ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫНЫҢ

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НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН

N E W S

OF THE ACADEMY OF SCIENCES
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ГЕОЛОГИЯ ЖӘНЕ ТЕХНИКАЛЫҚ ҒЫЛЫМДАР СЕРИЯСЫ

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СЕРИЯ ГЕОЛОГИИ И ТЕХНИЧЕСКИХ НАУК

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SERIES OF GEOLOGY AND TECHNICAL SCIENCES

1 (421)

ҚАҢТАР – АҚПАН 2017 ж.
ЯНВАРЬ – ФЕВРАЛЬ 2017 г.
JANUARY – FEBRUARY 2017

ЖУРНАЛ 1940 ЖЫЛДАН ШЫҒА БАСТАҒАН
ЖУРНАЛ ИЗДАЕТСЯ С 1940 г.
THE JOURNAL WAS FOUNDED IN 1940.

ЖЫЛЫНА 6 РЕТ ШЫҒАДЫ
ВЫХОДИТ 6 РАЗ В ГОД
PUBLISHED 6 TIMES A YEAR

АЛМАТЫ, ҚР ҰҒА
АЛМАТЫ, НАН РК
ALMATY, NAS RK

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«ҚР ҰҒА Хабарлары. Геология мен техникалық ғылымдар сериясы».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Меншіктенуші: «Қазақстан Республикасының Ұлттық ғылым академиясы» РҚБ (Алматы қ.).
Қазақстан республикасының Мәдениет пен ақпарат министрлігінің Ақпарат және мұрағат комитетінде 30.04.2010 ж. берілген **№10892-Ж** мерзімдік басылым тіркеуіне қойылу туралы куәлік.

Мерзімділігі: жылына 6 рет.
Тиражы: 300 дана.

Редакцияның мекенжайы: 050010, Алматы қ., Шевченко көш., 28, 219 бөл., 220, тел.: 272-13-19, 272-13-18, http://nauka-nanrk.kz /geology-technical.kz

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Редакцияның мекенжайы: Қазақстан, 050010, Алматы қ., Қабанбай батыра көш., 69а. Қ. И. Сәтбаев атындағы геология ғылымдар институты, 334 бөлме. Тел.: 291-59-38.

Типографияның мекенжайы: «Аруна» ЖК, Алматы қ., Муратбаева көш., 75.

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«Известия НАН РК. Серия геологии и технических наук».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Собственник: Республиканское общественное объединение «Национальная академия наук Республики Казахстан (г. Алматы)

Свидетельство о постановке на учет периодического печатного издания в Комитете информации и архивов Министерства культуры и информации Республики Казахстан **№10892-Ж,** выданное 30.04.2010 г.

Периодичность: 6 раз в год
Тираж: 300 экземпляров

Адрес редакции: 050010, г. Алматы, ул. Шевченко, 28, ком. 219, 220, тел.: 272-13-19, 272-13-18,
http://nauka-nanrk.kz /geology-technical.kz

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Owner: RPA "National Academy of Sciences of the Republic of Kazakhstan" (Almaty)
The certificate of registration of a periodic printed publication in the Committee of information and archives of the Ministry of culture and information of the Republic of Kazakhstan N 10892-Ж, issued 30.04.2010

Periodicity: 6 times a year
Circulation: 300 copies

Editorial address: 28, Shevchenko str., of. 219, 220, Almaty, 050010, tel. 272-13-19, 272-13-18,
http://nauka-nanrk.kz/geology-technical.kz

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Editorial address: Institute of Geological Sciences named after K.I. Satpayev
69a, Kabanbai batyr str., of. 334, Almaty, 050010, Kazakhstan, tel.: 291-59-38.

Address of printing house: ST "Aruna", 75, Muratbayev str, Almaty

N E W S
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN
SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224-5278
Volume 1, Number 421 (2017), 141 – 148

UDC 625.7/.8:691.16

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EVALUATION OF FATIGUE CHARACTERISTICS OF HOT MIX ASPHALT WITH POLYMER ADDITIVES

Abstract. This article shows test results of conventional hot mix asphalt and hot mix asphalt with polymers Kraton and Calprene for fatigue in a regime of controlled strain by the device of four-point bending with loading frequency of 10 Hz and temperature of 10 ^{0}C. Dissipated pseudo strain energy, connected with the increase of phase angle and reduce of complex modulus, as well as total dissipated pseudo strain energy were determined. Diagrams of dissipated strain energy changes were made depending on the number of loading cycles. Correlations were stated between the number of loading cycles to failure and constant strain of testing, between the number of loading cycles and total dissipated strain energy at failure. It was found that hot mix asphalt with polymer Calprene has the highest fatigue strength.

