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Impact of loading rate on asphalt concrete deformation and failure

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Abstract. The results for experimental determination of characteristics have been given and analyzed in this article for deformation and failure of an asphalt concrete at eleven loading rates from 0.000563 MPa/s to 0.652 MPa/s differing in 1158 times. A hot fine-grained dense asphalt concrete of type B prepared with a viscous bitumen of grade BND 100/130 which is traditionally used in road construction has been selected for the research. The tests have been performed at the temperature of 22–24 °C in a specially invented and assembled device according to the scheme of direct tension. The asphalt concrete samples had a shape of rectangular beam with dimensions 5×5×15 cm. It is found that from the moment of loading to the moment of failure the asphalt concrete is deformed nonlinearly. The rate of nonlinearity is increased with the load increase. Loading rate effects greatly the characteristics of deformation and failure of the asphalt concrete: failure time, specific work of deformation and failure deformation are decreased in 242, 160 and 3 times respectively at the loading rate increase in 1158 (nearly 1200) times from 0.000563 MPa/s to 0.652 MPa/s and the strength is increased in 5 times. Dependences for characteristics of the asphalt concrete failure (failure time, failure deformation, specific work of deformation and strength) on a loading rate are described with a high accuracy by power functions.

1. Introduction

It is known that deformation and strength characteristics of many road materials and soils depend considerably on value and load duration [1–6]. The vehicles of different axle load (up to 13 tons and more) move along modern highways and their speed is varied within a wide range depending on specific road conditions [7–9]: the speed is equal to 0 at stops, at crossings, in front of auto barrier, etc., it can reach 200–220 kph and more at midblocks.

The above provisions show the importance for the study of loading rate impact on deformation and strength properties of road materials including asphalt concretes and soils.

Literature review [1–6, 10–17] shows that such situation emerged in road material science: practically all types of tests for the asphalt concretes are performed at the target strain rates. For example, the compression tests for the cylindrical asphalt concrete samples are preformed at the strain rate of 3 mm/min [15]. The strength of the asphalt concretes at uniaxial tension is determined at the strain rate of 2 mm/min. The fatigue characteristics of the asphalt concretes are performed at harmonic bending deflection variation (deformation amplitude remains constant till failure) [17]. Meanwhile, the above standard strain rates (2 and 3 mm/min) are incomparably higher than in real conditions.

In this work the samples of a conventional hot fine-grained dense asphalt concrete have been tested under the scheme of direct tension to failure at the temperature of 22–24 °C in conditions of loading with a constant rate. The loading rate was varied from 0.000563 MPa/s to 0.652 MPa/s, i.e. in 1158 (nearly 1200) times. Correlation relationships have been established for failure time, failure strain, strength and specific work of failure of the asphalt concrete on the loading rate. “Stress-strain” dependence (deformation diagram) has been constructed and analyzed for the asphalt concrete at different loading rates.

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2. Materials and Methods

In this paper a bitumen of grade 100-130 has been used meeting the requirements of the Kazakhstan standard ST RK 1373-2013 [18]. The bitumen grade on Superpave is PG 64-40 [19]. The bitumen has been produced by the Pavlodar processing plant from a crude oil of Western Siberia (Russia) by the direct oxidation method.

A hot dense asphalt concrete of type B meeting the requirements of the Kazakhstan standard ST RK 1225-2013 [15] was prepared using aggregate fractions of 5–10 mm (20 %), 10–15 mm (13 %), 15–20 mm (10 %) from Novo-Alekseevsk rock pit (Almaty region), sand of fraction 0–5 mm (50 %) from the plant “Asphaltconcrete-1” (Almaty city) and activated mineral powder (7%) from Kordai rock pit (Zhambyl region). Granularmetric curve of the asphalt concrete is shown in Figure 1.

