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Қ. И. Сәтпаев атындағы Қазақ ұлттық техникалық зерттеу университеті

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ИЗВЕСТИЯ

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СЕРИЯ ГЕОЛОГИИ И ТЕХНИЧЕСКИХ НАУК

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НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

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A NEW SIMPLE DAMAGE ACCUMULATION MODEL FOR PREDICTING OF AN ASPHALT CONCRETE CYCLIC STRENGTH

Abstract. Paper shows part of series test results for fine-grained dense asphalt concrete, prepared with the use of oxidated bitumen to failure at cyclic creep. Load and relax duration for each cycle were equal to 10 and 60 s respectively. Test temperature: 22 °C. It has been determined that creep strain under load and recovered strain at relax increase with the growth of cyclic number. The value of the recovered strain in the end of relax period decreases (from 52 to 20%) till half of the cyclic number to failure according to exponential dependence with the growth of cyclic number and further it remains constant till sample failure.

Using the curve of asphalt concrete long-term strength, constructed according to the test results of more than 110 samples to failure under creep scheme at the stresses from 0.05 to 0.31 MPa, based on Bailey's criterion, the expression was obtained for determination of cyclic strength for the asphalt concrete.

Key words: asphalt concrete, cyclic creep, creep strain, recovered strain, cyclic strength, Bailey's criterion, damage accumulation model.

Introduction. Asphalt concrete layers of highways during operational period are subject to complex combinations of mechanical impacts of vehicles' wheels and ambient temperature. As it is known, mechanical properties of asphalt concrete depend greatly on temperature and load characteristics, such as value, duration and rate of loading [1-3]. Therefore, the experimental determination of asphalt concrete characteristics, as well as modeling of its mechanical behavior in conditions close to the real ones, is practically important.

Mechanical failure of asphalt concrete pavement of the highway occurs gradually under impact of frequently repeated vehicle's load, i.e. damage, occurring with each passage of the vehicle's wheel, is accumulated.

There are several approaches to taking into account the damage accumulation in asphalt concrete pavements.

Regarding asphalt concrete the specialists know well the so-called the viscoelastic continuum damage mechanics approach (VECD), which is based on the extended elastic-viscoelastic correspondence principle, proposed by R.A. Schapery [4]. This approach, used for the first time by Little D.N. and Kim Y.R. [5-8], has been often applied by other researchers for characterization of asphalt concrete fatigue considering non-linear strain and healing [9, 10]. In the VECD-approach the physical strain and physical stiffness of the viscoelastic material (asphalt concrete) are replaced for their pseudo similarities, i.e. for pseudo strain and pseudo stiffness respectively, which are varied from one loading cycle to another. Calculation of pseudo strain requires knowledge of dynamic modulus and phase angle, which can be determined experimentally by appropriate devices.

In recent years in Kazakhstan the intensive experimental and theoretical investigations have been started on processes of deformation and failure of an asphalt concrete in various loading conditions [11-

18]. This work is a continuation of the mentioned investigations. In this work tensile strain of an asphalt concrete is analyzed experimentally under impact of cyclic stress with relax period and based on the Bailey's summation principle of damage, a formula has been proposed for determination of cyclic strength for an asphalt concrete.

Materials and methods.

1. Bitumen. Bitumen of grade 100–130, which meets the requirements of the Kazakhstan standard [19], was used in this study. The bitumen grade on Superpave is PG (Performance Grade) 64–40 [20]. Basic standard indicators of the bitumen are shown in Table 1. Bitumen is produced by the Pavlodar processing plant from the crude oil of Western Siberia (Oil processing plant, Omsk, Russia) by the direct oxidation method.

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

2. Asphalt Concrete. Hot dense asphalt concrete of type B that meets the requirements of the Kazakhstan standard [21] was prepared with the use of aggregate fractions of 5–10 mm (20%); 10–15 mm (13%); and 15–20 mm (10%) from the Novo-Alekseevsk rock pit (Almaty region, Kazakhstan); sand of fraction 0–5 mm (50%) from the plant "Asphaltconcrete-1" (Almaty city, Kazakhstan); and activated mineral powder (7%) from the Kordai rock pit (Zhambyl region, Kazakhstan).