Keywords: hot mix asphalt, Bitumen, Polymer additives, Fatigue.

1. Introduction. Asphalt concrete is one of the main pavement materials of modern highways. It represents a composite material including bitumen binder, crushed stone, sand, mineral powder and other additives [1].

Fatigue cracking is one of the main types of destruction for asphalt concrete layers of pavement. Fatigue cracking occurs and develops under the influence of multiple loading [2-4]. Adding of polymers in asphalt concrete increases its resistance to destruction, including a fatigue cracking.

Nowadays, the most widespread test method of hot mix asphalt for fatigue is the test under cycle loading on the device of four-point bending [5-7]. Usually the tests are carried out in a regime of constant strain.

Dissipated energy, connected with increase of defect sizes, has a special place in the continuum damage mechanics. From this classical point of view, it is reasonable to evaluate amount of dissipated strain energy with increase of the number of loading cycles. Dependencies are practically important, which are determined between amount of dissipated strain energy and characteristics of fatigue strength.

2. Materials used.

2.1. Bitumens. Pure bitumen of grade 90-130, meeting the requirements of Kazakhstan standard ST RK 1373-2005, and bitumens modified with polymers Kraton and Calprene 501, meeting the requirements of Kazakhstan standard ST RK 1025-2010, were used in this paper. Polymers Kraton and Calprene 501 were added into the pure bitumen in amount of 4 % from the mass of bitumen. According to Superpave the bitumen grade is PG 64-40 [8]. Tables 1 and 2 show main standard characteristics of pure bitumen and bitumens modified with polymers. Pavlodar petrochemical plant manufactured pure bitumen from crude oil of Western Siberia (Russia) by direct oxidation.

2.2. Hot Mix Asphalt. Dense hot mix asphalt of type B, according to the Kazakhstan standard ST RK 1225-2003, was prepared with the use of aggregate of fractions 5-10 mm (20 %), 10-15 mm (13 %), 15-20 mm (10 %) from Novoalekseyevsk borrow pit (Almaty Region), sand fraction 0-5 mm (50 %) from the plant “Asphalt concrete-1” (Almaty city) and activated mineral powder (7 %) from Kordai borrow pit (Zhambyl Region). Content of the pure bitumen of grade 90-130 in hot mix asphalt is 4,8 % by weight of dry mineral filler. Main standard characteristics of aggregate and hot mix asphalts are shown in Tables 3-5.

Table 1 – Main standard characteristics of pure bitumen

Characteristics	Measurement unit	ST RK 1373-2005 requirements	Value
Penetration, 25 ^{0}C, 100 g, 5 s	0,1 mm	91-130	98
Penetration index PI	–	-1,0… +1,0	-0,96
Elasticity:	cm		
25 ^{0}C		≥ 65	139
0 ^{0}C		≥ 4,0	5,5
Ring and ball temperature	^{0}C	≥ 43	45,3
Fraas point	^{0}C	≤ -20	-24,6
Dynamic viscosity, 60 ^{0}C	Pa·s	≥ 75	174,2
Cinematic viscosity, 135 ^{0}C	mm^2/s	≥ 180	409,0

Table 2 – Main standard characteristics of bitumen with polymers

Characteristics	Measurement unit	ST RK 1025-2010 requirements	Value	
			Bitumen + Kraton	Bitumen + Calprene 501
Penetration, 25 ^{0}C, 100 g, 5 s	0,1 mm	≥ 60	84	52
Elasticity:	cm			
25 ^{0}C		≥ 65	58	64
0 ^{0}C		≥ 40	8,1	16
Ring and ball temperature	^{0}C	≥60	65,3	76
Fraas point	^{0}C	≤ -22	-26,5	-23,7

