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MODELING AND INVESTIGATION OF THE INFLUENCE OF LOADING MODE ON THE DEFORMATION PROCESS OF ASPHALT CONCRETE MATERIALS

The article considers a problem of calculating the deformations of forward and reversed creep tension of rheonomic materials. The hereditary theory of creep by Yu.N. Rabotnov is used to describe the nonlinear deformation process. Proposed a method for determining the necessary material characteristics from forward and reversed creep data. During the experiments, there were tested two batches of asphalt concrete samples. Also, was shown behavior of asphalt concrete at cyclic increasing and constant loading modes. At a temperature $T = 24°C$ were tested 10 samples at cyclic increasing loading mode. Cyclic stresses were equal to 0.041; 0.074; 0.111; 0.148; 0.183 MPa and duration period between loading and relax period were chosen to be 570 seconds. At cyclic constant loading were investigated individual samples for the parameters of forward and reversed creep at stresses of 0.041; 0.117 MPa. Then, investigated the affect of reloading two reversed creep process of asphalt concrete samples. From first batch of samples were tested 9 samples before destruction with a period 65 seconds: forward creep of samples at $\sigma = 0.3053$ MPa for the following 5 seconds; reversed creep at $\sigma = 0$ for the following 60 seconds. From the second batch of samples were tested 11 samples of asphalt concrete before destruction with a period 70 seconds: forward creep $\sigma = 0.3053$ MPa for the following 10 seconds and reversed creep at $\sigma = 0$ for the following 60 seconds. Test results showed that the level of return of second batch increased than the first batch of samples.
In the work were tested 5 samples of asphalt concrete according to the direct tensile scheme until a complete failure. Test temperature was $T = 22-24°C$. For each level of loading with constant rate: $0,6519$; $0,4678$; $0,0580$; $0,0489$; $0,0055$ MPa^{s-1}. Using experimental data, were found parameters of the deformation at different constant rate of loading. As a result, all samples fractured brittle at small deformations.
Key words: cyclic loading, loading rate, asphalt concrete, forward creep, reversed creep, deformation, loading, unloading.

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Асфальтбетон материалдарының деформациялану процесіне жүктеме режимінің әсерін модельдеу және зерттеу

Мақалада реономды материалдардың созылуға сынау кезіндегі тура және кері жылжымалылық деформацияларын есептеу қарастырылады. Сызықтық емес деформациялану процесін сипаттауда Ю.Н. Работновтың жылжымалылық мұралық теориясы қолданылады. Тура және кері жылжымалылықтың тәжірибелік берілгендерінен материалдың қажетті сипаттамаларын анықтау әдістемесі ұсынылады. Нәтижесінде алынған анықтауыш теңдеулер асфальтбетон үлгілерін созылуға сынау кезінде тура және кері жылжымалылық деформациясы есептеулерінде қолданылды. Зерттеуде асфальтбетон үлгілерінің екі партиясы сыналды. Асфальтбетонның өсуі мен тұрақты циклдік жүктеме циклдік режиміндегі күйі көрсетілді. Циклдік өсу жүктемесінде $T = 24°C$ температурада 10 асфальтбетон үлгілері сыналды. Кернеулер мәні: $0,041$; $0,074$; $0,111$; $0,148$; $0,183$ МПа, ал жүктеу периоды мен тынығу периодының ұзақтығы 570 секундтқа тең болды. Циклдік тұрақты жүктемеде сынау кернеулері $0,041$; $0,117$ МПа асфальтбетонның жекелеген үлгілері тура және кері жылжымалылыққа зерттелді. Асфальтбетон үлгілерінің қайта жүктеу кезіндегі кері жылжымалылық процесіне әсері де қарастырылды. Үлгілердің бірінші партиясынан қирауға дейін 9 үлгі 65 секундтық периодымен сыналды: үлгілердің тура жылжымалылығы $\sigma = 0.3053$ МПа болғанда 5 секунд бойы; кері жылжымалылық $\sigma = 0$ болғанда 60 секунд бойы. Екінші партияның дайындамасынан 11 асфальтбетон үлгілері қирауға дейін 70 секундтық периодымен сыналды: тура жылжымалылығы $\sigma = 0.3053$ МПа болғанда 10 секунд бойы; кері жылжымалылық $\sigma = 0$ болғанда 60 секунд бойы. Сынақ нәтижелерінен екінші партия дайындама үлгілерінің қайту деңгейі бірінші партиядан алынған үлгілерді қайту деңгейімен салыстырғанда ұлғайғанын көрсетті.
Зерттеу жұмысында $22 - 24°C$ температурада асфальтбетонның 5 үлгісінен тұрақты жүктеу жылдамдығында қирауға дейін созылу схемасы бойынша сыналды: $0,6519$; $0,4678$; $0,0580$; $0,0489$; $0,0055$ МПа$^{\text{сек}-1}$. Әрбір жүктеу жылдамдықтарында тәжірибелік берілгендерді қолдана отырып, жылжымалылық деформациясы мәнінің параметрлері табылды, нәтижесінде барлық үлгілер аз деформацияда морт қирағанын көрсетті.
Түйін сөздер: циклдік жүктеме, жүктелу жылдамдығы, асфальтбетон, тура жылжымалылық, кері жылжымалылық, деформация, жүктеме, жүксіздеу.

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Моделирование и исследование влияния режима нагружения на процесс деформирования асфальтобетонных материалов

В статье рассматривается задача расчета деформаций прямой и обратной ползучести при растяжении реономных материалов. Для описания процесса нелинейного деформирования используется наследственная теория ползучести Ю.Н. Работнова. Предлагается методика определения необходимых характеристик материала из данных прямой и обратной ползучести. Полученные в результате определяющие уравнения апробированы на задаче расчета деформаций прямой и обратной ползучести при растяжении асфальтобетона. Было испытано две партии образцов асфальтобетона. Показаны поведение асфальтобетона в режиме циклически возрастающей и постоянной нагрузке. Схемы испытании в режиме циклически возрастающей нагрузке испытаны 10 образцов асфальтобетона при температуре $T = 24°C$. Напряжения в циклах были равными $0,041$; $0,074$; $0,111$; $0,148$; $0,183$ МПа, а продолжительность периода нагружения и периода отдыха были выбраны равными 570 секунд. Схемы испытании в режиме циклически постоянной нагрузке исследованы отдельные образцы асфальтобетона на параметры прямой и обратной ползучести при напряжениях $0,041$; $0,117$ МПа. Также исследуется влияния повторного нагружения на процесс обратной ползучести образцов асфальтобетона. Из первой партии заготовок испытаны 9 образцов до разрушения с периодом 65 секунд: прямая ползучести образцов при $\sigma = 0.3053$ МПа в течении 5 секунд;

обратная ползучесть при $\sigma = 0$ в течении 60 секунд. Из второй партии заготовок были испытаны 11 образцов до разрушения с периодом 70 секунд: прямая ползучесть образцов асфальтобетона при $\sigma = 0.3053$ МПа в течении 10 секунд; обратная ползучесть образцов при $\sigma = 0$ в течении 60 секунд. Результаты испытаний показали, что уровень возврата образцов второй партии выросли по сравнению с уровнем возврата образцов из первой партии заготовок.
В работе по 5 образцов асфальтобетона испытаны по схеме прямого растяжения до разрушения при температуре $22 - 24°C$ в условиях на каждой нагружения с постоянной скоростью: $0,6519$; $0,4678$; $0,0580$; $0,0489$; $0,0055$ МПа$^{\text{сек}-1}$. При различных скоростях нагружения, используя экспериментальные данные, были найдены параметры значения деформации ползучести. В результате все образцы разрушились хрупко при малых деформациях.
Ключевые слова: циклическое нагружение, скорость нагружения, асфальтобетон, прямая ползучесть, обратная ползучесть, деформация, нагрузка, разгрузка.

