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Deformation and strength of asphalt concrete under static and step loadings

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ABSTRACT: Deformation and strength of fine-grained asphalt concrete were investigated under static and step loadings experimentally in the paper. Temperature varied within the range of 20 ± 2°C. The stress varied within the range of 0.055 MPa and 0.311 MPa during creep test. The results of experiments showed that creep curves have three sites within specified ranges of stress—site of unstabilized creep, site of stabilized creep and site of accelerating creep. The long-term strength curve is described successfully by exponential function. The stress affects greatly the long-term strength of asphalt concrete: the increase of stress for single order reduces failure time for four orders. The sequence of impacts also affects greatly the long-term strength of asphalt concrete.

1 INTRODUCTION

Asphalt concrete is one of the main materials for highway pavements. Mechanical properties of an asphalt concrete are highly depending on temperature, value, duration, and rate of loading (MS-4 2008, Papagiannakis & Masad 2008, Yoder & Witczak 1975). In real road conditions temperature in points of asphalt concrete layers of pavement structures due to variations of ambient temperature, track wheels load values, their action duration and rate varies within wide limits. Therefore, determination of mechanical behavior of an asphalt concrete taking into account the variation of the above mentioned factors has important practical value.

It is known that the basic methods for evaluation of mechanical behavior of viscoelastic materials are tests on creep and relaxation (Cristensen 1971, Ferry 1980, Tschoegl 1989). Technically, realization of creep test is easier. It is possible to construct creep curves and long-term strength with using its results. Relaxation curves can be obtained from the creep curves by using known methods (Tschoegl 1989, Hopkins & Hamming 1957). The long-term strength curves enable to determine service life of a road asphalt concrete pavement.

In this paper test results of hot fine-grained asphalt concrete samples on creep are presented. Creep tests were carried out by the direct tensile scheme until complete fracture of the asphalt concrete samples. Test temperature was 20 ± 2°C. The applied stress was changed from 0.055 to 0.311 MPa. Creep curves under different loads and long-term strength curve of the asphalt concrete have been constructed. Three characteristic sites of creep curves—the unstabilized, stabilized and accelerating creep sites are shown.

2 MODELS FOR PREDICTION OF ASPHALT CONCRETE DAMAGE

The vehicles, running along the highways, have different number of axles, the loads on which varies within the wide range. It is natural that the axles with different values of loads cause different damage level for pavement. One of the prediction models for materials and structures damage, considering load impact of different values, is well-known Miner's law (Miner 1945). Miner's law is also known as the principle of linear summation of damages (Talreja & Sing 2012) and found wide application in engineering calculations. For example, in the USA it is used for prediction of fatigue life for asphalt concrete pavement of highways (ARA, ERES 2004). In this regard fatigue damage is calculated under the following equation:

$$D = \sum_{i=1}^{T} \frac{n_i}{N_i} \tag{1}$$

where D = damage; T = total number of periods; n_i = actual traffic period i; and N_i = traffic allowed under conditions prevailing in i.

Vehicles run along the highways with different speed, i.e. they affect the pavement structure with different duration. As under real road conditions the speed of the vehicles varies within the wide ranges, axle load duration differs greatly. Unfortunately, equation (1), based on Miner's law, does not consider load duration, which can be a source of systematic large inaccuracies during determination of fatigue life for asphalt concrete pavement of the highway.

At present, the so-called Bailey's criterion is well-known in science and engineering practice (Bailey 1939), which can be described in the following form:

$$\int_0^{t_p} \frac{dt}{\tau[\sigma(t)]} = 1 \tag{2}$$

where t_p = failure time; $\sigma(t)$ = stress, varied in time; and $\tau[\sigma(t)]$ = dependence of material failure time on stress.

Contrary to Miner's law (1), Bailey's criterion (2) considers load duration, i.e. the speed of the vehicle along the highway. Dependence $\tau[\sigma(t)]$ of Bailey's criterion represents by itself the analytical equation for the so-called curve of long-term strength, which is constructed based on the test results of the material according to the creep scheme (Kachanov 1986, Rabotnov 1987).