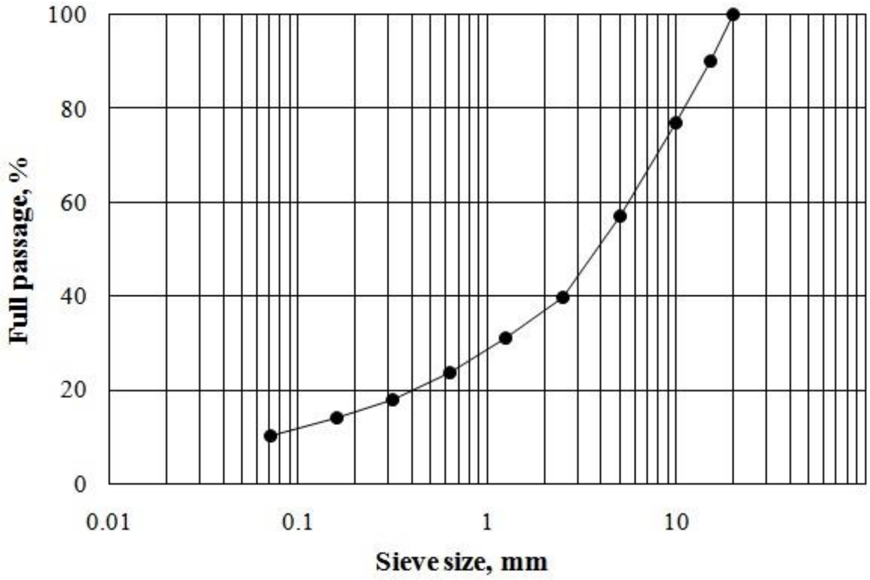

Figure 1. Granularmetric curve of the asphalt concrete.

The bitumen content of grade 100-130 in the asphalt concrete is 4.8 % by weight of the dry mineral material.

Samples of the hot asphalt concrete (Figure 2) were prepared in form of a rectangular prism with length of 150 mm, width of 50 mm and height of 50 mm in two step procedures. The first step, the asphalt concrete samples were prepared in form of a square slab (Figure 3) by means of the Cooper compactor (UK, model CRT-RC2S) (Figure 4) according to the standard EN 12697-33 [20]. The second step, the samples were cut from the asphalt concrete slabs in form of a prism. Deviations in sizes of the samples did not exceed 2 mm.

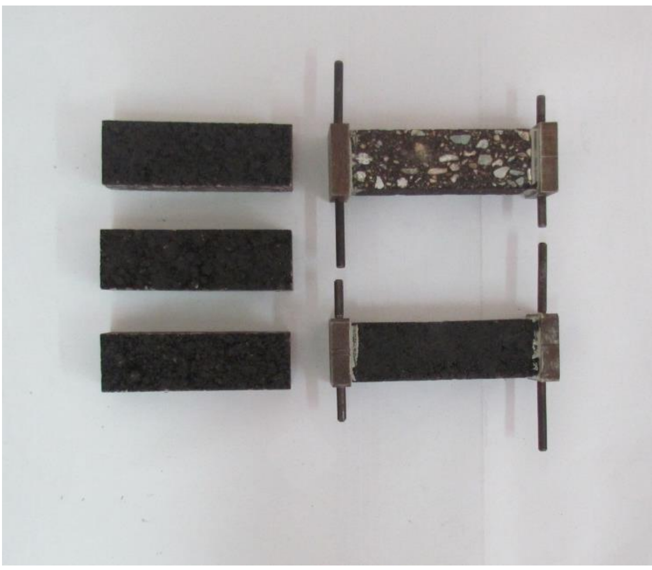

Figure 2. The asphalt concrete samples in the shape of rectangular prism (150×50×50 mm).

Figure 3. The asphalt concrete sample in the shape of square slab (300×300×100mm).

Figure 4. The Cooper compactor.

A detailed information about standard characteristics of the bitumen and the asphalt concrete and about the asphalt concrete samples one can find in the authors' works [21–23] published earlier.