1 Introduction

In everyday life transports with different weights move along the highway. The intensity of traffic causes the accumulation of rapid fatigue damage of asphalt concrete coatings and an increase in the corresponding cycles. The characteristic of the development of fatigue damage in the material affects the magnitude of the cyclic load [1-3].

It can be seen from the research of many authors [4-7] that with cyclic loading, there is an increase in recovery during the rest period of an asphalt concrete over a long period of time. Therefore, the experimental study of deformation and destruction of an asphalt concrete under cyclic loading is becoming increasingly important.

This work presents the results of tensile creep tests of asphalt concrete samples until a complete failure, conducted in Kazakhstan Highway Research Institute. The purpose of this research is to study the deformation of asphalt concrete material under forward and reversed creep, as well as at a constant loading rate of asphalt concrete.

2 Determining relation for ergonomic material

2.1 Even if the deformation $\varepsilon(t)$ in the interval $(0, t_1)$ (t – time, $t_1 > 0$) is a non-decreasing function of time, $\dfrac{d\varepsilon(t)}{dt} > 0$. In this case, we take the defining relation as

$$\varepsilon(t) = \varphi[\sigma(t)] + \int_0^t K(t-\tau)\varphi[\sigma(\tau)]d\tau, \tag{1}$$

where σ is the conditional stress, $\varphi(\sigma)$ is the function of conditionally instantaneous loading; $K(t-\tau)$ – kernel of forward creep.

2.2 Even if the deformation $\varepsilon(t)$ in the interval $(t_1, t)(t > t_1)$ be a decreasing function of time $\dfrac{d\varepsilon}{dt} < 0$.

The defining relation for processes with decreasing deformation is written as

$$\varepsilon(t,t_1) = \varphi_1[\sigma(t)] - \int_{t_1}^{t} K_1(t-\tau)\varphi_1[\sigma(\tau)]d\tau, \tag{2}$$

where $\varphi_1(\sigma)$ is the function of conditionally instantaneous unloading; $K_1(t-\tau)$ is kernel of reversed creep.

3 A method for determining the necessary material characteristics from data of forward and reversed creep

3.1 Tension of samples at $\sigma = const$ and constant temperature $T = const$

Creep kernel

$$K(t-\tau) = \delta(t-\tau)^{-\alpha}, \tag{3}$$

where $\alpha \in (0,1)$; $\delta > 0$.

Considering equation (3) from (1), we will obtain the equation of simple creep:

$$\varepsilon_m(t,\sigma) = \varphi[\sigma(0)]\left(1 + \frac{\delta}{1-\alpha}t^{1-\alpha}\right), \tag{4}$$

where $\varphi[\sigma(0)] = \varepsilon_0^m(\sigma)$ – conditionally instantaneous deformation, $\varepsilon_m(t,\sigma)$ – calculated values of creep deformation of the material.

Equation (4) contains three unknown parameters $\varepsilon_0^m(\sigma), \alpha$ and δ. Following [8-9], the parameter α will be considered as known from the interval (0,1), and the unknown parameters $\varepsilon_0^m(\sigma)$ and δ are determined using the least squares method:

$$\begin{gathered} \varepsilon_0^m = \frac{\sum\limits_{i=1}^{m}\varepsilon_e(t_i)\sum\limits_{i=1}^{m}t_i^{2(1-\alpha)} - \sum\limits_{i=1}^{m}\varepsilon_e(t_i)t_i^{(1-\alpha)}\sum\limits_{i=1}^{m}t_i^{(1-\alpha)}}{m\sum\limits_{i=1}^{m}t_i^{2(1-\alpha)} - \left[\sum\limits_{i=1}^{m}t_i^{(1-\alpha)}\right]^2}, \\ \delta = \frac{\sum\limits_{i=1}^{m}\left(\dfrac{\varepsilon_e(t_i)}{\varepsilon_0^m} - 1\right)t_i^{(1-\alpha)}}{\dfrac{1}{1-\alpha}\sum\limits_{i=1}^{m}t_i^{2(1-\alpha)}}, \end{gathered} \tag{5}$$

where $\varepsilon_e(t)$ – creep strain values determined experimentally; m – creep strain number.

Following [9], we accept that

$$\varepsilon_0^m(\sigma) \approx \varepsilon_0^e(\sigma), \tag{6}$$

where $\varepsilon_0^e(\sigma)$ – the value of the conditionally instantaneous deformation determined experimentally.

Considering equation (6) from (5), we will obtain

$$1 = \frac{\sum\limits_{i=1}^{m} K_e(t_i) \sum\limits_{i=1}^{m} t_i^{2(1-\alpha)} - \sum\limits_{i=1}^{m} t_i^{(1-\alpha)} \sum\limits_{i=1}^{m} K_e(t_i) t_i^{(1-\alpha)}}{m \sum\limits_{i=1}^{m} t_i^{2(1-\alpha)} - \left[\sum\limits_{i=1}^{m} t_i^{(1-\alpha)} \right]^2}, \tag{7}$$

$$\delta = \frac{\sum\limits_{i=1}^{m} (K_e(t_i) - 1)}{\dfrac{1}{1-\alpha} \sum\limits_{i=1}^{m} t_i^{2(1-\alpha)}}. \tag{8}$$

Here

$$K_e(t, \sigma_\xi, T) = \frac{\varepsilon_e(t, \sigma_\xi, T)}{\varepsilon_0^e(\sigma_\xi, T)}, \tag{9}$$

$\sigma_\xi(\xi = 1 - n)$, n is the number of loadings; $K_e(t)$is the experimental rheological creep parameter [8].

The analysis of the relation (7) – (9) shows that finding the values of the entire set of parameters determining the relation is not unique. There are three types of creep curves.

I. If $K_e(t)$ is particular independent of value of the stresses, then (7) and (8) have a unique solution of the form:

$$\alpha(T) = const; \quad \delta(T) = const. \tag{10}$$

In this case, the creep curves will be similar.

II. If $K_e(t, \sigma_\xi)(\xi = 1 - n)$ depend on the value of the σ_ξ stresses, then (7) and (8) will have n+1 solutions of the form:

$$\alpha(\sigma_\xi, T) = const; \quad \delta(\sigma_\xi, T) = const, \tag{11}$$

$$\alpha(\overline{K}_e, T) = const; \quad \delta(\overline{K}_e, T) = const, \tag{12}$$

where

$$\overline{K}_e(t, T) = \frac{1}{n} \sum_{\xi=1}^{n} K_e(t, \sigma_\xi, T). \tag{13}$$

In this case, creep curves will be considered almost similar, if they can be described by a single set of forward creep parameters.

III. Creep curves are not similar to each other, if they cannot be described by a single set of forward creep parameters.