3 MATERIALS

3.1 *Bitumen*

In this paper bitumen of grade 100–130 has been used which meets the requirements of the Kazakhstan standard (ST RK 1373 2013). The bitumen grade on Superpave is PG 64–40 (Superpave series No.1 2003). Basic standard indicators of the bitumen are shown in Table 1. Bitumen has been produced by Pavlodar processing plant from crude oil of Western Siberia (Russia) by the direct oxidation method.

3.2 *Asphalt concrete*

Hot dense asphalt concrete of type B that meets the requirements of the Kazakhstan Standard (ST RK 1225 2013) was prepared with use of 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).

Bitumen content of grade 100–130 in the asphalt concrete is 4,8% by weight of dry mineral material. Basic standard indicators of the aggregate and the asphalt concrete are shown in Tables 2 and 3 respectively. Granulometric composition curve for mineral part of the asphalt concrete is shown in Figure 1.

Table 1. Basic standard indicators of the bitumen.

Indicator	Measurement unit	Requirements of ST RK 1373	Value
Penetration, 25°C, 100 gr, 5 s	0.1 mm	101–130	104
Penetration Index PI	–	–1.0… +1.0	–0.34
Tensility at temperature:	cm		
25°C		≥ 90	140
0°C		≥ 4,0	5.7
Softening point	°C	≥ 43	46.0
Fraas point	°C	≤ –22	–25.9
Dynamic viscosity, 60°C	Pa·s	≥ 120	175.0
Kinematic viscosity	mm^2/s	≥ 180	398.0

Table 2. Basic standard indicators of the crushed stone.

Indicator	Measurement unit	Requirements of ST RK 1284	Value	
			fraction 5–10 mm	fraction 10–20 mm
Average density	g/cm^3	–	2.55	2.62
Elongated particle content	%	≤ 25	13	9
Clay particle content	%	≤ 1,0	0.3	0.2
Bitumen adhesion	–	–	satisf.	satisf.
Water absorption	%	–	1.93	0.90

Table 3. Basic standard indicators of the asphalt concrete.

Indicator	Measurement unit	Requirements of ST RK 1225	Value
Average density	g/cm^3	–	2.39
Water saturation	%	1.5–4.0	2.3
Voids in mineral aggregate	%	≤ 19	14
Air void content in asphalt concrete	%	2.5–5.0	3.8
Compression strength at temperature:	MPa		
0°C		≤ 13.0	7.0
20°C			3.4
50°C		≥ 1.3	1.4
Water stability	–	≥ 0.85	0.92
Shear stability	MPa	≥ 0.38	0.39
Crack stability	MPa	4.0–6.5	4.1

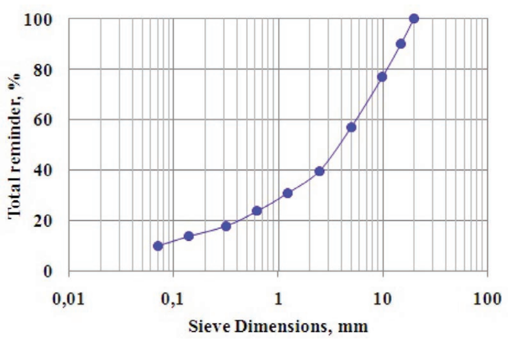

Figure 1. Granulometric curve of mineral part of the asphalt concrete.

4 TEST METHODS

4.1 *Sample preparation*

Samples of the hot asphalt concrete in form of a rectangular prism with length of 150 mm, width of 50 mm and height of 50 mm were manufactured in the following way. Firstly the asphalt concrete samples were prepared in form of a square slab by means of the Cooper compactor (UK, model CRT-RC2S) according to the standard (EN 12697-33 2003). Then the samples were cut from the asphalt concrete slabs in form of a prism. Deviations in sizes of the beams didn't exceed 2 mm.

4.2 *Test*

Tests of hot asphalt concrete samples in a form of rectangular prism on creep were carried out according to the direct tensile scheme until a complete failure. The test temperature was equal to 20 ± 2 °C, stress was changing from 0.055 to 0.311 MPa·s. The tests were carried out in a special assembled installation. The sample strain was measured by means of two clock typed indicators while data was recorded in a video camera.