The bitumen content of grade 100–130 in the asphalt concrete was 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. A granulometric composition curve for the mineral part of the asphalt concrete is shown in figure 1.

Table 2 – Basic standard indicators of the crushed stone

Indicator	Measurement unit	Requirements of ST RK 1284 [22]	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	$g/cм^3$	–	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

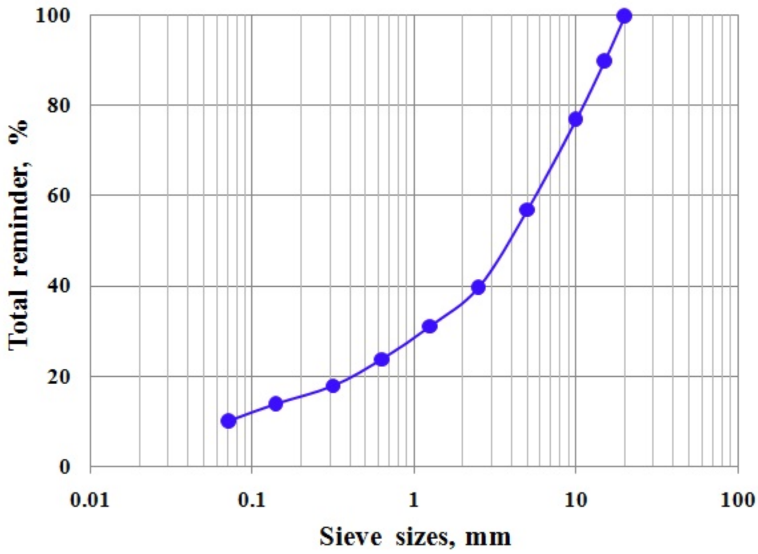

Figure 1 – Granulometric curve of mineral part of the asphalt concrete

3. Sample Preparation. Samples of the hot asphalt concrete in the form of a rectangular prism with dimensions 150x150x50 mm (figure 2) were manufactured as follows. First, the asphalt concrete samples were prepared in the form of a square slab (figure 3) using a Cooper compactor (Cooper, Nottingham, UK, model CRT-RC2S) (figure 4) according to the standard in Reference [23]. The samples were then cut from the asphalt concrete slabs in the form of a prism. Deviations in sizes of the beams did not exceed 2 millimeters.

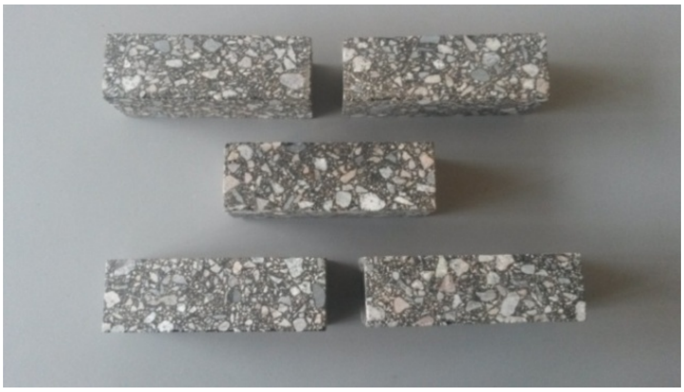

Figure 2 – Samples of the asphalt concrete with dimension 150x50x50 mm

Figure 3 – A square slab with dimension 305x305x50 mm

Figure 4 – The Cooper compactor CRT-RC2S

4. Test. Tests of hot asphalt concrete samples in a form of rectangular prism on cyclic creep were carried out according to the direct tensile scheme until a complete failure. The stress was applied to the tested sample quickly, equal to 0.305 MPa, which was kept constant for 10 seconds. Then the stress was removed quickly, and the sample was free of stress for the following 60 seconds. The test temperature was equal to 22 °C. The tests were carried out in a special homemade assembled equipment (figure 5), 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.

