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Regularities of creep and long-term strength of hot asphalt concrete under tensile

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ABSTRACT: In this paper test results of hot fine-grained asphalt concrete samples on creep by the direct tensile scheme at temperature of 20±2°C and stress from 0.04 to 0.24 MPa are presented. It is shown that the asphalt concrete creep curve has three characteristic sites. On the first site creep strain is described by the integral equation of Boltzmann-Volterra with the Abel's creep kernel. The kernel parameters determining method is given. On the second site the creep curve is described by the straight line equation and characterized by the strain rate which is a power function of stress. The creep curve sites durations and the asphalt concrete long-term strength have been defined. The creep curve sites durations and the asphalt concrete failure time depend on stress. Stress influence degree is such that stress change on one order causes their change more than three orders.

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 0.04 to 0.24 MPa. Creep curves under different loads and long-term strength curves of the asphalt concrete have been constructed. Three characteristic sites of creep curves—the unstabilized, stabilized and accelerating creep sites are shown. Dependences of these sites durations on stress are established. The first creep curve site of the asphalt concrete is satisfactorily approximated by the Abel's kernel. The Abel's kernel parameters have been determined by the proposed method. The second creep curve site is characterized by constant creep rate. Creep rate dependence on stress has been established. Description of the third creep curve site should be carried out on the basis of continuum damage mechanics approach, it is not considered here and will be given in other works of authors. Dependences of creep curve sites durations and long-term strength of the asphalt concrete have been approximated.

2 MATERIALS

2.1 *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.

2.2 *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:	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/см^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:	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

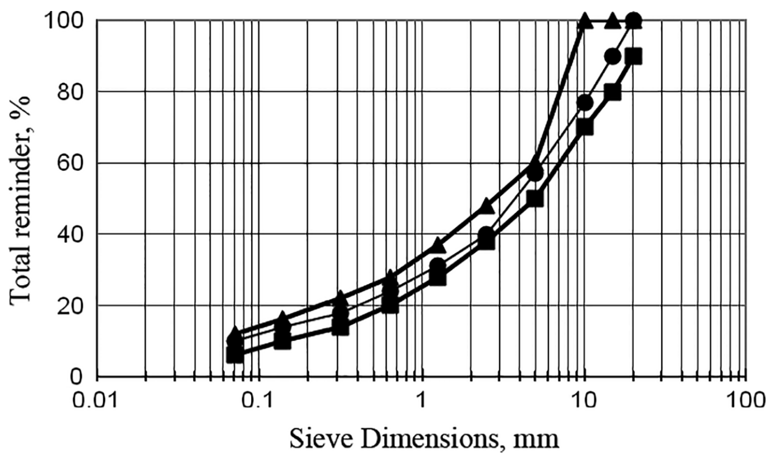

Figure 1. Granulometric curve of mineral part of the asphalt concrete.

3 TEST METHODS

3.1 *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.

3.2 *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 0.04 to 0,24 MPas. The tests were carried out in a special assembled installation, which allows applying a load to the asphalt concrete sample within 1 second. The sample strain was measured by means of two clock typed indicators while data was recorded in a video camera.

4 THEORY

4.1 *Creep equation and kernel*

As it is known 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 (Fig. 2).

In this paper the site I of the asphalt concrete creep curves under uniaxial tensile is described by the integral equation of Boltzmann-Volterra:

$$\varepsilon(t) = \frac{1}{E}\left[\sigma(t) + \int_0^t K(t-\tau)\sigma(\tau)d\tau\right] \tag{1}$$

where $\varepsilon(t)$ = the strain at the time point t; $\sigma(t),\sigma(\tau)$ = the stresses at time points t and τ; $K(t-\tau)$ = the creep kernel; E = the instant modulus of elasticity; t = the observation time; and τ = the time preceding the observation time.

Taking into account that for creep process σ_0=*const* from the Equation 1 we find:

$$\varepsilon(t) = \varepsilon_0\left[1 + \int_0^t K(t-\tau)d\tau\right] \tag{2}$$

where ε_0 = the conditionally instantaneous strain.

In Equation 2 it was accounted that on the Hooke's law $\delta_0 = E.\varepsilon_0$

The asphalt concrete creep kernel is presented in the form of Abel's functions:

$$K(t-\tau) = \frac{\delta}{(t-\tau)} \tag{3}$$

where α and δ = parameters ($0 < \alpha < 1$, $\delta > 0$).