5 EXPERIMENT

5.1 *Creep curves*

Our previous works (Iskakbayev et al. 2016a, b, Teltayev et al. 2016) showed that an asphalt concrete creep curve as the most of viscoelastic materials has three characteristic sites: the site I of unstabilized creep with decreasing rate, the site II of stabilized creep with constant (minimum) rate and the site III of accelerating creep with increasing rate which precedes failure. The above works show test results of asphalt concrete for creep with relatively narrow ranges of stress variation. This work includes test results for seven values of stress from 0.055 MPa to 0.311 MPa. Practically five samples of asphalt concrete were tested for each value of stress.

Figures 2 and 3 show creep curves for asphalt concrete with stresses 0.055 MPa and 0.260 MPa respectively. It is clearly seen that at small stress (0.055 MPa), as well as at high stress (0.260 MPa) creep curves have all three sites. It is important to remember that since the beginning of loading to the failure moment (t_f) asphalt concrete passes three sites of deformation.

Figure 4 shows creep curves for five samples of asphalt concrete with stress 0.188 MPa. This figure shows well the impact of structural non-homogeneity of asphalt concrete on its deformability and durability: values of long-term strength and also deformation characteristics have static dispersion.

5.2 *Long-term strength*

The dependence of failure time on stress is called long-term strength of a material (Kachanov 1986, Rabotnov 1987). The long-term strength curve of

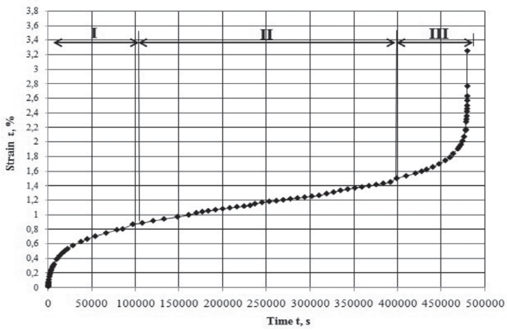

Figure 2. The asphalt concrete creep curve at stress 0,055 MPa.

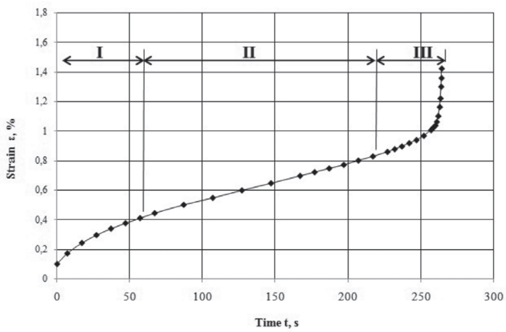

Figure 3. The asphalt concrete creep curve at stress 0,260 MPa.

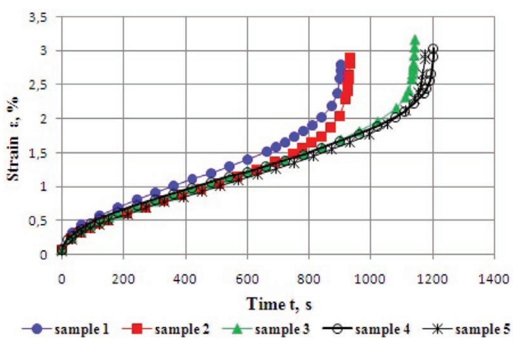

Figure 4. The asphalt concrete creep curves at stress 0,188 MPa.

the asphalt concrete constructed by results of the test on creep is shown in Figure 5. As it can be seen, the long-term strength curve is successfully described by exponential function:

$$t_f = 1,4072\ \sigma^{-4,063} \tag{3}$$

T_f – failure time, s; and σ = stress, MPa.

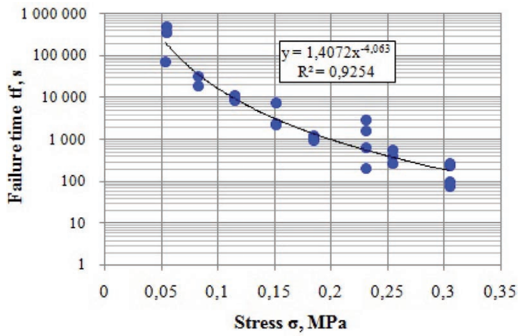

Figure 5. The long-term strength curve of the asphalt concrete.