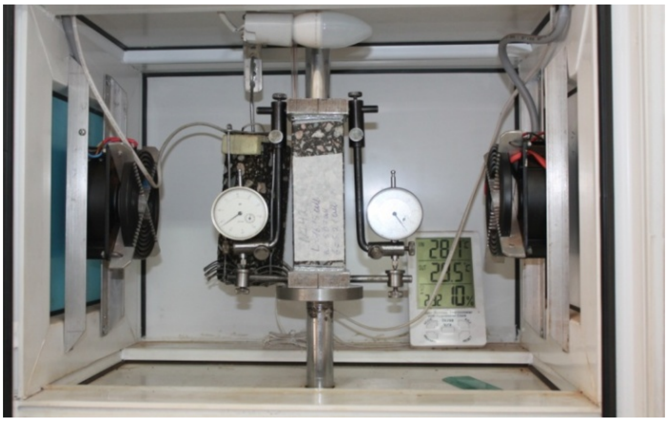

Figure 5 – A specially assembled installation for creep test

Test results. Figure 6 shows the graph of cyclic strain for asphalt concrete sample. This sample have resisted to full 12 cycles "load-relax", and it was failed in the 13th cycle. Damage time was equal to 848 seconds. Each cycle consists of loading period and relax period. The graphs, showing increase of strain under stress and its recovery during relax period in cycles, are represented in figures 7 and 8. It is clearly seen how the increase of creep strain rate under stress as well as the rate of its recovery during relax period increase with the growth of cycle number.

It is clear that maximum creep strain of each cycle occurs in the end of loading period, and maximum recovered strain occurs in the end of relax period. As it is seen from the figure 9, both these strains increase with the growth of cycle number, but the rate for the increase of the first one is considerably higher than for the second one.

It turned out that the value of the recovered strain in the end of relax period decreases (from 52 to 20 %) till 7th cycle according to exponential dependence with the growth of cycle number and further it remain constant (equal to 20 %) till sample failure (figure 10). It seems that the increased recoverability of strain in the initial cycles can be explained by the hardening of asphalt concrete.

Total 10 samples were tested in the above conditions (loading duration 10 s, relax period duration 60 s). The number of cycles to failure of samples is shown in table 4.