Table 3 – Main standard characteristics of aggregate

Characteristics	Measurement unit	ST RK 1284-2004 requirements	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	-	–	satisfactory	satisfactory
Water saturation	%	–	1,93	0,90

Table 4 – Main standard characteristics of conventional hot mix asphalt

Characteristics	Measurement unit	ST RK 1225-2003 requirements	Value
Average density	g/cm^3	–	2,39
Water saturation	%	1,5-4,0	3,2
Voids in mineral aggregate	%	≤ 19	14
Air void content	%	2,5-5,0	3,8
Compression strength:	MPa		
0 ^{0}C		≤13	7,0
20 ^{0}C		≥ 2,5	3,4
50 ^{0}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	4,0

Table 5 – Main characteristics of hot mix asphalts with polymers

Characteristics	Measurement unit	ST RK 1223-2013 requirements	Value	
			HMA+ Kraton	HMA+Calprene 501
Average density	g/cm^3	–	2,40	2,42
Water saturation	%	1,5-3,0	2,4	2,2
Voids in mineral aggregate	%	≤ 19	14,8	16,2
Air void content	%	2,5-5,0	3,3	3,2
Compression strength:	MPa			
0 ^{0}C		≤9,0	7,9	7,7
50 ^{0}C		≥ 1,8	2,3	2,3
Water stability	–	≥ 0,80	0,88	0,96
Shear stability	MPa	≥ 0,38	0,44	0,43
Crack stability	MPa	4-6	4,4	4,4

3. Test methods.

3.1. Sample Preparation. Samples of hot mix asphalts in the form of rectangular beam with the length of 380 mm, width of 50 mm and height of 50 mm were manufactured in the following way. First, samples of hot mix asphalts were prepared in the form of square slab by roller compactor of Cooper company (United Kingdom, model CRT-RC2S) according to the standard EN 12697-33, 2003 [9]. Then the samples in the form of beam were cut from hot mix asphalt slabs. Discrepancies in dimensions did not exceed 2 mm.

3.2. Test. Testing of hot mix asphalts samples in the form of rectangular beam was carried out according to the standard EN 12697-24 (2004) on the device of Cooper company according to the scheme of four-point bending (4PB beam test, model CRT-SA4PT-BB) in regime of controlled strain. Strain values were set as follows: ε = 200, 250, 300, 350 and 400 $\mu\varepsilon$. Frequency of loading and test temperature were set equal to 10 Hz and 10 ^{0}C respectively. All samples were tested up to reach 50 % of its initial stiffness (complex modulus).

4. Dissipated pseudo strain energy.

It is known that there is reliable correlation dependence between the number of cycles to failure N_f and total dissipated energy W of hot mix asphalt [10, 11]. Total dissipated strain energy in each cycle is calculated according to “Eq. 1” [12]:

$$W = \pi\sigma\,\varepsilon\sin\delta_N\,, \tag{1}$$

where W is total dissipated energy, σ is stress, ε is strain and δ_N is phase angle.

Conditions of deformation for tested sample are close to deformation of purely viscoelastic material for the initial cycles of loading, as a damage is not available or little available. Accumulated damage in samples increases with increase of the number of loading cycles, which results in reduce of stiffness (complex modulus) and increase of phase angle. Total dissipated strain energy in any cycle W, calculated according to equation (1), includes part of energy dissipated due to viscoelastic deformation of non-damaged material as well as energy dissipated due to accumulated damage in material.

A relationship between stress and pseudo strain was used in the papers [13, 14] to separate dissipated energy due to damage of material from viscoelastic energy. For the case of testing in a regime of controlled strain the following expressions were obtained:

$$W_{R1} = \frac{1}{2}\varepsilon^2(E^*_{VE} - E^*_N)\,, \tag{2}$$

$$W_{R2} = \pi E^*_{VE}\,\varepsilon^2\sin(\delta_N - \delta_{VE})\,, \tag{3}$$

where W_{R1} is dissipated pseudo strain energy connected with reduce of complex modulus, W_{R2} is dissipated pseudo strain energy connected with increase of phase angle, E^*_{VE} is complex modulus of non-damaged viscoelastic material, δ_{VE} is phase angle of non-damaged viscoelastic material, E^*_N is complex modulus of damaged viscoelastic material in cycle *N* and δ_N is phase angle of damaged viscoelastic material in cycle *N*.