The calculated rheological creep parameter is determined by the formula:

$$K_m(t, T) = 1 + \frac{\delta}{1-\alpha} t^{1-\alpha}, \tag{14}$$

where $\alpha(T) \in (0,1)$; $\delta(T) > 0$, $t \in [0,t_1]$.

The similarity coefficient.

$$K_m(t_s,T) = 1 + \frac{\delta}{1-\alpha} t_s^{1-\alpha}, \tag{15}$$

where $t_s \in [0,t_1]$.

Then $\varepsilon_0^m(\sigma_\xi,T)$ is defined by the formula:

$$\varepsilon_0^m(\sigma_\xi,T) = \frac{1}{m}\sum_{s=1}^{m} \frac{\varepsilon_e(t_s,\sigma_\xi,T)}{K_m(t_s,T)}, \tag{16}$$

where $\varepsilon_e(t)$ – experimental values of creep deformation of the material; $K_m(t_s)$ – defined by (15).

3.2 Tension of samples at $\dot{\sigma} = const$ and constant temperature $T = const$.

Put in

$$\sigma(t) = \dot{\sigma} t, \tag{17}$$

$$\varphi[\sigma(t)] = a\sigma^\gamma(t), \tag{18}$$

where $a > 0$; $\gamma \geq 1$.

Considering equations (3), (17) and (18) from (1) we will obtain:

$$\varepsilon_m(t,T) = a(\dot{\sigma}t)^\gamma \left[1 + \overline{\delta}\frac{\Gamma(1+\gamma)\Gamma(1-\overline{\alpha})}{\Gamma(2+\gamma-\overline{\alpha})} t^{(1-\overline{\alpha})}\right], \tag{19}$$

where $\dot{\sigma} > 0$; $\Gamma(\cdot)$ – gamma function; $t \in [0,t_1]$; $\overline{\alpha} \in (0,1)$.

Using the least squares method, we will obtain $\overline{\delta} = \overline{\delta}(\overline{\alpha},T)$:

$$\overline{\delta}(\overline{\alpha},T) = \frac{\Gamma(2+\gamma-\overline{\alpha})}{\Gamma(1+\gamma)\Gamma(1-\overline{\alpha})} \cdot \frac{1}{\sum\limits_{i=1}^{m} t_i^{2(\gamma+1-\overline{\alpha})}} \cdot \left[\frac{1}{a(\dot{\sigma})^\gamma}\sum_{i=1}^{m}\varepsilon_e(t_i,\dot{\sigma})t_i^{(\gamma+1-\overline{\alpha})} - \sum_{i=1}^{m} t_i^{(2\gamma+1-\overline{\alpha})}\right], \tag{20}$$

where $\varepsilon_e(t,\dot{\sigma})$ – creep strain values determined experimentally at $\dot{\sigma} = const$.

3.3 Determination of material characteristics in case of reversed creep

We take reversed creep kernel in the form:

$$K_1(t-\tau) = \delta_1(t-\tau)^{-\alpha_1}, \tag{21}$$

where $\alpha_1 \in (0,1)$; $\delta_1 > 0$.

Considering equation (21) from (2), we will obtain

$$\varepsilon_m(t,t_1) = \varepsilon_*^m(\sigma)\left(1 - \frac{\delta_1}{1-\alpha_1}(t-t_1)^{(1-\alpha_1)}\right), \tag{22}$$

where $t \geq t_1$; $\varepsilon_*^m(\sigma)$ – calculated values of conditionally instantaneous deformation during unloading process.

Put in

$$\varepsilon_*^m(\sigma) \approx \varepsilon_*^e(\sigma), \tag{23}$$

here $\varepsilon_*^e(\sigma)$ – experimental values of conditionally instantaneous deformation during unloading.

We introducing the notation:

$$\Gamma_e(t, t_1, \sigma_\xi) = \frac{\varepsilon_e(t, t_1, \sigma_\xi)}{\varepsilon_*^e(\sigma_\xi)}, \tag{24}$$

$$\Gamma_m(t, t_1) = 1 - \frac{\delta_1}{1-\alpha_1}(t - t_1)^{1-\alpha_1}, \tag{25}$$

here $\Gamma_e(t, t_1)$ – experimental rheological parameter of the reversed creep of material; $\Gamma_m(t, t_1)$ – the calculated rheological parameter of the reversed creep of material.

Using the least squares method, we determine the α_1 and δ_1 parameters:

$$\begin{aligned} 1 = &\left\{ \sum_{i=1}^{m} \Gamma_e(t_i) \sum_{i=1}^{m} (t_i - t_1)^{2(1-\alpha_1)} - \sum_{i=1}^{m} (t_i - t_1)^{(1-\alpha_1)} \sum_{i=1}^{m} \Gamma_e(t_i)(t_i - t_1)^{(1-\alpha_1)} \right\} \cdot \\ &\cdot \left\{ m \sum_{i=1}^{m} (t_i - t_1)^{2(1-\alpha_1)} - \left[\sum_{i=1}^{m} (t_i - t_1)^{(1-\alpha_1)} \right]^2 \right\}^{-1}, \end{aligned} \tag{26}$$

$$\delta_1 = \frac{\sum_{i=1}^{m} (1 - \Gamma_e(t_i))}{\frac{1}{1-\alpha_1} \sum_{i=1}^{m} (t_i - t)^{2(1-\alpha_1)}}, \tag{27}$$

where $t > t_1$; $\Gamma_e(t_i, t_1)$ – determined by the relation (24); when deducing (26) and (27), (23) were considered. Based on (26) and (27), we will analyze the reversed creep curves. There are three types of reversed creep curves.

I. If $\Gamma_e(t_i, t_1)$ practically does not depend on the value of the stresses, then (26) and (27) have a unique solution of the form (10):

$$\alpha_1(T) = const; \quad \delta_1(T) = const.$$

In this case, the reversed creep curves will be similar.

II. If $\Gamma_e(t_i, t_1, \sigma_\xi)(\xi = 1 - n)$ depend on the value of the σ_ξ stresses, then (26) and (27) will have n+1 solutions of the form (11) and (12). Reversed creep curves will be considered almost – similar, if they can be described by a single set of α_1 and δ_1 parameters.

III. If the reversed creep curves cannot be described by a single set of α_1 and δ_1 parameters, then they are not similar to each other.

From (25) at $t = t_s$, we determine the similarity coefficient

$$\Gamma_m(t_s, t_1) = 1 - \frac{\delta_1}{1-\alpha_1}(t_s - t_1)^{1-\alpha_1}, \tag{28}$$

where $t_s \geq t_1$; $\alpha_1 \in (0,1)$; $\delta_1 > 0$; the unknown $\varepsilon_*^m(t_1, \sigma_\xi)$ is determined by the formula:

$$\varepsilon_*^m(t_1, \sigma_\xi) = \frac{1}{m} \sum_{s=1}^{m} \frac{\varepsilon_e(t_s, t_1, \sigma_\xi)}{\Gamma_m(t_s, t_1)}, \tag{29}$$

where $\varepsilon_e(t, t_1)$ – experimental values of the reversed creep deformation of the material; $\Gamma_m(t_s, t_1)$ – defined by (28).