As we can see the Abel's function at $t = 0$ has singularity of α order.

After substitution of expression for the creep kernel (3) into (2) the creep equation takes the form:

$$\varepsilon(t) = \varepsilon_0\left[1 + \frac{\delta}{1-\alpha}t^{1-\alpha}\right] \tag{4}$$

Thus the creep equation with the Abel's kernel contains three unknown parameters – ε_0, α and δ.

4.2 *Creep parameters determining method*

According to the least squares method the best values of the parameters ε_0 and δ are those for which the following condition is performed:

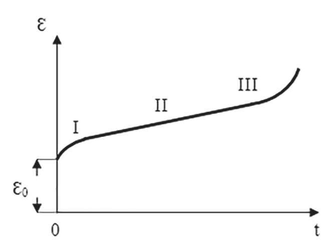

Figure 2. Typical creep curve of the asphalt concrete.

$$S(\varepsilon_0,\delta)=\sum_{i=1}^{m}\left[\varepsilon_0\left(1+\frac{\delta}{1-\alpha}t_i^{1-\alpha}\right)-\varepsilon_{ei}\right]^2\rightarrow \min \tag{5}$$

where $S(\varepsilon_0,\delta)$ = the sum of squares of deviations; and m = the number of creep strain values determined experimentally.

From two equations composed on the expressions and we find expressions to determine parameters ε_0 and δ:

$$\varepsilon_0=\frac{\sum_{i=1}^{m}\varepsilon_i\sum_{i=1}^{m}t_i^{2(1-\alpha)}-\sum_{i=1}^{m}t_i^{(1-\alpha)}\sum_{i=1}^{m}\varepsilon_1 t_i^{(1-\alpha)}}{m\sum_{i=1}^{m}t_i^{2(1-\alpha)}-\left[\sum_{i=1}^{m}t_i^{(1-\alpha)}\right]^2} \tag{6}$$

$$\delta=\frac{\sum_{i=1}^{m}\left(\frac{\varepsilon_i}{\varepsilon_0}-1\right)t_i^{(1-\alpha)}}{\frac{1}{1-\alpha}\sum_{i=1}^{m}t_i^{2(1-\alpha)}} \tag{7}$$

Setting values of the parameter α in the interval (0, 1) with a certain step from the expression (6) we will find values of the parameter $\varepsilon_0=\varepsilon_0(\alpha)$. Substituting the found values of the parameter ε_0 and corresponding values of the singularity parameter α in the expression (7) values of the parameter $\delta=\delta(\varepsilon_0,\alpha)$ have been determined.

Further sequentially substituting values of the singularity parameter α and calculated corresponding values of the parameters ε_0 and δ in the expression (4) values of creep strain $\varepsilon(\mathrm{t}_i)=\varepsilon(t_i,\alpha,\varepsilon_0,\delta)$ are calculated.

If we designate an average deviation of calculated values of creep strains from experimental values using $\Delta\varepsilon_m(\lambda,\varepsilon,\delta)$ as a selecting criterion of the best values of the parameters α, ε_0 and δ the following condition can be accepted:

$$\Delta\varepsilon_{mi}(\alpha_i,\varepsilon_{0i},\delta_i)\rightarrow \min \tag{8}$$

5 EXPERIMENT

5.1 *Creep curves and their approximation*

Creep curves were constructed using test results of the asphalt concrete samples. As an example Figure 3 shows the asphalt concrete creep curve at stress of 0.24 MPa. As you can see this creep curve has three characteristic sites as mentioned above. Creep curves at all stresses imposed in the test have three characteristic sites.

Figure 4 shows the site I of the asphalt concrete creep curve at stress of 0.24 MPa. In this figure the experimental strains are designated by points and the approximation curve is designated by the solid line corresponding to the Equation 4. As can be seen compliance of the approximation curve to the experimental strain is high.

In process of determining the optimal values of the creep parameters α, ε_0 and δ according to the above stated method it is established that the discrepancy $\Delta\varepsilon$ (Fig. 5) and the parameter δ (Fig. 6) linearly depend on the singularity parameter α.