Total amount of dissipated pseudo strain energy in loading cycle *N* is calculated as the sum of expressions (2) and (3):

$$W_R = W_{R1} + W_{R2} . \quad (4)$$

5. Results and discussion.

5.1. Number of Loading Cycles to Failure. Obtained correlation dependencies between the number of loading cycles to failure and constant strain of testing are given in Figure 1. It was found that hot mix asphalt HMA+Calprene showed the highest fatigue strength at the intermediate strains (250-350 $\mu\varepsilon$) of testing. It is known that the value of tension strain in asphalt concrete layers of pavement is usually within 50-150 $\mu\varepsilon$ in real cases of truck wheel loading. Therefore, practical use of stated correlation dependence for hot mix asphalt HMA+ Calprene will show essential high fatigue strength.

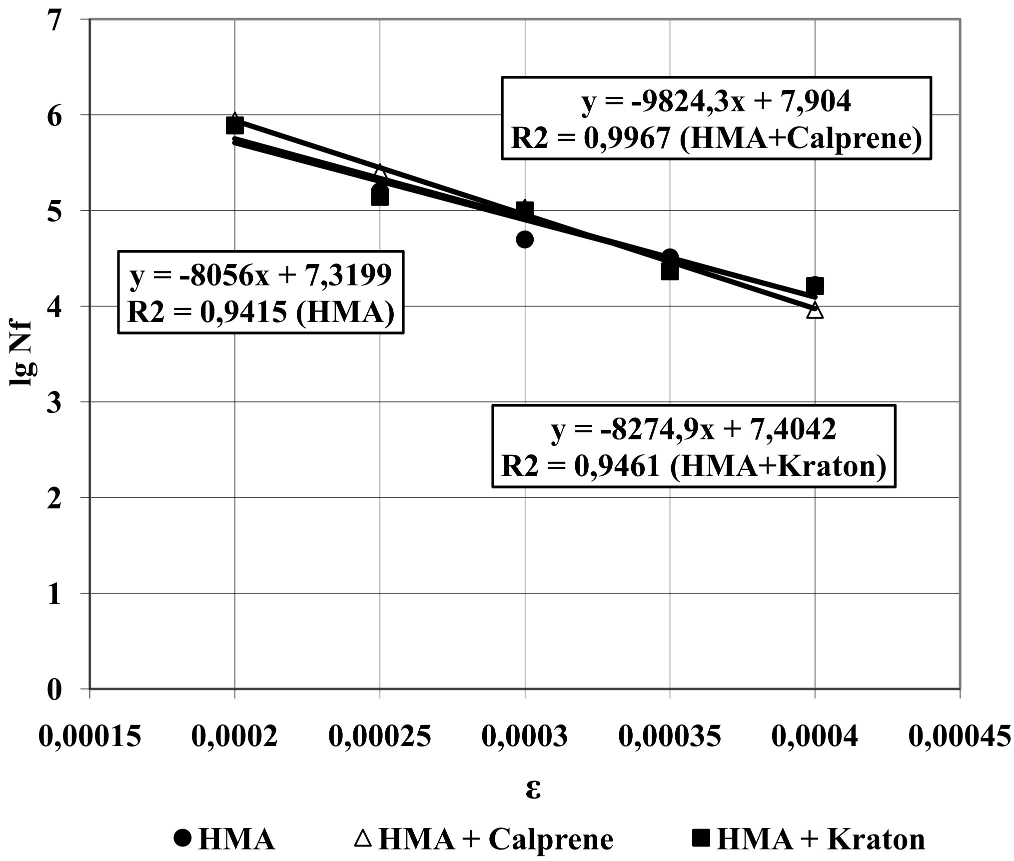

Figure 1 – Number of loading cycles to failure of hot mix asphalts versus constant strain of testing.