4 Experimental verification of the defining equation for asphalt concrete during loading and unloading

4.1 Behavior of asphalt concrete in cyclic loading

The test scheme in the increasing cyclic loading mode is shown in figure 1. Asphalt concrete 10 samples were tested at a temperature of $T = 24°C$. The experimental average values of the forward creep deformation $\varepsilon_e(t, \sigma)$ of an asphalt concrete are presented in table 1. According to table 1, we calculate:

$$\begin{array}{ll} K_e(570, 0.041) = 3.13; & K_e(570, 0.074) = 3.24; \\ K_e(570, 0.111) = 2.92; & K_e(570, 0.148) = 2.77; \\ K_e(570, 0.183) = 3.22. & \end{array} \tag{30}$$

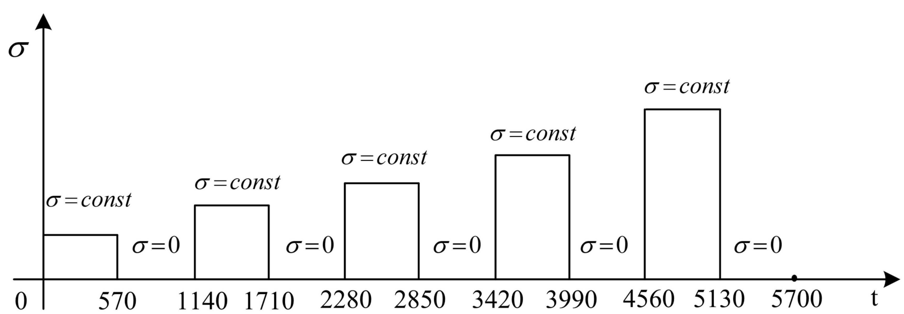


Figure 1: Test scheme in the increasing cyclic loading mode

In the work [8] we will obtain:

$$\alpha(T = 24°C) = 0.3; \quad \delta(T = 24°C) = 0.0153 s^{\alpha - 1}.$$

Similarity coefficients:

$$K_m(t_s, T) = 1 + 0.0218 t_s^{0.7}, \tag{31}$$

where $t_s \in [0, 570]$; t – time in seconds.

Based on the analysis of data (30) and (31), we conclude that in the segment [0,570] the forward creep curves of asphalt concrete are almost similar.

Considering equation (31) and (16), using the formula (4), we compute the calculated values of the creep strain $\varepsilon_m(t, \sigma)$ of an asphalt concrete, they are presented in table 2.The coincidence is satisfactory.

Table 1: Experimental deformations of forward and reversed creep of an asphalt concrete samples

t, s	0	90	210	330	450	570	Number of cycles
$\sigma = 0.041$ MPa	0.0475	0.0849	0.1099	0.1255	0.1415	0.1488	1
0	0.1414	0.1389	0.1380	0.1287	0.1282	0.1268	
0.074	0.0543	0.0932	0.1232	0.1457	0.1627	0.1759	2
0	0.1565	0.1432	0.1358	0.1315	0.1287	0.1259	
0.111	0.0805	0.1338	0.1643	0.1937	0.2158	0.2349	3
0	0.1996	0.1762	0.1632	0.1572	0.1497	0.1489	
0.148	0.1313	0.1782	0.2484	0.2839	0.3293	0.3632	4
0	0.3049	0.2783	0.2471	0.2350	0.2286	0.2174	
0.183	0.1782	0.2855	0.3710	0.4482	0.5105	0.5741	5
0	0.4852	0.4176	0.3808	0.3567	0.3357	0.3308	

Table 2: Calculated values of the deformation of the forward reversed creep of asphalt concrete samples

t, s	0	90	210	330	450	570	Number of cycles
$\sigma = 0.041$ MPa	0.0522	0.0787	0.1002	0.1181	0.1341	0.1488	1
0	0.1446	0.1384	0.1346	0.1316	0.1291	0.1269	
0.074	0.0593	0.0894	0.1139	0.1342	0.1624	0.1691	2
0	0.1670	0.1478	0.1385	0.1319	0.1264	0.1217	
0.111	0.0824	0.1243	0.1582	0.1865	0.2117	0.2350	3
0	0.1994	0.1765	0.1654	0.1575	0.1509	0.1453	
0.148	0.1274	0.1922	0.2447	0.2883	0.3273	0.3633	4
0	0.3021	0.2673	0.2506	0.2385	0.2286	0.2201	
0.183	0.1892	0.2854	0.3634	0.4282	0.4861	0.5395	5
0	0.4560	0.4036	0.3782	0.3601	0.3451	0.3323	

4.2 Analysis of asphalt concrete behavior during unloading

The experimental average values of the reversed creep deformation of asphalt concrete are presented in table 1. According to table 1, the parameters of reversed creep are determined:

$$\Gamma_e(t, 0.041); \quad \alpha_{11} = 0.43; \quad \delta_{11} = 0.0019\ s^{\alpha-1};$$
$$\Gamma_e(t, 0.074); \quad \alpha_{12} = 0.5641; \quad \delta_{12} = 0.0054\ s^{\alpha-1};$$
$$\Gamma_e(t, 0.111); \quad \alpha_{13} = 0.5863; \quad \delta_{13} = 0.0079\ s^{\alpha-1};$$
$$\Gamma_e(t, 0.148); \quad \alpha_{14} = 0.4394; \quad \delta_{14} = 0.0047 s^{\alpha-1};$$
$$\Gamma_e(t, 0.183); \quad \alpha_{15} = 0.5535; \quad \delta_{15} = 0.0087 s^{\alpha-1};$$
$$\overline{\Gamma}_e(t); \quad \alpha_{16} = 0.5351; \quad \delta_{16} = 0.0066\ s^{\alpha-1}.$$

The analysis of the data is obtained above shows that the reversed creep curves of asphalt concrete are not similar in the segment [0, 570]. The reversed creep curve at $\sigma = 0.041$ is described by the equation

$$\Gamma_m(t) = 1 - 0.0033 t^{0.57}, \tag{32}$$

where $t \in [0, 570]$.

The remaining curves of the reversed creep of asphalt concrete are modeled by the relation

$$\Gamma_m(t) = 1 - 0.0142t^{0.4649}, \tag{33}$$

where $t \in [0, 570]$.

Considering expressions (32) and (33) the equation (29), using the formula (22), calculated values of the reversed creep deformation $\varepsilon_m(t)$ of asphalt concrete, they are presented in table 2. The coincidence is satisfactory. It was shown in [10-11] that microstresses cause reversed creep of materials. The degree of reversed creep of the asphalt concrete material shows that the level of microstress values increases during cyclic loading.The source of micro-damage is the micro-stresses arising in the material [12].The root cause of the appearance of the microstress field in asphalt concrete is the microinhomogeneity and microanisotropy of the material structure. In the loading mode, the deformation of asphalt concrete samples is determined by the expression

$$\varepsilon_m(t,\sigma) = \varepsilon_m^c(t,\sigma) + \varepsilon_m^d(t,\sigma), \tag{34}$$

here $\varepsilon_m^c(t,\sigma)$ – failure of the material due to creep; $\varepsilon_m^d(t,\sigma)$ – failure of the material due to damage.