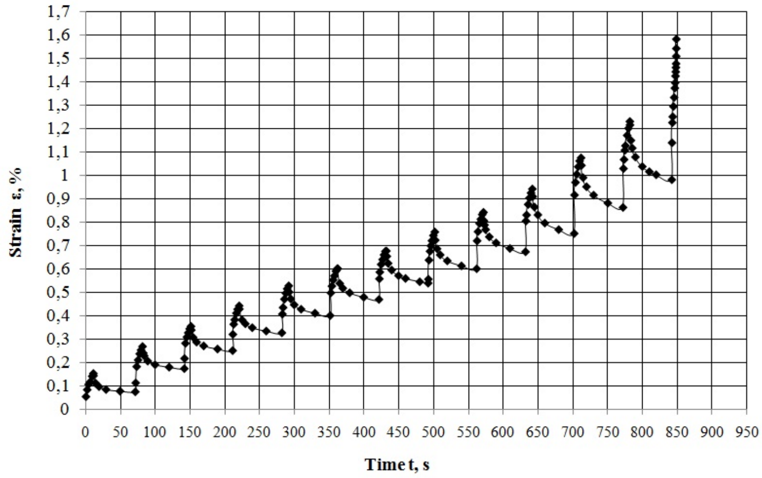

Figure 6 – Cyclic Strain of Asphalt Concrete

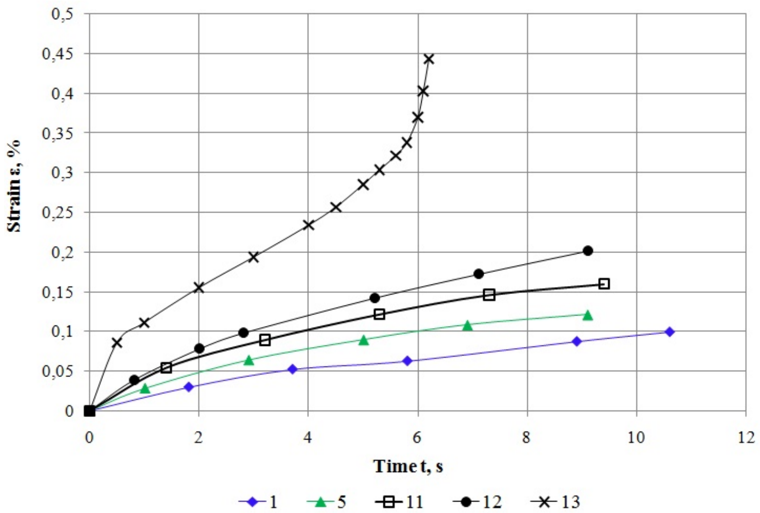

Figure 7 – Deformation of Asphalt Concrete under Stress in Various Cycles

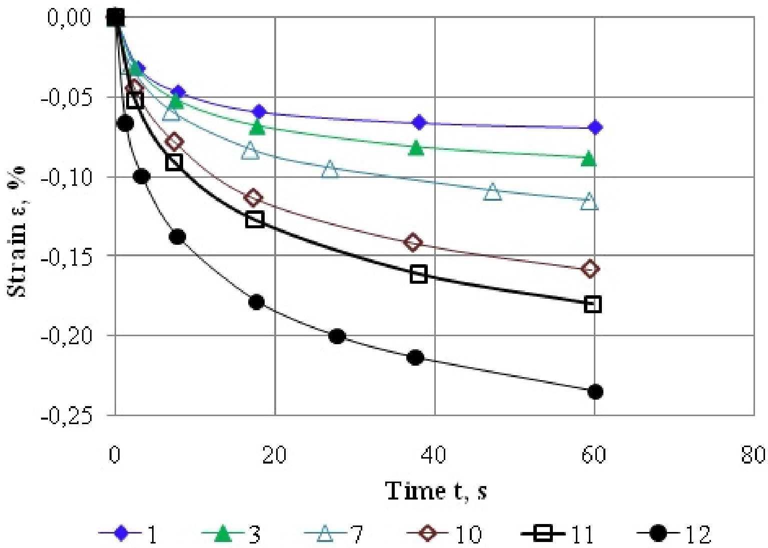

Figure 8 – Recovery of Asphalt Concrete Strain after Removal of Stress in Various Cycles

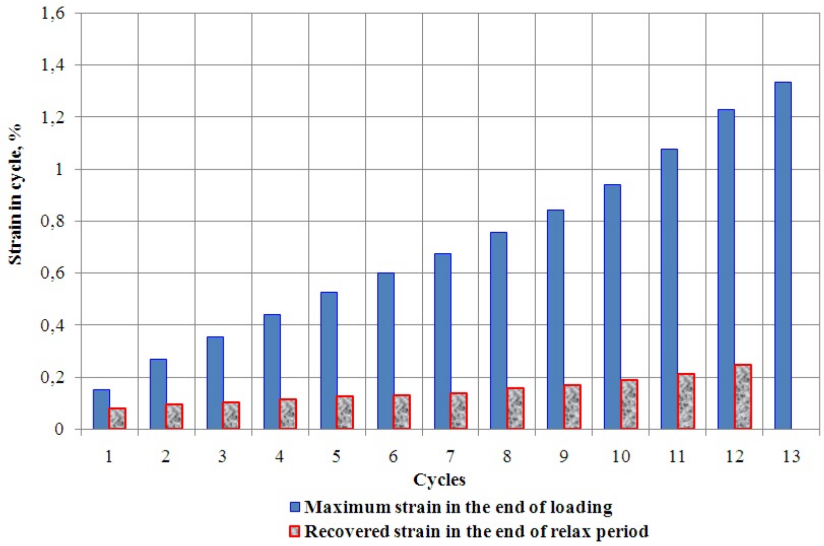

Figure 9 – Bar Charts of Maximum Strain of Asphalt Concrete
in the End of Loading and Recovered Strain in the End of Relax Period in Cycles