5.2. Dissipated Pseudo Strain Energies. Values of complex modulus E^*_{VE} and phase angle δ_{VE} in calculations carried out using "Eqs. 2-3", conform to the non-damaged pure viscoelastic state of hot mix asphalt. They were determined by means of testing of other hot mix asphalt samples on the four-point bending device at constant strain $\varepsilon = 50\mu\varepsilon$. Values of characteristics E^*_{VE} and δ_{VE} for the considered hot mix asphalt are given in Table 6.

Diagrams of changes of dissipated pseudo strain energy connected with the reduce of complex modulus W_{R1}, dissipated pseudo strain energy connected with the increase of phase angle W_{R2} and total dissipated pseudo strain energy W_R for the conventional hot mix asphalt at constant strain 200 με are presented in Figure 2. This figure shows that energies W_{R1}, W_{R2} and W_R in semi-logarithmic coordinates

Table 6 – Values of characteristics E^{*}_{VE} and δ_{VE} for hot mix asphalt

Hot mix asphalt	E^{*}_{VE}, MPa	δ_{VE}, *grade*
HMA	6097,6	24,54
HMA + Kraton	7993,4	18,51
HMA+ Calprene	8103,45	19,00

increase approximately linearly with the increase of the number of loading cycles. Value of dissipated pseudo strain energy connected with the increase of phase angle W_{R2} is approximately 2–2,5 times more than the pseudo strain energy connected with the reduce of complex modulus W_{R1}.

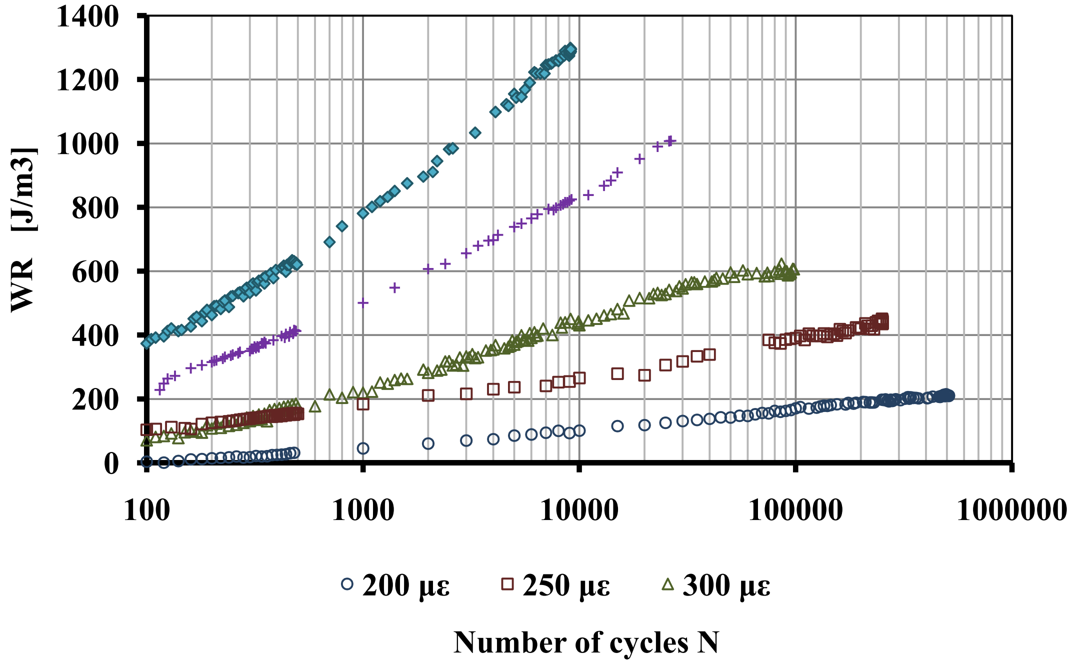

Figure 2 – Types of energies at constant strain 200 με

Diagrams of total dissipated pseudo strain energy changes versus the number of loading cycles for the conventional hot mix asphalt are shown in Figure 3. As it can be seen the total dissipated pseudo strain energy W_{R2} in semi-logarithmic coordinates increases almost linearly with the increase of the number of loading cycles at small strains of testing. Nonlinearity of the above indicated dependence is revealed more with the increase of constant strain of testing.

Similar conformities of changes of energy W_{R1}, W_{R2} and W_{R} have been also determined for the hot mix asphalt with polymers Kraton and Calprene.