Linear dependence of the discrepancy $\Delta\varepsilon$ on the singularity parameter α is important. It allows a significant reduction of the calculation volume in determining the optimum values of the creep parameters. We can choose two values (for example, 0.10 and 0.95) of the singularity parameter α. Substituting these values in the expressions (6) and (7) we find the corresponding values of the parameters ε_0 and δ. By Equation 4 we calculate the creep strain values. Finally we define the corresponding average values of the discrepancy $\Delta\varepsilon$. Know-

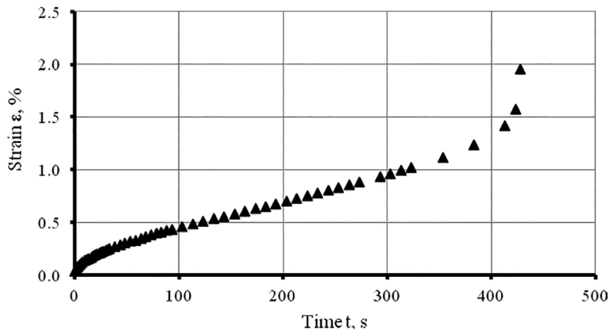

Figure 3. The asphalt concrete creep curve at stress 0.24 MPa.

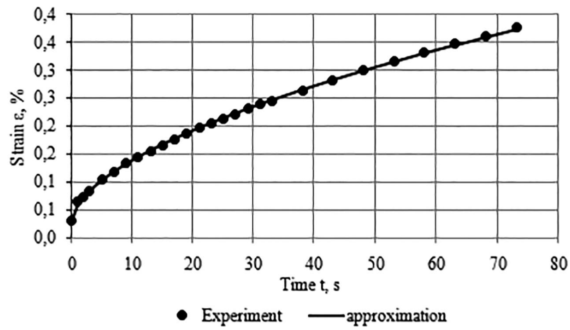

Figure 4. The site I of the asphalt concrete creep curve at stress 0.24 MPa.

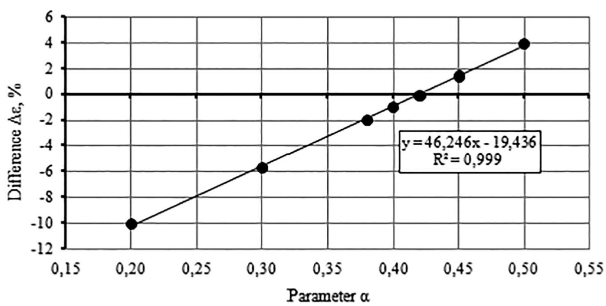

Figure 5. Dependence of the discrepancy $\Delta\varepsilon$ on the parameter α.

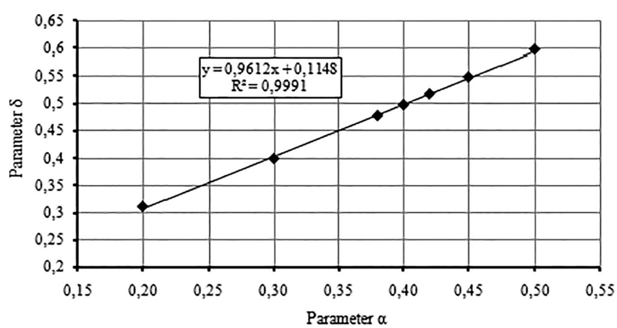

Figure 6. Dependence of the parameter δ on the parameter α.

ing two values of the singularity parameter α and two values of the discrepancy $\Delta\varepsilon$ we can construct straight line graphics. On this straight line we find a value of the parameter α corresponding to the average discrepancy $\Delta\varepsilon = 0$. From the expressions (6) and (7) taking into account the found value of the parameter α we define the optimum values of the parameters ε_0 and δ.

The optimal values of the creep parameters defined at approximation of the site I of the asphalt concrete creep curves at different stresses are given in Table 4.

Figure 7 presents the site II of the asphalt concrete creep curve at stress of 0.24 MPa where experimental strains are designated by points and the solid line represent the approximating line. We can see that the asphalt concrete strains on the site II of the creep curve is accurately described by the straight line equation. On this site the creep process is characterized by a constant strain rate $\dot{\varepsilon}_{II}$. The rate values at different test stresses are given in Table 5. As can be seen the site II of the asphalt concrete creep curve at all testing stresses is described by a straight line with high accuracy. It was found that strain rate depends on stress and this dependence is satisfactorily described by a power function (Fig. 8). With increasing of stress the strain rate also increases.