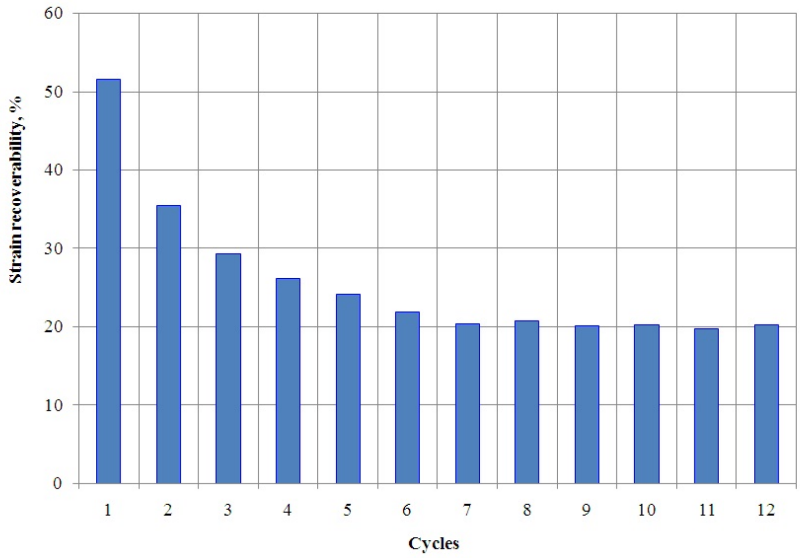

Figure 10 – Recoverability of Asphalt Concrete Strains in Cycles

Table 4 – Number of Cycles to Failure (N) of Asphalt Concrete Samples

Sample number	277	278	279	280	281	282	283	284	285	286	Average number of cycles
N	5	8	14	13	11	12	9	7	5	4	9

Cyclic strength model.

1. Bailey's criterion. At present the so-called Bailey's criterion is well-known in science and engineering practice [24] which can be described in the following form:

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

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

Bailey's criterion (1) 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.

2. Long-term strength. Long-term strength is the time, on the expiry of which the material is failed under the impact of the load, suddenly applied and kept constantly [25-27]. It is determined based on the test results for the material under the scheme of creep. Figure 6 shows the graph of long-term stress for fine-grained hot asphalt concrete at the temperature of 20-22 °C.

It is seen from figure 11 that the curve of long-term strength of the considered asphalt concrete is approximated satisfactorily by exponential function. Therefore, in accordance with [25-27], approximation function we can adopt in the following form:

$$t_p = \frac{1}{A(n+1)\sigma^n}, \tag{2}$$

t_p – failure time, s; σ – stress, MPa; A – constant, having unit $MPa^{-n}\cdot s^{-1}$; n – dimensionless exponent.

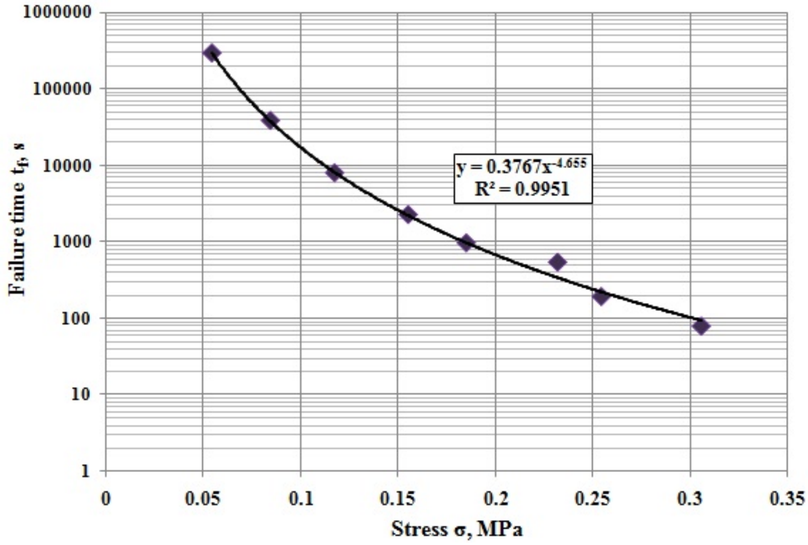

Figure 11 – Curve of long-term strength for asphalt concrete at the temperature of 20-22°C