The tests have been performed at the temperature of 22–24°C in a specially invented and assembled device [24, 25] (Figure 5) in Kazakhstan Highway Research Institute according to the scheme of direct tension. Loading rates were equal to (MPa/s): 1 – 0.000563; 2 – 0.001698; 3 – 0.005507; 4 – 0.007244; 5 – 0.015137; 6 – 0.023918; 7 – 0.048869; 8 – 0.058036; 9 – 0.205869; 10 – 0.467757; 11 –0.651864. As it is seen a loading rate is varied within a wide range – 1158 (nearly 1200) times.

Figure 5. The device for determination of mechanical characteristics for materials.

3. Results and Discussions

According to the test results performed under the method described in Section 2 the graphs have been constructed for variation of stress, strain, specific work of deformation in time and the graphs of dependence “stress-strain” at the considered loading rates. By way of illustration the mentioned graphs for five loading rates are shown in Figures (6–9). As it is seen, the strain is varied to a significant degree nonlinearly (Figure 7) at linear variation of stress in time (Figure 6). Nonlinearity of the asphalt concrete strain is increased with the stress increase. It is seen in Figure 8 that it is difficult to distinguish some initial section within the limits of which it could be possible to adopt linear strain and to introduce an elasticity modulus.

As a consequence of nonlinear deformation, the specific work of deformation is also varied in time to a significant degree nonlinearly (Figure 9). Meanwhile, the biggest values of the specific strain energy occur at the moment of failure. We can also note that approximately during the first half of loading at all loading rates the specific strain energy has relatively small values; it has the biggest values in the last quarter of the loading process.

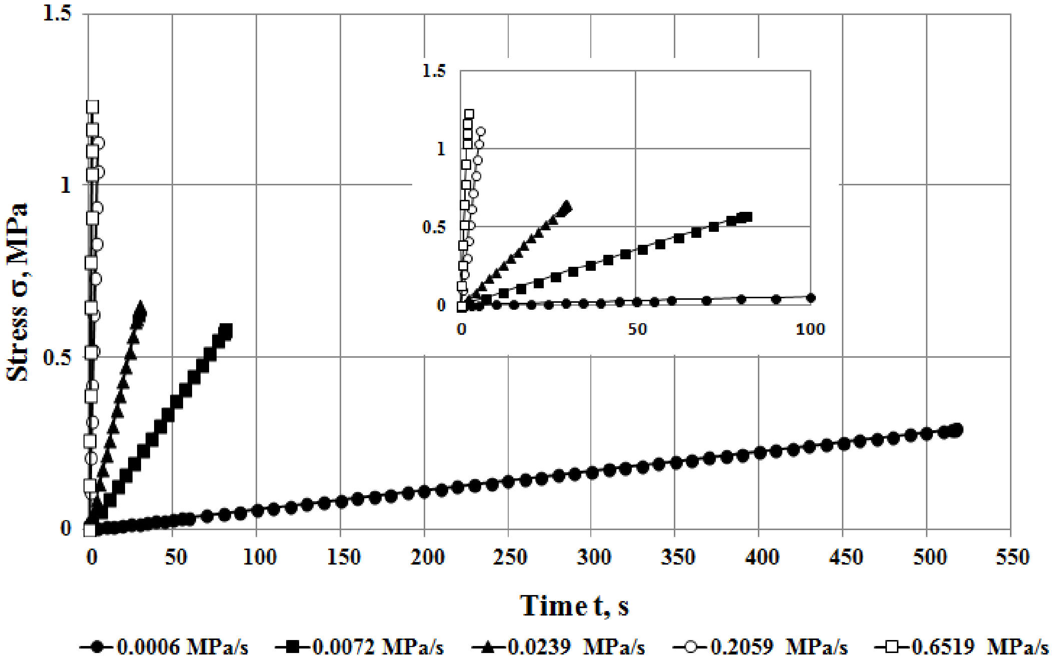

Figure 6. Graphs of stress variation in time at various loading rates.