Since the forward creep curves of asphalt concrete are almost similar, we conclude from (34):

$$\varepsilon_m^d(t,\sigma) << \varepsilon_m^c(t,\sigma). \tag{35}$$

Considering equation (35), in cyclic loading, together (34) we take

$$\varepsilon_m(t,\sigma) = \varepsilon_m^c(t,\sigma). \tag{36}$$

For the cyclic loading scheme (figure 1) we have:

$$\begin{aligned}
&\varepsilon_m(t,\sigma) = 0.0522(1 + 0.0218t^{0.7}) + 0.1446[1 - 0.0033(t-570)^{0.57}]+\\
&+0.0593[1 + 0.0218(t-1140)^{0.7}] + 0.1670[1 - 0.0142(t-1710)^{0.4649}]+\\
&+0.0824[1 + 0.0218(t-2280)^{0.7}] + 0.1994[1 - 0.0142(t-2859)^{0.4649}]+\\
&+0.1274[1 + 0.0218(t-3420)^{0.7}] + 0.3021[1 - 0.0142(t-3990)^{0.4649}]+\\
&+0.1892[1 + 0.0218(t-4560)^{0.7}] + 0.4560[1 - 0.0142(t-5130)^{0.4649}],
\end{aligned} \tag{37}$$

where $t \in [0, 5700]$, t – time in seconds.

4.3 Investigation of asphalt concrete creep in the constant cyclic loading mode

The test scheme of the N68 asphalt concrete sample in the constant cyclic loading mode is shown in figure 2. The experimental values of forward and reversed creep deformation of the N68 sample are shown in table 3. Based on the analysis of the data in table 3:

1) the forward creep of sample N68 is described by equation (31);

2) the reversed creep of sample N68 is modeled by equation (33).

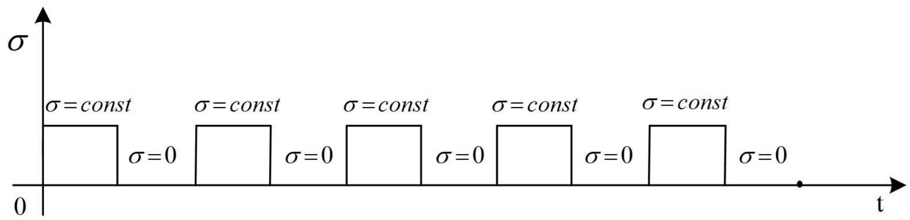


Figure 2: Test scheme in the constant cyclic loading mode

Table 3: Experimental values of forward and reversed creep deformation of sample N68

t, s	0	30	60	90	150	270	Number of cycles
$\sigma = 0.117$ MPa	0.0976	0.1259	0.1477	0.1651			1
0	0.1412	0.1337	0.1294	0.1266	0.1228	0.1157	
$\sigma = 0.117$ MPa	0.0802	0.1001	0.1160	0.1300			2
0	0.1020	0.0899	0.0852	0.0815	0.0768	0.0681	
$\sigma = 0.117$ MPa	0.0790	0.0970	0.1107	0.1231			3
0	0.0899	0.0808	0.0749	0.0712	0.0659	0.0560	
$\sigma = 0.117$ MPa	0.0808	0.0973	0.1098	0.1228			4
0	0.0855	0.0771	0.0715	0.0675	0.0612	0.0513	
$\sigma = 0.117$ MPa	0.0836	0.0998	0.1122	0.1253			5
0	0.0871	0.0777	0.0709	0.0662	0.0600	0.0516	

Table 4: Calculated values of forward and reversed creep deformation of sample N68

t, s	0	30	60	90	150	270	Number of cycles
$\sigma = 0.117$ MPa	0.1019	0.1259	0.1409	0.1537			1
0	0.1437	0.1338	0.1300	0.1272	0.1227	0.1162	
$\sigma = 0.117$ MPa	0.0831	0.1027	0.1149	0.1254			2
0	0.0909	0.0846	0.0823	0.0805	0.0776	0.0735	
$\sigma = 0.117$ MPa	0.0816	0.1008	0.1128	0.1231			3
0	0.0783	0.0729	0.0708	0.0693	0.0669	0.0633	
$\sigma = 0.117$ MPa	0.0814	0.1006	0.1126	0.1228			4
0	0.0738	0.0687	0.0668	0.0653	0.0630	0.0596	
$\sigma = 0.117$ MPa	0.0831	0.1026	0.1148	0.1253			5
0	0.0728	0.0678	0.0659	0.0644	0.0622	0.0589	

The calculated values of forward and reversed creep deformation of sample N68 asphalt concrete are presented in table 4. The coincidence of tables 3 and 4 is satisfactory.

4.4 Investigation the influence of structure of individual asphalt concrete samples on the parameters of forward and reversed creep

The experimental values of forward and reversed creep deformation of 10 individual asphalt concrete samples are shown in table 5. From the data in table 5, it can be seen that data at a stress $\sigma = 0.041$ MPa $\varepsilon_0(0.041)$ and $\varepsilon_*(0.041)$ of all 10 samples does not match

(ε_0 – conditionally instantaneous deformation of samples during loading; ε_* – conditionally instantaneous deformation of samples during unloading). Table 1 shows the average values of forward and reversed creep deformation for the tested 10 asphalt concrete samples. According to table 1, we found the parameters of forward and reversed creep:

1) forward creep is described by equation (31);

2) the reversed creep is modeled by equation (32).

Considering equation (31) and (32), we find the calculated values of forward and reversed creep deformation of all 10 asphalt concrete samples. The data obtained from the calculated values completely coincided with the data presented in table 5.

Table 5: Experimental values of forward and reversed creep deformation of individual asphalt concrete samples

t, s	0	90	210	330	450	570	Sample number
$\sigma = 0.041$ MPa	0.0498	0.0845	0.1122	0.1285	0.1445	0.1561	252
0	0.1476	0.1454	0.1415	0.1402	0.1380	0.1372	
$\sigma = 0.041$ MPa	0.0475	0.0849	0.1099	0.1254	0.1415	0.1488	253
0	0.1414	0.1389	0.1380	0.1287	0.1282	0.1268	
$\sigma = 0.041$ MPa	0.0355	0.0785	0.1033	0.1193	0.1311	0.1425	254
0	0.1299	0.1222	0.1205	0.1189	0.1176	0.1171	
$\sigma = 0.041$ MPa	0.0332	0.0588	0.0777	0.0899	0.1001	0.1099	255
0	0.0989	0.0945	0.0929	0.0902	0.0899	0.0887	
$\sigma = 0.041$ MPa	0.0233	0.0452	0.0622	0.0732	0.0853	0.0945	257
0	0.0822	0.0777	0.0737	0.0730	0.0720	0.0710	
$\sigma = 0.041$ MPa	0.0262	0.0503	0.0672	0.0795	0.0897	0.0974	258
0	0.0907	0.0846	0.0820	0.0817	0.0813	0.0801	
$\sigma = 0.041$ MPa	0.0375	0.0656	0.0736	0.0812	0.0897	0.0966	259
0	0.0845	0.0796	0.0770	0.0754	0.0747	0.0714	
$\sigma = 0.041$ MPa	0.0486	0.0912	0.1215	0.1456	0.1633	0.1758	260
0	0.1634	0.1552	0.1522	0.1499	0.1496	0.1485	
$\sigma = 0.041$ MPa	0.0546	0.0997	0.1293	0.1543	0.1723	0.1872	261
0	0.1754	0.1687	0.1645	0.1633	0.1630	0.1623	
$\sigma = 0.041$ MPa	0.1096	0.1623	0.1933	0.2142	0.2304	0.2433	262
0	0.2283	0.2203	0.2178	0.2160	0.2146	0.2136	

The above samples were from the same batch of samples. Now let's consider the forward and reversed creep of sample N76 from another batch of samples. The experimental values of forward and reversed creep deformation of sample N76 are shown in table 6. Considering equations (31), (32) and (33), the calculated data of forward and reversed creep deformation of sample N76 are found and presented in table 7. The coincidence of table 6 and table 7 is satisfactory.