Table 4. The Abel's kernel parameter values in the site I of the creep curve.

	Parameters			Average discrepancy
Stress σ, MPa	ε_0	α	δ	$\Delta\varepsilon$,%
0.04	0.002890	0.50	0.732	1.8
0.08	0.004060	0.50	0.540	0.3
0.11	0.003309	0.40	1.302	0.6
0.16	0.015217	0.35	0.323	1.5
0.19	0.016871	0.18	0.213	0.5
0.24	0.031750	0.42	0.518	0.1

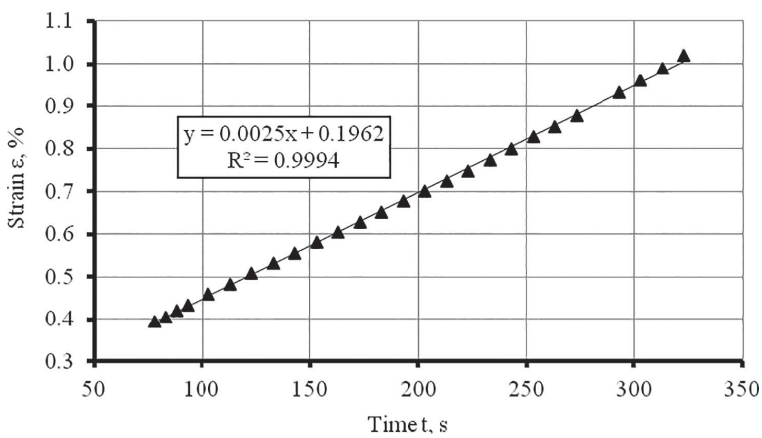

Figure 7. The site II of the asphalt concrete creep curve at stress of 0.24 MPa.

Table 5. Strain rate values on the site II of creep curve.

Stress σ, MPa	0.04	0.08	0.11	0.16	0.19	0.24
Strain rate $\dot{\varepsilon}_{II}$, 10^{4}%/s	0.09	0.9	2	4	9	25
R^2	0.9963	0.9996	0.9995	0.9990	0.9946	0.9994

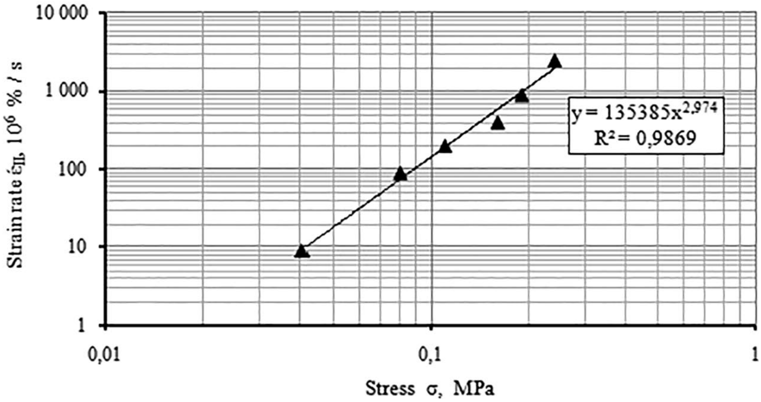

Figure 8. The strain rate dependence on the site II of the asphalt concrete creep curve on stress.

Table 6. The creep curve sites durations.

	Sites duration, s/%		
Stress σ, MPa	Δt_1	Δt_2	Δt_3
0.04	10 799	84 600	35 353
	8.3	64.7	27.0
0.08	2 876	9 180	3 422
	18.7	59.5	21.8
0.11	794	3 460	1 576
	13.6	59.4	27.0
0.16	234	1 380	240
	12.6	74.2	13.2
0.19	72	794	405
	5.7	62.4	31.9
0.24	73	250	105
	16.8	57.5	25.7

5.2 *Creep curve sites duration*

The creep curve sites durations at different stresses is presented in Table 6. It is seen that with stress increase the duration of all sites is decreasing. Moreover, their dependence on stress is described by the straight line equation in logarithmic coordinates with high accuracy (Fig. 9). Also it is clearly seen that the second site has the largest duration (63%) within which strain increases with a constant rate. The third site has an average duration (24%) with increasing strain rate, preceding failure. And the first site has a minimum duration (13%) with decreasing strain rate. Straight lines in Figure 9 are almost parallel. It means that stress influence degree on duration of all sites is identical. From correlation equations in Figure 9 it is clearly seen that if the stress increases with one order the duration of all three sites of creep curves increases more than three orders.