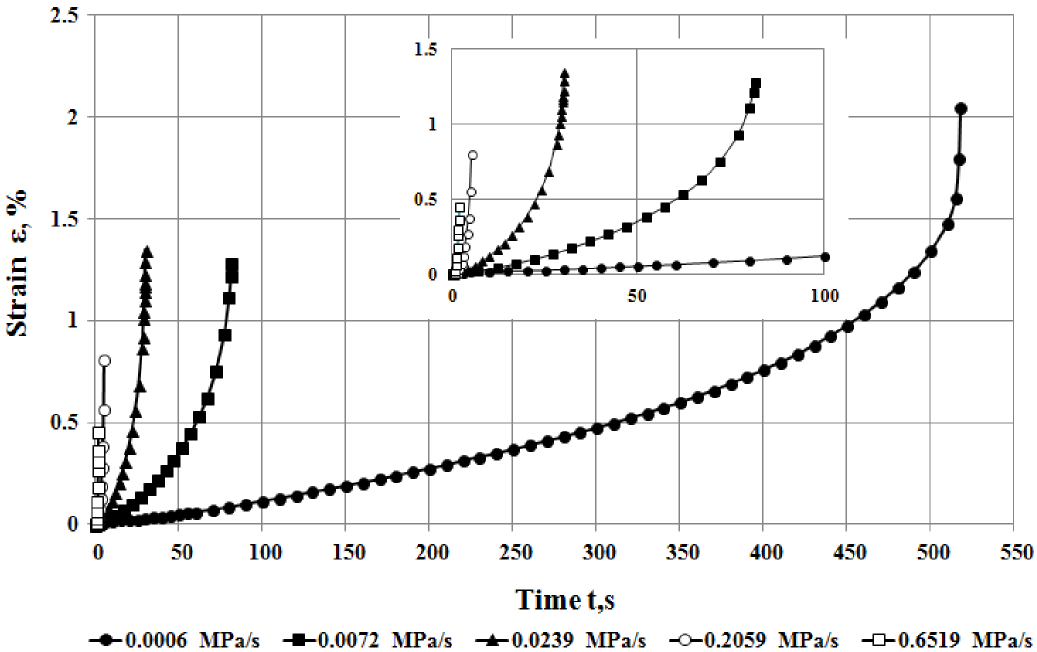

Figure 7. Graphs of strain variation in time at various loading rates.

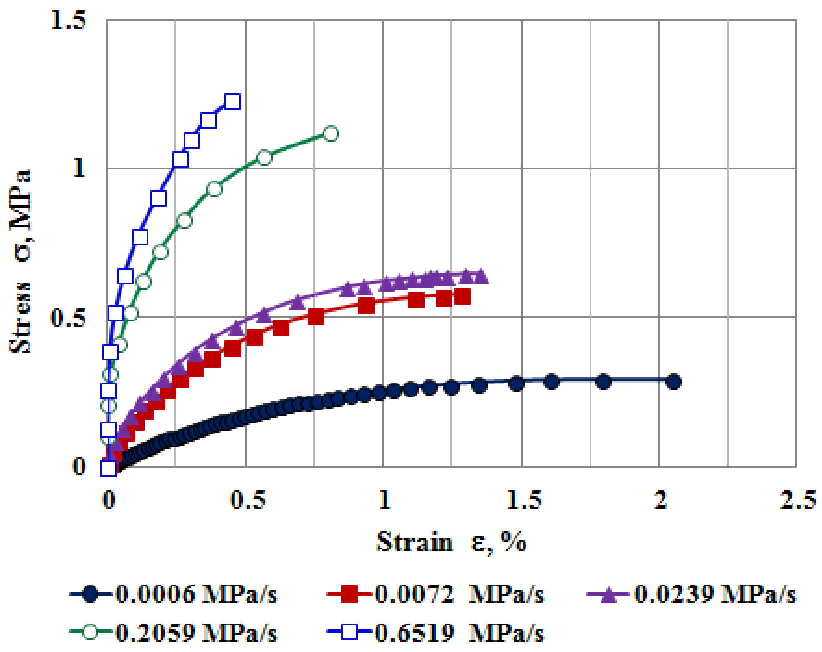

Figure 8. Graphs of "stress-strain" relationship at various loading rates.