4.5 Investigation of the reloading effect on the reversed creep process of asphalt concrete samples

The sample testing scheme is shown in Figure 2. From the first batch of samples, 9 samples were tested,until moment a failure with a period of 65 seconds: forward creep of the samples at $\sigma = 0.3053$ MPa for the following 5 seconds; reversed creep at $\sigma = 0$ for the following 60 seconds.

Table 6: Experimental values of forward and reversed creep deformation of sample N76

t, s	0	90	210	330	450	570	Number of cycles
$\sigma = 0.074$ MPa	0.0668	0.1324	0.1792	0.2099	0.2348	0.2584	1
0	0.2388	0.2345	0.2242	0.2223	0.2205	0.2196	
$\sigma = 0.1448$ MPa	0.0932	0.1661	0.2289	0.2761	0.3171	0.3428	2
0	0.3149	0.2950	0.2838	0.2767	0.2708	0.2643	
$\sigma = 0.2232$ MPa	0.1519	0.2581	0.3574	0.4426	0.5224	0.5755	3
0	0.5261	0.4823	0.4559	0.4404	0.4295	0.4255	

Table 7: Calculated values of forward and reversed creep deformation of sample N76

t, s	0	90	210	330	450	570	Number of cycles
$\sigma = 0.074$ MPa	0.0878	0.1324	0.1686	0.1987	0.2256	0.2504	1
0	0.2449	0.2344	0.2279	0.2229	0.2186	0.2149	
$\sigma = 0.1448$ MPa	0.1123	0.1694	0.2157	0.2541	0.2885	0.3202	2
0	0.3493	0.3091	0.2897	0.2758	0.2644	0.2545	
$\sigma = 0.2232$ MPa	0.1861	0.2808	0.3573	0.4211	0.4781	0.5307	3
0	0.5608	0.4963	0.4651	0.4428	0.4244	0.4086	

The average experimental values of the creep strain of 9 samples $\varepsilon_e(t)$ are shown in table 8. According to table 8, were found:

$$\alpha = 0.3; \quad \delta = 1.1204; \quad K_m(t) = 1 + 1.6005t^{0.7}, \tag{38}$$

where $t \in [0, 5]$, t – time in seconds. Considering equation(38), the average calculated values of forward creep strain of 9 samples $\varepsilon_m(t)$ are calculated and presented in table 8. Data analysis of table 8 shows:

1) creep occurs with the hardening of the material;
2) creep of the samples is modeled by one rheological parameter (38);
3) creep rate of the samples is determined by the rated stress, i.e. $\varepsilon^d(t) << \varepsilon^c(t)$;
4) reloading significantly affect the conditionally instantaneous deformations of samples $\varepsilon_e\,(t = 0)$;
5) on the segment [1, 5], the coincidence of $\varepsilon_m(t)$ and $\varepsilon_e(t)$ is satisfactory.

All tested samples fractured brittle under small deformations (table 8). In this case, fractured brittle of asphalt concrete samples occurs as a result of local accumulation of micro-damages around a weak section.

Table 8: Translations into Kazakh for different types of sentences and assessment of translation errors

t, s	0	1	2	3	4	5	Number of cycles
$\varepsilon_e, \%$	0.0751	0.1953	0.2880	0.3562	0.4033	0.4379	1
$\varepsilon_m, \%$	0.0772	0.2008	0.2780	0.3439	0.4034	0.4585	
$\varepsilon_e, \%$	0.0203	0.1226	0.2041	0.2454	0.2800	0.3178	2

$\varepsilon_m, \%$	0.0518	0.1347	0.1865	0.2307	0.2706	0.3076	
$\varepsilon_e, \%$	0.0214	0.1237	0.2040	0.2518	0.2970	0.3281	3
$\varepsilon_m, \%$	0.0518	0.1347	0.1865	0.2307	0.2706	0.3076	
$\varepsilon_e, \%$	0.0264	0.1495	0.2347	0.2630	0.2976	0.3201	4
$\varepsilon_m, \%$	0.0593	0.1542	0.2135	0.2641	0.3098	0.3521	
$\varepsilon_e, \%$	0.0125	0.1414	0.2142	0.2664	0.3060	0.3331	5
$\varepsilon_m, \%$	0.0577	0.1500	0.2076	0.2569	0.3013	0.3425	
$\varepsilon_e, \%$	0.0322	0.1811	0.2628	0.3241	0.3732	0.4273	6
$\varepsilon_m, \%$	0.0718	0.1866	0.2584	0.3196	0.3749	0.4261	
$\varepsilon_e, \%$	0.0172	0.1735	0.2393	0.2796	0.3112	0.3414	7
$\varepsilon_m, \%$	0.0626	0.1628	0.2254	0.2789	0.3271	0.3718	
$\varepsilon_e, \%$	0.0318	0.1707	0.2501	0.2987	0.3368	0.3480	8
$\varepsilon_m, \%$	0.0642	0.1670	0.2311	0.2859	0.3354	0.3812	
$\varepsilon_e, \%$	0.0242	0.1602	0.2236	0.2799	0.3223	0.3515	9
$\varepsilon_m, \%$	0.0615	0.1599	0.2213	0.2739	0.3212	0.3652	
$\varepsilon_e, \%$	0.0207	0.1829	0.2933	0.3499	0.4052	0.4483	10
$\varepsilon_m, \%$	0.0767	0.1994	0.2761	0.3416	0.4006	0.4554	
$\varepsilon_e, \%$	0.0402	0.2402	0.3286	0.3797	0.4324	0.4648	11
$\varepsilon_m, \%$	0.0863	0.2219	0.3072	0.3800	0.4458	0.5067	
$\varepsilon_e, \%$	0.0588	0.2045	0.3347	0.3657	0.4587	0.4941	12
$\varepsilon_m, \%$	0.0849	0.2209	0.3057	0.3783	0.4437	0.5044	

After that, forward creep process of 9 samples is considered separately. Computed deformation values are calculated using the formula (38) of the forward creep of individual samples (N366, N367, N368, N369, N370, N371, N372, N373, N374) of asphalt concrete. As a result, the experimental strain values coincided with the results of the calculated strain values on the segment [1, 5].