5.3 *Long-term strength*

The dependence of failure time on stress is called long-term strength of a material (Kachanov 1986, Rabotnov 1987). Graphics of the asphalt concrete long-term strength constructed by results of the test on creep is shown in Figure 10. It is seen that the graphics of long-term strength also represents a straight line in logarithmic coordinates. Influence degree of stress

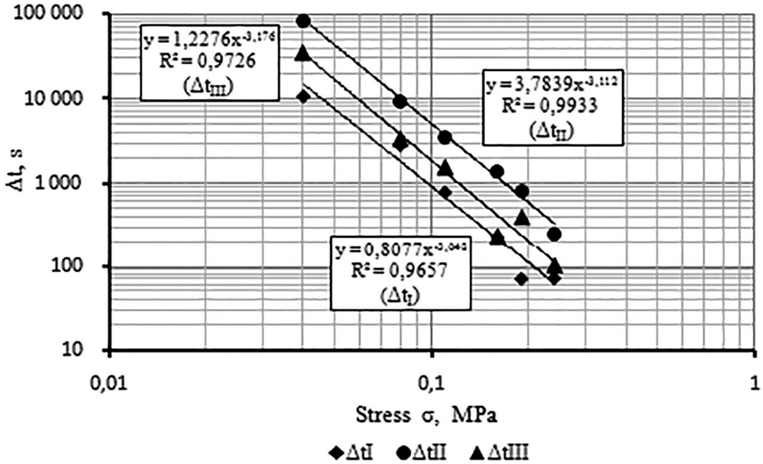

Figure 9. Dependence of the creep curve sites durations on stress.

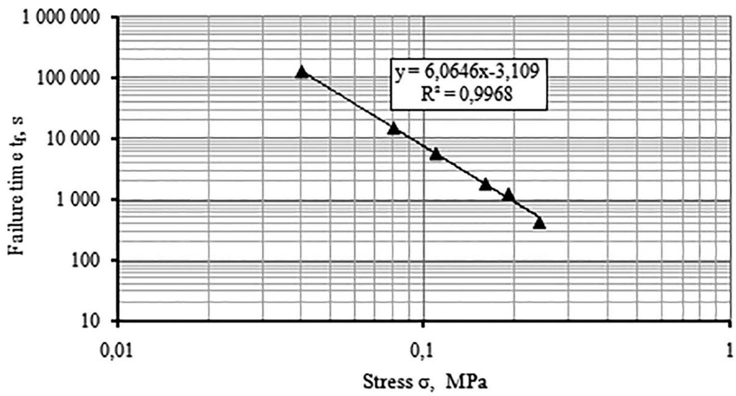

Figure 10. Graphics of the asphalt concrete long-term strength.

on long-term strength of the asphalt concrete is practically the same as on the creep curve sites durations: the stress change with one order causing change of the failure time of three orders.

6 CONCLUSION

Hot fine-grained asphalt concrete samples were tested on creep by direct tensile scheme at a temperature of 20±2°C and stress from 0.04 to 0.24 MPa.

An asphalt concrete creep curve as the most viscoelastic materials at average temperatures and stresses has three characteristic sites: the site of unstabilized creep with decreasing strain rate, the site of stabilized creep with constant (minimum) strain rate and the site of accelerating creep with increasing rate which precedes failure.

Herein, it is proposed to describe a creep process of asphalt concrete within the first site by the integral equation of Boltsmana-Volterra with the Abel's creep kernel. The method of determining the kernel parameters is given. It is shown that the proposed model describes with high accuracy a creep process on the first site.

Moreover, creep strain of the asphalt concrete on the second site is accurately described by a straight line. Creep process at this site is characterized by a strain rate. It was found that the strain rate depends on stress and this dependence is satisfactorily described by a power function.

Durations of all three creep curves sites with high accuracy are approximated by a power function. With increase in stress the durations of the sites are decreased. Influence degree of stress on durations of all sites of the creep curves is identical: change of stress by one order causes change of the durations by more than three orders.

Finally, long-term strength of the asphalt concrete is also satisfactorily approximated by a power function. As well as in the case of the creep curve sites durations, the stress influence degree on long-term strength of the asphalt concrete such that stress change by one order causes change of the failure time by three orders.

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