road surface to fatigue can improve), using the initially “hard” grade of bitumen binder or due to its overheating during production time that initiated the aging process.

It is known that aging of a bitumen binder affects the rigidity of asphalt mixtures and can lead to its excessive rigidity. Obviously, a series of samples characterized by increased stiffness is prone to aging of bitumen binder. In accordance with the current specifications for bitumen binders, evaluation of their tendency to intensive aging occupies key positions. Destructive processes launched in a bitumen binder are a reason for refusing to use it in road asphalt composites [26]. However, the bitumen binders used in the work met the requirements put forward within the framework of the established brand. Thus, to predict the fatigue life of asphalt concrete coatings, knowledge of only the aging rate of a bitumen binder is not enough. Bitumen involved in the technology of preparing a road composite does not age by itself, but as a part of the mixture. Thus, in order to predict an increase in the fatigue life of the composite, the entire mixture must be aged.

Another important factor in assessing the fatigue life of asphalt concrete is the lack of a clear standardization of the studied indicator. The results obtained are of value only in a comparative analysis of samples among themselves, on the basis of which it is assumed which one will be more durable.

4 Conclusion
Based on the studies performed, it can be assumed that there is no linear relationship between the mark of bituminous binder marked according to PG and the fatigue life of a road composite made on its basis. It is necessary to have data not only on the aging dynamics of bitumen binders, but on the entire asphalt composition to predict the increase in the fatigue life of the composite.

It is necessary to continue research in this direction to produce a statistical sample that will allow us to develop an acceptable range of indicators, identifying characteristic dependencies for designing compositions of durable asphalt concrete with predetermined properties.

References
[1] Khafizov E R, Vdovin E A, Fomin A Y, Mavliev L F, Bulanov P E 2017 Modern methods of assessment of operating ability of road asphalt concrete News of the KSUAЕ 1 (39), pp 279-285.
[2] Khafizov E R, Vdovin E A, Ilina O N, Fomin A Y 2016 Researches of physical and mechanical properties macadam asphalt concrete on the basis of the polymer-bitumen binders News of the KSUAЕ 1 (35), pp 211-215.
[3] Rudenskiy A V, Kalashnikova T N 1973 Investigation of asphalt concrete fatigue Works Of GiprodnII 7, pp 3-13.
[4] Aniq Gul M, Irfan M, Sarfraz A, Yasir A, Shahab K 2018 Modelling and characterising the fatigue behaviour of asphaltic concrete mixtures Construction and Building Materials 184, pp 723-732. doi: 10.1016/j.conbuildmat.2018.07.022
[5] Sun Y, Huang B, Chen Ji 2015 A unified procedure for rapidly determining asphalt concrete discrete relaxation and retardation spectra Construction and Building Materials 93, pp 35-48. doi: 10.1016/j.conbuildmat.2015.04.055
[6] Xu G, Wang H 2016 Rotational relaxation times of individual compounds within simulations of molecular asphalt models Computational Materials Science 112(A), pp 161-169.
[7] Wang R, Qi Z, Li R, Yue Li 2020 Investigation of the effect of aging on the thermodynamic parameters and the intrinsic healing capability of graphene oxide modified asphalt binders Construction and Building Materials 230, 116984. doi: 10.1016/j.conbuildmat.2019.116984
[8] Castrea M, Sánchez José A 2008 Estimation of asphalt concrete fatigue curves – A damage theory approach Construction and Building Materials 22(6), pp 1232-1238. doi: 10.1016/j.conbuildmat.2007.01.012
[9] Bhasin A, Palvadi S, Little D N 2011 Influence of aging and temperature on intrinsic healing of asphalt binders Transport. Res. Rec 2207, pp 70-78. doi: 10.3141/2207-10
[10] Perraton D, Benedetto H D, Carter A, Proteau M 2019 Link between different bottom-up
fatigue’s law coefficients of mechanical-empirical pavement design software Construction and Building Materials 216, pp 552-563. doi: 10.1016/j.conbuildmat.2019.04.256

[11] Sousa J B, Pais J C, Prates M, Barros R, Langlois P, Leclerc A-M 1998 Effect of Aggregate Gradation on Fatigue Life of Asphalt Concrete Mixes Transportation Research Record 1630 (1), pp 62-68. doi: 10.3141/1630-08

[12] Zhang Ju, Wangb Yi D, Su Yo 2019 Fatigue damage evolution model of asphalt mixture considering influence of loading frequency Construction and Building Materials 218, pp 712-720.