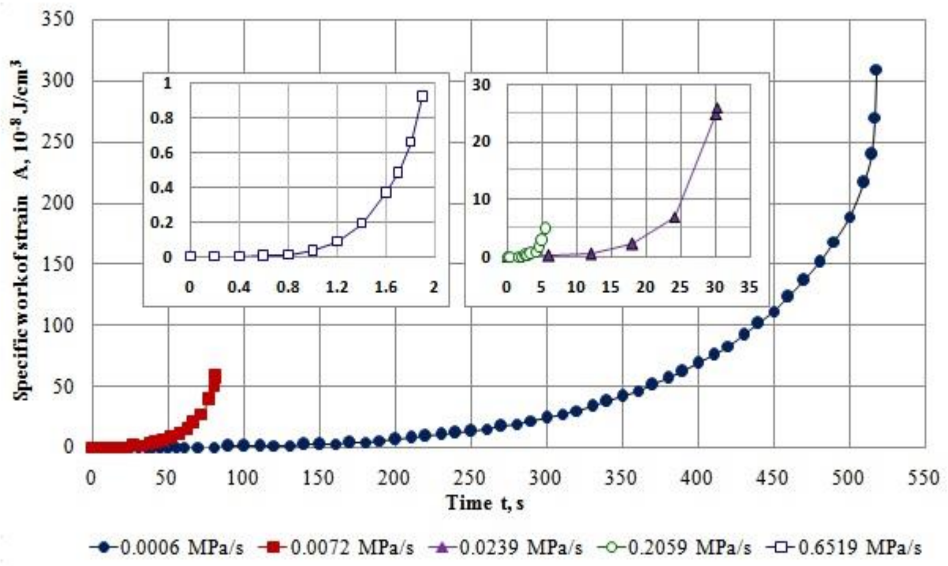

Figure 9. Graphs for variation of specific work of deformation at various loading rates.

Important characteristics of failure are time of failure, strain, stress (strength) and specific work of deformation of the material at the moment of its failure. Dependence of these characteristics for the asphalt concrete on loading rate is represented in Figures 10-13. As it is seen a loading rate impacts greatly on the characteristics of the asphalt concrete. For example, at the loading rate increase in 1158 (nearly 1200) times from 0.000563 MPA/s to 0.652 MPa/s failure time, specific work of deformation and failure strain are decreased in 242,160 and 3 times respectively, and the strength is increased in 5 times.

It is known that depending on specific and traffic conditions the vehicles move with different speeds along the highways (on various road sections). The results of experimental investigations performed in this work show that the characteristics of deformation and failure of an asphalt concrete depend greatly on the loading rate. The above regulations cause the idea that the highways should be divided into sections with the fixed estimated speeds for vehicles and the mechanical characteristics of asphalt concrete layers of a pavement should be defined considering these estimated speeds at designing of pavement structures.

Our previous works [21–23, 26] have determined experimentally that dependences of long-term strength (failure time) and steady-state strain of an asphalt concrete at creep on stress is approximated by a power function with a high accuracy. As it is seen from Figures 10–13 the characteristics of failure for the asphalt concrete are also described by power functions at loading with a constant rate. Meanwhile, as it is expected, failure time of an asphalt concrete is decreased with loading rate increase (with the working stress increase in time).Failure strain and specific work of the asphalt concrete failure are also decreased with the loading rate increase. And the asphalt concrete strength, on the contrary, is increased with the loading rate increase. Failure time and specific work of deformation have been found to be the most sensitive to the loading rate among the considered characteristics of the asphalt concrete failure: these characteristics are varied for 0.77 and 0.70 orders respectively at a loading rate variation for one order. Failure strain has the least sensitivity to the loading rate: power coefficient is equal to n = 0.14. The strength of the asphalt concrete has the intermediate sensitivity: n = 0.23.

The essential influence of the strain rate on characteristics of deformation and failure of asphalt concretes is also determined in the works of other researchers [10–12, 27–30]. Fakhri M. et al. [27] have reported that a strain rate influences greatly on fracture energy of an asphalt concrete at intermediate temperatures (5 °C, 15 °C and 25 °C). Zolotaryov V.A. et al. [10] and Islam M.D.R. et al. [12] have determined that dependence of strength for the asphalt concretes at three-point and four-point bending, compression, tension and initial stiffness at three-point bending on strain rate is satisfactorily described by a power function.