5.3. Dissipated Pseudo Strain Energies at Failure. It is reasonable that values of dissipated pseudo strain energies in cycle corresponding to failure of hot mix asphalt W_{R1f}, W_{R2f} and W_{Rf} are of interest. Table 7 and 8 show the values of these characteristics for the tested hot mix asphalts. We can see that all pseudo strain energies at failure for conventional hot mix asphalt (HMA) are slightly less than for hot mix asphalts with polymers. The biggest values of pseudo strain energies at failure are dissipated from hot mix asphalt with polymer Calprene.

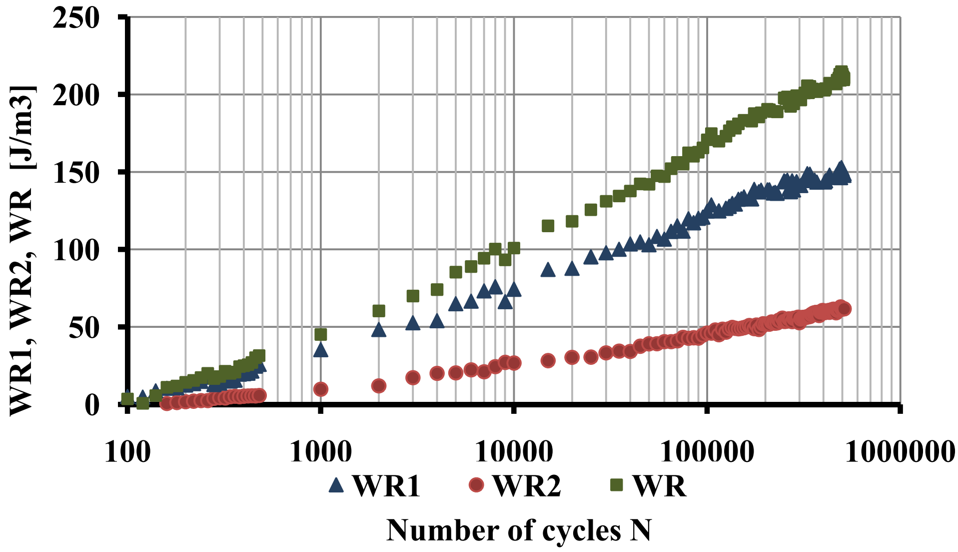

Figure 3 – Total dissipated pseudo strain energy at different constant strain (HMA)

Table 7 – Dissipated pseudo strain energies W_{R1f} and W_{R2f} of hot mix asphalts

Constant strain of testing, $\mu\varepsilon$	Dissipated energy W_{R1f}, J/m^3			Dissipated energy W_{R2f}, J/m^3		
	HMA	HMA+ Kraton	HMA + Calprene	HMA	HMA + Kraton	HMA + Calprene
200	110,31	116,83	135,43	60,11	81,28	82,72
250	194,20	291,66	284,01	75,23	150,95	117,23
300	390,04	406,10	484,68	165,56	166,04	184,55
350	565,63	717,55	653,90	189,63	268,04	258,28
400	766,57	921,34	1032,90	249,83	358,37	309,92

Table 8 – Total dissipated pseudo strain energy W_{Rf} of hot mix asphalts

Constant strain of testing, $\mu\varepsilon$	Total dissipated energy W_{Rf}, J/m^3		
	HMA	HMA+ Kraton	HMA+ Calprene
200	170,42	198,12	218,15
250	269,42	442,62	401,74
300	555,60	572,13	669,23
350	755,25	985,59	912,15
400	1016,40	1279,71	1342,82

Reliable correlation dependences are established between the number of loading cycles to failure and total dissipated pseudo strain energy at failure for considered hot mix asphalts (Figure 4). These Figures clearly show the advantage of hot mix asphalts with polymers compared to conventional hot mix asphalt. At similar small values of total dissipated pseudo strain energy at failure ($W_R \le 600$ J/m^3), hot mix asphalt with polymer Calprene has the biggest number of loading cycles to failure which has N_f more than half of one order compared to conventional hot mix asphalt.