3. Cyclic loading. As it is known the points of pavement structures are under cyclic loadings when vehicle passing. One can adopt sequential cyclic loading approximately as it is shown in figure 12, during which each cycle consists of two periods. During the first period (t_0) the applied stress σ remains constant (loading period), and during the second one (P-t_0) the stress does not occur, i.e. $\sigma = 0$ (relax period). One full loading cycle has the duration P. In this work the duration of cycles P, loading period t_0 and relax period P-t_0 are adopted as constant.

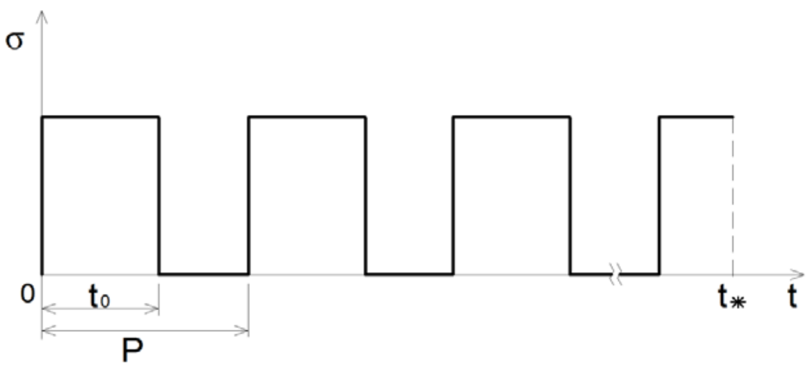

Figure 12 – Scheme of Cyclic Loading

4. Cyclic strength. Considering equation (2) Bailey's integral (1) may be written as:

$$A(n+1)\int_0^{t_p}\sigma^n(\tau)\,d\tau = 1. \qquad (3)$$

In case of cyclic loading:

$$t_* = N\cdot P, \qquad (4)$$

where t_* – failure time of material (asphalt concrete) during cyclic loading; N – number of cycles "load-relax" till failure.

Transferring from t_p to t_*, and for the case when σ = const from expression (3) we can have:

$$A(n+1)\,\sigma^n\,t_0\,\frac{t_*}{P} = 1. \qquad (5)$$

From expression (5) we can determine:

$$t_* = \frac{P}{t_0}\left[A(n+1)\,\sigma^n\right]^{-1}. \qquad (6)$$

Comparing expression (6) with expression (2), we can find that:

$$t_* = \frac{P}{t_0}t_p. \qquad (7)$$

In case of $P = t_0$, i.e. when between loading periods there is no relax, then $t_* = t_p$ occurs, i.e. time till failure is equal to long-term strength. When there is a relax period between loading periods, as could be expected, $P > t_0$, therefore $t_* > t_p$. It is logically correct. Relax between loadings should increase time till failure.

Considering expression (4), from expression (6) we can find the number of cycles "load-relax" till failure:

$$N = \frac{1}{t_0\left[A(n+1)\sigma^n\right]}. \qquad (8)$$

Values of unknown parameters A and n of the formula (8) have been determined by regression equation in Figure 6 and approximation function (2):

n = 4.655; A = 0.4694 $MPa^{-n}\cdot c^{-1}$.

Number of cycles "load-relax" till failure of asphalt concrete sample, calculated under formula (8), was equal to 9. As it was mentioned above, average number of cycles to failure of the tested ten samples was 9.

Thus, one can consider that formula (8), derived on the basis of Bailey's summation principle of damage using the equation for the curve of long-term strength, which was obtained experimentally, determines satisfactorily the cyclic tensile strength of the asphalt concrete.

Conclusion.

1. The value and rate of creep strain for an asphalt concrete under constant load are increased with the increasing of loading cycles number, the value and rate of the recovered strain are decreased during relaxation after load removal.