Good correlation relationships have been found in the work [28] between tensile strength of the asphalt concretes and the deformation rate at the temperatures of 10 °C, 0 °C and -20 °C, and they represent the straight lines in the logarithmic coordinates; and the tensile strength of the asphalt concrete does not depend on the deformation rate at the temperature of -20 °C. Similar correlation relationships for a number of “neat” and modified asphalt concretes have been determined in the work [29] as well. The test temperatures are 5 °C, 15 °C, 25 °C and 35 °C, the deformation rate is 50 mm/min. Meanwhile, it is found that the strength of a “neat” asphalt concrete at the temperature of 25 °C is equal to 1.7 MPa; such strength according to our experimental data corresponds to a loading rate of 0.7 MPa/s. The paper [30] determines that the asphalt concretes strength at the deformation rates of 1 mm/min and 50 mm/min and at the temperature of 0 °C is equal to 0.9 MPa and 2.6 MPa respectively, i.e. deformation rate variation in 50 times provides the asphalt concrete strength variation approximately in 3 times.

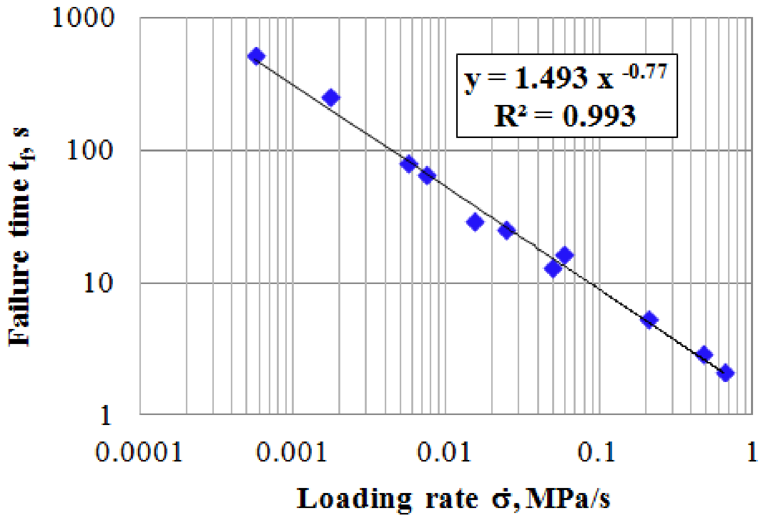

Figure 10. Dependence of failure time of the asphalt concrete on loading rate.

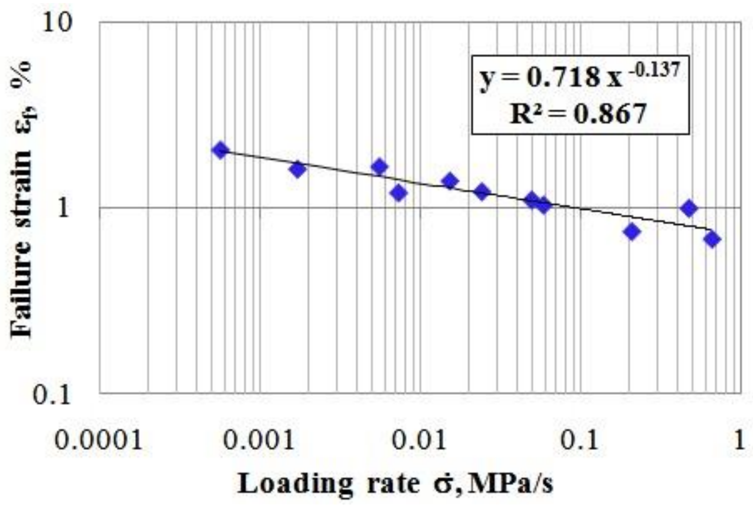

Figure 11. Dependence of strain failure of the asphalt concrete on loading rate.