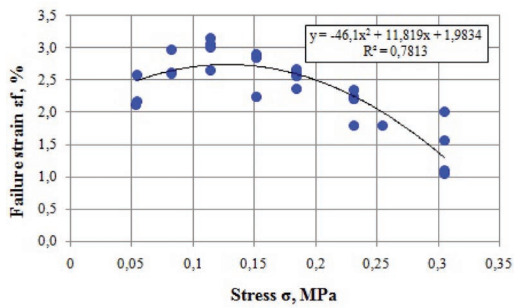

Figure 6. Dependence of failure strain on stress.

Equation shows that the stress impacts greatly on long-term strength of asphalt concrete: stress increase for single-order reduces long-term strength for four orders.

5.3 *Failure strain*

It is known that one of the first criteria for strength in mechanics of materials is connected with limit value of strain. Due to the above it is important to evaluate the values of failure strain at different stresses. Figure 6 shows the dependence of failure strain for asphalt concrete on stress, where you can see that failure strain value is not constant, i.e. it cannot be the criterion of strength. In addition, this dependence is of complicated character and described by quadric polynomial: failure strain is increased monotonously up to the stress of 0.12–0.13 MPa and reduces with further stress increase.

5.4 *Step loading*

As it was said previously, vehicles with different axle load run along the highways. Even loads on certain axles of one vehicle differ significantly. The sequence of impacts for these axle loads on

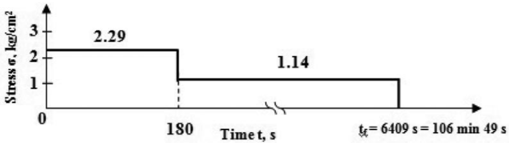

Figure 7. The first scheme of loading for the sample of the asphalt concrete.

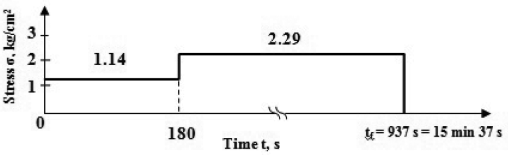

Figure 8. The second scheme of loading for the sample of the asphalt concrete.

pavement, differing in value, is of changeable character. Therefore, to evaluate the sequence of impacts on asphalt concrete strength, the following tests were carried out under the scheme of step loading.

The first five samples were loaded by stress equal to 2.29 kg/cm^2 which had not changed for 180 seconds. Then the stress was reduced till 1.14 kg/cm^2 which was constant till the sample failure. The samples average failure time was 6409seconds (Figure 7).

The next five samples were loaded firstly by stress equal to 1.14 kg/cm^2 which was constant during 180 seconds. Then the stress was increased till 2.29 kg/cm^2 which was constant till the sample failed. The samples average failure time was 937 seconds (Figure 8).

There was established that changes in small and big tension stresses sequences eventually influence on the asphalt concrete failure time. In the case when the sample was firstly loaded by big stresses and then by small ones the failure time increases almost for seven times than the sample which was loaded firstly by small stresses and then by big ones. This fact can be explained by the fact that in the first case the duration of acting of big stress is essentially less than duration of acting of small stresses.

As the sequence of load impact affects greatly the failure time of asphalt concrete, it is required to develop a new strength criterion, which differs from Miner's law and Bailey's criterion, mentioned above.

6 CONCLUSION

The results of experimental investigation for strain and strength of fine-grained asphalt concrete at static and step loading at temperature 20 ± 2°C and at stresses from 0.055 MPa to 0.311 MPa showed that:

– creep curves have three sites—unstabilized creep, stabilized creep and accelerating creep. It is important to know that since the beginning of loading to failure point the deformation of asphalt concrete increases with different rate, which is characteristic for certain segments of the creep curve;
– the long-term strength curve for asphalt concrete is successfully described by exponential function. The stress impacts greatly on long-term strength of asphalt concrete: stress increase for single-order reduces failure time for four orders;
– the sequence of impacts affects greatly the strength of asphalt concrete. It requires the development of a new strength criterion for asphalt concretes;
– due to structural non-homogeneity of asphalt concrete its long-term strength and characteristics of deformability have essential static dispersion.

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