2. In each cycle maximum accumulated creep strain occurs in the end of loading period and maximum recovered strain after load removal also occurs in the end of relaxation period. Meanwhile both maximum accumulated creep strain and maximum recovered strain are increased with the increasing of loading cycles number. But the rate of the first strain is considerably bigger then of the second one.

3. Elastic strain value is decreased with the increasing of loading cycles number. For example, in the first cycle it was 52%, and reaching 20% in the 7^{th} cycle, remained constant till failure of the asphalt concrete sample in the 13^{th} cycle.

4. Using the curve of asphalt concrete long-term strength, constructed according to the test results of more than 110 samples to failure under creep scheme at the stresses from 0.05 to 0.31 MPa, based on Bailey's criterion, the expression was obtained for determination of cyclic strength for the asphalt concrete. The obtained expression gives the result, satisfactorily coinciding with the experimental one.

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АСФАЛЬТБЕТОННЫҢ ЦИКЛДЫҚ БЕРІКТІГІН БОЛЖАУҒА АРНАЛҒАН БҰЗЫЛУДЫҢ ЖИНАҚТАЛУЫНЫҢ ЖАҢА ҚАРАПАЙЫМ МОДЕЛІ

Аннотация. Мақалада тотықтырылған битумды пайдаланып әзірленген тығыз майда түйіршікті асфальтбетонды циклдық шаршауға қирауға дейін тәжрибелік сынықтар серияларың нәтижелерінің бір бөлігі берілген. Әр циклдағы жүктеу және демалу кезеңдерінің ұзақтығы 10 және 60 с. Сынақ температурасы: 22 °С. Күштен болған деформация мен демалу кезіндегі қайтымды деформация циклдар санының өсуіне қарай артатыны анықталды. Демалу кезеңінің соңындағы қайтымды деформация мәні қирау мерзімінің ортасына дейін экспоненциалдық заңдылық бойынша (52 %-дан 20 %-ға дейін) азаяды да, одан әрі асфальтбетон үлгісінің қирауына дейін тұрақты болып қалады.

0,05 МПа-дан 0,31 МПа аралығындағы кернеулерде жылжу схемасы бойынша қирауға дейін тәжрибелік сынақтан өткен 110 үлгінің нәтижелеріне сай анықталған асфальтбетонның ұзақ мерзімді беріктігінің қисық сызығын пайдалана отырып, және Бейли критериінің негізінде асфальтбетонның циклдық беріктігін анықтауға арналған математиқалық модель алынды.

Түйін сөздер: асфальтбетон, циклдық жылжу, жылжу деформациясы, қайтымды деформация, циклдық беріктіқ, Бейли критериі, бұзылудың жинақталу моделі.

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НОВАЯ ПРОСТАЯ МОДЕЛЬ НАКОПЛЕНИЯ ПОВРЕЖДЕНИЯ ДЛЯ ПРЕДСКАЗАНЕИЯ ЦИКЛИЧЕСКОЙ ПРОЧНОСТИ АСФАЛЬТОБЕТОНА

Аннотация. Настоящая статья представляет часть результатов серий экспериментальных испытаний плотного мелкозернистого асфальтобетона, приготовленного с использованием окисленного битума, до разрушения при циклической усталости. Длительности периодов нагружения и отдыха в каждом цикле были равны 10 с и 60 с соответственно. Температура испытания: 22 °С. Было определено, что деформация ползучести под нагрузкой и восстанавливаемая деформация при отдыхе увеличиваются с ростом числа циклов. Величина восстанавливаемой деформации в конце периода отдыха уменьшается (от 52 до 20 %) примерно до половины полного числа циклов до разрушения по экспоненциальной зависимости и в дальнейшем остается постоянной до разрушения образца асфальтобетона.

Используя кривую длительной прочности асфальтобетона, построенную в соответствии с результатами испытания 110 образцов до разрушения по схеме ползучести при напряжениях от 0,05 до 0,31 МПа, и на основе критерия Бейли было получено выражение для определения циклической прочности асфальтобетона.

Ключевые слова: асфальтобетон, циклическая ползучесть, деформация ползучести, восстанавливаемая деформация, циклическая прочность, критерий Бейли, модель накопления повреждения.

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