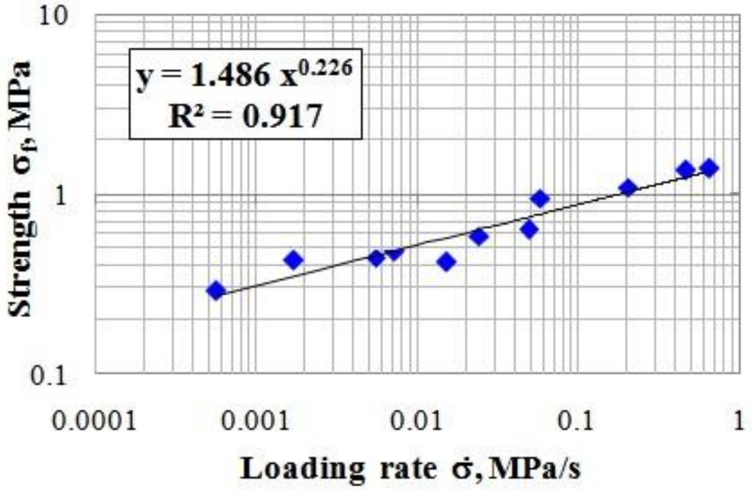

Figure 12. Dependence of the asphalt concrete strength on loading rate.

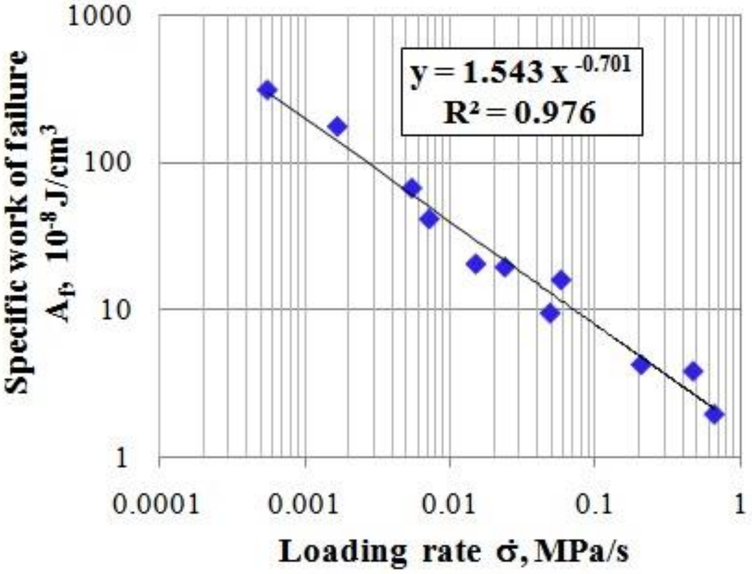

Figure 13. Dependence of specific work for the asphalt concrete failure on loading rate.

4. Conclusions

The results for experimental determining of characteristics of deformation and failure of the asphalt concrete at direct tension at the temperature of 22–24°C at the considered loading rates differing in 1158 times allowed drawing the following conclusions:

1. From the beginning of loading to the moment of failure the asphalt concrete is deformed nonlinearly. The rate of nonlinearity is increased with the load increase. It is difficult to distinguish some initial section on the graph "stress-strain", within the limits of which it could be possible to postulate linear strain and introduce elasticity modulus.

2. The loading rate impacts greatly on the characteristics of deformation and failure of the asphalt concrete: failure time, specific work of deformation and failure strain are decreased in 242, 160 and 3 times respectively at the loading rate increase in 1158 (nearly 1200) times from 0.000563 MPa/s to 0.652 MPa/s, and the strength is increased in 5 times.

3. Dependences of characteristics for the asphalt concrete failure (failure time, failure strain, specific work of failure and strength) on a loading rate are described by power functions with a high accuracy.

4. On the designing stage highways should be divided into sections with the fixed estimated speeds of vehicles and mechanical characteristics of asphalt concrete layers should be defined considering these estimated speeds at designing of pavement structures.

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