[13] Mascio P, Moretti L 2019 Implementation of a pavement management system for maintenance and rehabilitation of airport surfaces Case Studies in Construction Materials 11, e00251. doi: 10.1016/j.cscm.2019.e00251

[14] Raithby K D, Sterling A B 1970 The effect of rest periods on the fatigue performance of a hot-rolled asphalt under repeated loading Journal of the Association of Asphalt Paving Technologists 39, pp 134-152.

[15] Botella R, Pérez-Jiménez F E, López-Montero T, Miró R 2020 Cyclic testing setups to highlight the importance of heating and other reversible phenomena on asphalt mixtures International Journal of Fatigue 134, 105514. doi: 10.1016/j.ijfatigue.2020.105514

[16] Baaj H, Mikhailenko P, Almutairi H, Benedetto H 2018 Recovery of asphalt mixture stiffness during fatigue loading rest periods Construction and Building Materials 158, pp 591-600. doi: 10.1016/j.conbuildmat.2017.10.016

[17] Robert Y Liang, Jian Zhou 1997 Prediction of fatigue life of asphalt concrete beam International Journal of Fatigue 19 (2), pp 117-124. doi: 10.1016/S0142-1123(96)00066-7

[18] Ming H, Weidong H 2016 Laboratory investigation on fatigue performance of modified asphalt concretes considering healing Construction and Building Materials 113, pp 68-76. doi: 10.1016/j.conbuildmat.2016.02.083

[19] Luo Z, Xiao F, Hu S, Yang Y 2013 Probabilistic analysis on fatigue life of rubberized asphalt concrete mixtures containing reclaimed asphalt pavement Construction and Building Materials 41, pp 401-410. doi: 10.1016/j.conbuildmat.2012.12.013

[20] Menozzi A, Garcia A, Partl M N, Tebaldi G, Schuetz Ph 2015 Induction healing of fatigue damage in asphalt test samples Construction and Building Materials 74, pp 162-168. doi: 10.1016/j.conbuildmat.2014.10.034

[21] Rodrigues de Mello L G, Muniz de Farias M, Kaloush K E 2018 Using damage theory to analyze fatigue of asphalt mixtures on flexural tests International Journal of Pavement Research and Technology 11 (6), pp 617-626. doi: 10.1016/j.ijprt.2018.02.003

[22] Behnia B, Reis H 2019 Self-healing of thermal cracks in asphalt pavements Construction and Building Materials 218, pp 316-322. doi: 10.1016/j.conbuildmat.2019.05.095

[23] Darabi M K, Abu Al-Rubb R K, Eyad A Masad E A, Little D N 2013 Constitutive modeling of fatigue damage response of asphalt concrete materials with consideration of micro-damage healing International Journal of Solids and Structures 50 (19), pp 2901-2913. doi: 10.1016/j.ijsolstr.2013.05.007

[24] Garciaa A, Saliha S, Gómez-Meijjide B 2020 Optimum moment to heal cracks in asphalt roads by means electromagnetic induction Construction and Building Materials 238, 117627. doi: 10.1016/j.conbuildmat.2019.117627

[25] Mun S, Guddati M, Kim Y R 2004 Fatigue Cracking Mechanisms in Asphalt Pavements with Viscoelastic Continuum Damage Finite-Element Program Journal of Transportation Research Board 1896, pp 96-106. doi: 10.3141/1896-10

[26] Kerboua M, Megnounif A, Benguediab M, Benrahou Kh, Kaoulala F 2014 Bituminous Materials with a High Resistance to Flow Rutting American Journal of Civil Engineering and Architecture 2 (1), pp 1-11. doi: 10.12691/ajcea-2-1-1