When the samples were unloading the following values of elastic deformation were found:

$$N366 - \varepsilon^{ee} = 0.0160; \quad N367 - \varepsilon^{ee} = 0.0081; \quad N368 - \varepsilon^{ee} = 0.0108;$$

$$N369 - \varepsilon^{ee} = 0.0108; \quad N370 - \varepsilon^{ee} = 0.0186; \quad N371 - \varepsilon^{ee} = 0.0155;$$

$$N372 - \varepsilon^{ee} = 0.0075; \quad N373 - \varepsilon^{ee} = 0.0078; \quad N374 - \varepsilon^{ee} = 0.0249.$$

Rheological parameters of reversed creep (1 cycle) were found from the tested asphalt concrete samples of experimental values of reversed creep deformation:

$$\alpha_1 = 0.65; \quad \delta_1 = 0.0187; \quad \Gamma_m(t) = 1 - 0.0535t^{0.35}, \tag{39}$$

where $t \in [0, 60]$, t – time in seconds. Considering equation (39), the calculated values of reversed creep deformation of individual samples are found. As a result, coincidence $\varepsilon_m(t)$ and $\varepsilon_e(t)$ on the segment [0, 60] are good.

The average experimental values of reversed creep deformation of all 9 asphalt concrete samples were found values of rheological parameters of reversed creep:

$$\begin{aligned}
&2,3-cycles;\quad \alpha_1=0.65;\quad \delta_1=0.0327;\\
&4,5,6,7-cycles;\quad \alpha_1=0.65;\quad \delta_1=0.0467;\\
&8,12-cycles;\quad \alpha_1=0.65;\quad \delta_1=0.0502;\\
&9,11-cycles;\quad \alpha_1=0.65;\quad \delta_1=0.0572;\\
&10-cycle;\quad \alpha_1=0.65;\quad \delta_1=0.0537.
\end{aligned} \tag{40}$$

The average calculated values of reversed creep deformation of asphalt concrete samples are calculated using formulas (39) and (40). As a result, coincidence $\varepsilon_m(t)$ and $\varepsilon_e(t)$ are satisfactory. After the dependence of $\dfrac{\varepsilon_e(t)}{\varepsilon_e(0)}$ on the reloading of asphalt concrete samples was found, they are shown in figure 3. From the analysis of the data and figure 3 it follows:

1) the reversed creep curves of asphalt concrete have horizontal asymptotes;

2) non-loaded asphalt concrete samples continue to decline, this phenomenon is called a return;

3) the level of return of asphalt concrete samples significantly depends on the loading history;

4) the maximum return level reaches 70% of the level of forward creep of asphalt concrete;

5) the level of microstress in the sample increases with increasing reloading.

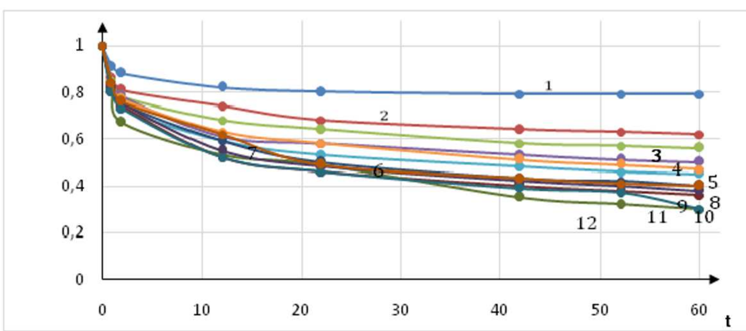


Figure 3: Recovery of the asphalt concrete strain after removing of the stress in different cycles

From the second batch, 11 samples were tested before destruction with a period of 70 seconds: forward creep of asphalt concrete samples at $\sigma = 0.3053$ MPa for the following 10 seconds; reversed creep of samples at $\sigma = 0$ for the following 60 seconds. According to the experimental values deformation of forward creep samples, the following values were found:

$$\alpha = 0.3;\quad \delta = 0.4227;\quad K_m(t) = 1 + 0.6038t^{0.7}, \tag{41}$$

where $t \in [0, 10]$, t – time in seconds. Considering equation (41), the calculated values of the creep deformation $\varepsilon_m(t)$ are calculated. The coincidence of $\varepsilon_m(t)$ with $\varepsilon_e(t)$ on the segment [1, 10] is satisfactory. From the co MParison (41) and (38) it follows that the rate of forward creep of asphalt concrete samples from the second batch of samples is almost three times lower than the rate of forward creep of asphalt concrete samples from the first batch of samples.

From the second batch of samples, the experimental values of reversed creep deformation of the samples are found:

$$\alpha_1 = 0.65; \quad \delta_1 = 0.0257; \quad \Gamma_m(t) = 1 - 0.0735t^{0.35}, \tag{42}$$

where $t \in [0, 60]$, t – time in seconds. Using the formula (42), we compute the calculated values of the reversed creep deformation of samples from the second batch of samples. The coincidence of $\varepsilon_m(t)$ and $\varepsilon_e(t)$ is good. According to the experimental data, the dependence of $\dfrac{\varepsilon_e(t)}{\varepsilon_e(0)}$ on reloading was found for samples N275 and N279, they are shown in figure 4 and figure 5. These figures show that the level of sample return has increased co MPared to the level of sample return from the first batch of samples (figure 3). All samples of the second batch of samples were fractured brittle with small deformations.

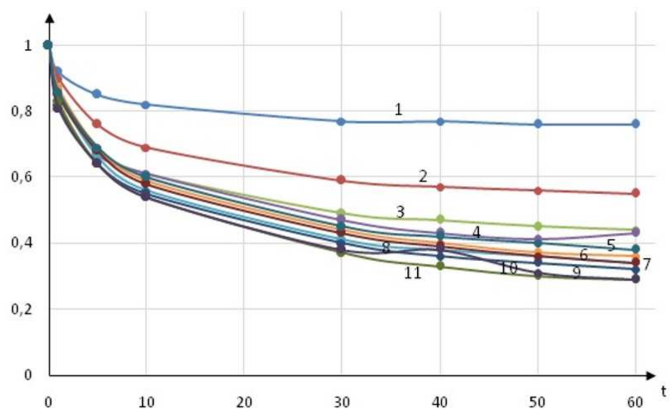


Figure 4: Recovery of the asphalt concrete strain after removing the stress in different cycles (Sample No. 275)

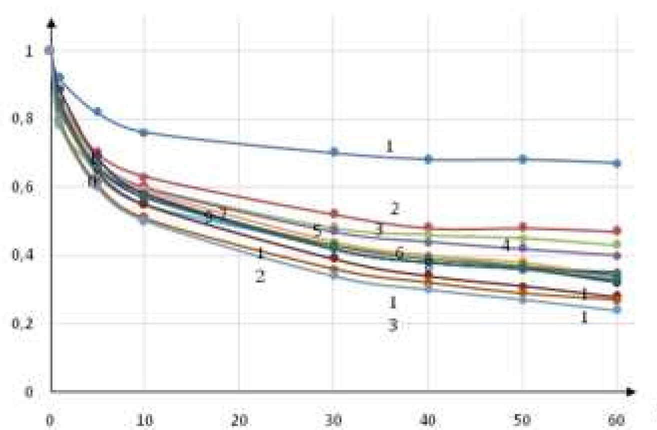
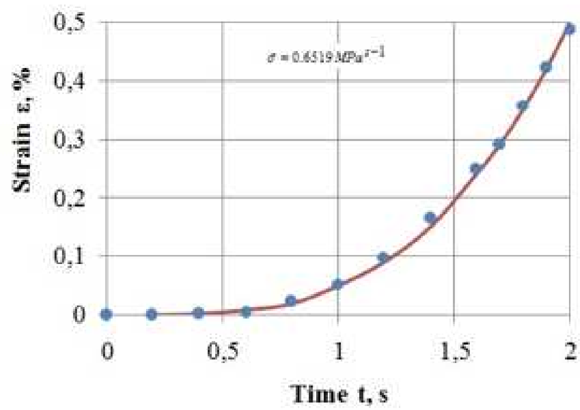


Figure 5: Recovery of the asphalt concrete strain after removing the stress in different cycles (Sample No. 279)

5 Analysis of the creep of asphalt concrete samples at $\dot{\sigma} = const$ until moment a failure at test temperature $T = 22°C - 24°C$

5.1. Loading rate $\dot{\sigma} = 0.6519$ MPa^{s-1}. Asphalt concrete 5 samples were tested. All samples were fractured brittle with small deformations. The experimental average values of creep deformation of asphalt concrete samples are shown in figure 6. Using experimental data, we will obtain:

$$a = 0.196; \quad \gamma = 3.3; \quad \overline{\alpha} = 0.9; \quad \overline{\delta} = 0.0073. \tag{43}$$



(●) – experiment, (-) - calculation

Figure 6: Graphs of strain variation in time at various loading rates $\dot{\sigma} = 0.6519$ MPa^{s-1}

Substituting (43) into (19), the calculated creep strain values $\varepsilon_m(t)$ are calculated at $\dot{\sigma} = 0.6519$ MPa^{s-1}, they are shown in figure 6. The coincidence is satisfactory. Creep parameters ($\overline{\alpha}$, $\overline{\delta}$) calculated by the above method and the correlation coefficients of asphalt concrete samples at the remaining loading rates:

$$\dot{\sigma} = 0.4678 \text{ MPa}^{s-1} : a = 0.297; \quad \gamma = 3.3; \quad \overline{\alpha} = 0.9; \quad \overline{\delta} = 0.0124.$$

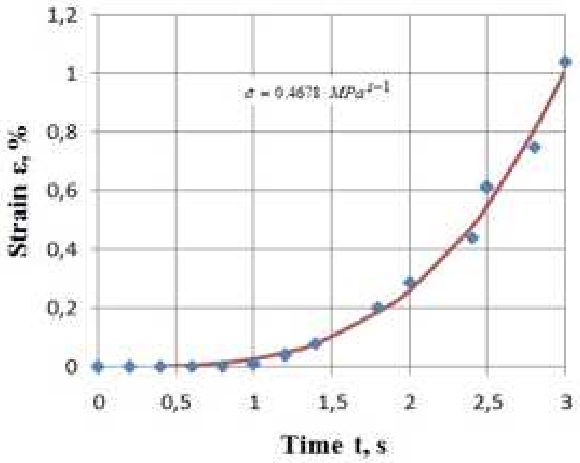
$$\dot{\sigma} = 0.0580 \text{ MPa}^{s-1} : a = 0.754; \quad \gamma = 1.6; \quad \overline{\alpha} = 0.9; \quad \overline{\delta} = 0.0004.$$

$$\dot{\sigma} = 0.0489 \text{ MPa}^{s-1} : a = 1.851; \quad \gamma = 1.8; \quad \overline{\alpha} = 0.9; \quad \overline{\delta} = 0.0032.$$

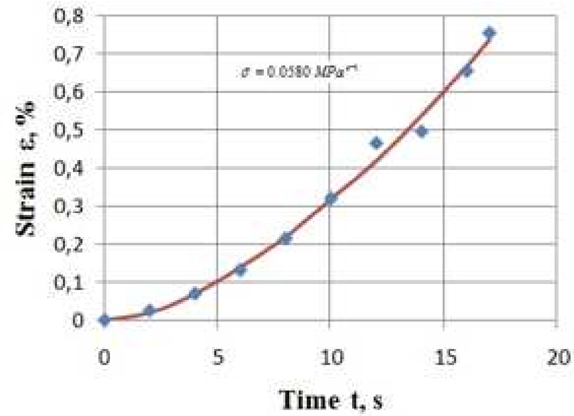
$$\dot{\sigma} = 0.0055 \text{ MPa}^{s-1} : a = 1.069; \quad \gamma = 1.01; \quad \overline{\alpha} = 0.6; \quad \overline{\delta} = 0.1517.$$

Asphalt concrete 5 samples were tested at each constant loading rate. Graphs of the deformation change over time at the found constant loading rates using the above parameters are shown in figures 7.

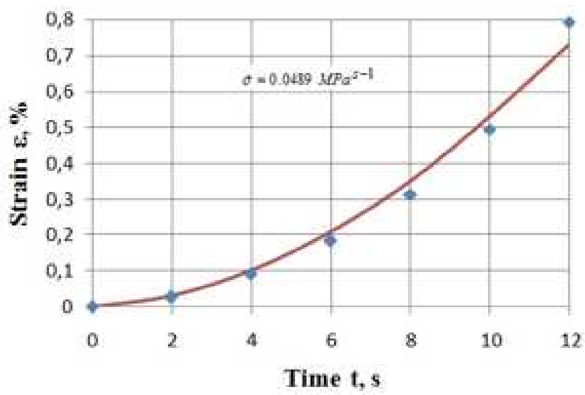
From the analysis of the constructed graphs, it can be seen that the calculated creep curves of asphalt concrete samples at each constant loading rate at a high level coincide with the corresponding experimental values.



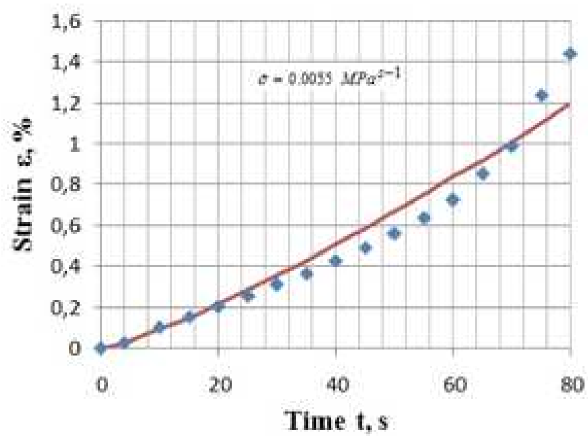
a) (•) – experiment, (–) – calculation



b) (•) – experiment, (–) – calculation



c) (•) – experiment, (–) – calculation



d) (•) – experiment, (–) – calculation

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

6 Conclusion

A method is proposed for determining the necessary material characteristics from the data of forward and reversed creep, as well as the tension of samples at a constant loading rate ($\dot{\sigma} = const$) and constant temperature ($T = const$) creep of rheonomic materials. The behavior of asphalt concrete in the increasing and constant cyclic loading is shown. The reloading effect on the reversed creep process of asphalt concrete samples has also been investigated. The analysis of the obtained results from experiments and calculations is conducted. In the course of the experiments, all samples were fractured brittle with small deformations. Until moment of failure, microcracks were observed in all samples. The source of microcracks was the local accumulation of microstress. At the same time, the level of microstress in the tested samples increased with increasing reloading. As a result of all the investigations, the result of the above equations fully corresponds to the results of the conducted experiments.

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