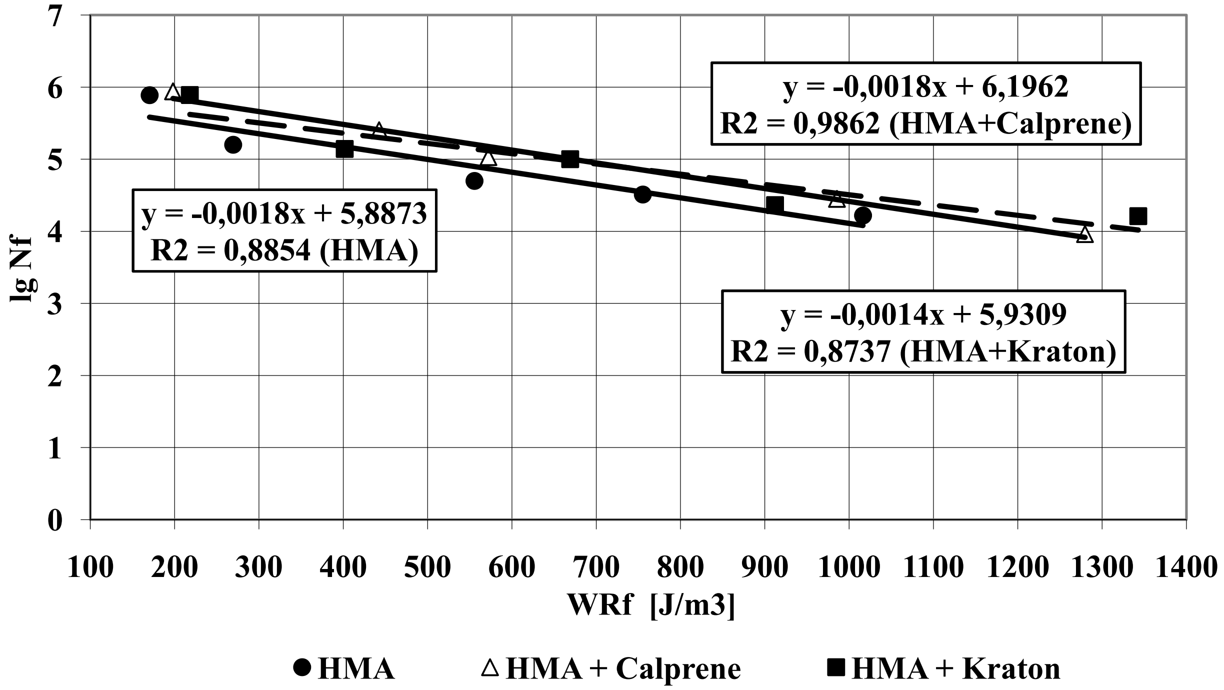

Figure 4 – Number of loading cycles to failure of hot mix asphalts versus total dissipated pseudo strain energy at failure

6. Conclusions.

1. Three types of hot mix asphalt – conventional hot mix asphalt and hot mix asphalts with polymers Kraton and Calprene were tested for fatigue on four-point bending equipment with frequency of loading 10 Hz and at temperature 10 ºC in controlled strain regime.

2. Correlation dependences are established between the number of loading cycles to failure and constant strain of testing for tested hot mix asphalts. All three types of hot mix asphalt have practically similar fatigue strength at average strains of testing (250-300 $\mu\varepsilon$), and hot mix asphalt with polymer Calprene showed the biggest fatigue strength at small strain (less than 200 $\mu\varepsilon$).

3. Values of dissipated pseudo strain energy related to the phase angle increasing, dissipated pseudo strain energy related to complex modulus decreasing and total dissipated pseudo strain energy were evaluated. Values of these types of energies increase approximately linearly in semi-logarithmic coordinates with increase of the number of loading. Value of dissipated pseudo strain energy related to the phase angle increases approximately 2-2,5 times more than of dissipated pseudo strain energy related to complex modulus decrease.

4. Reliable correlation dependences are established between the number of loading cycles to failure and total dissipated pseudo strain energy at failure for considered hot mix asphalts. Hot mix asphalt with polymer Calprene showed the biggest fatigue strength at small values of total dissipated pseudo strain energy which has the number of loading cycles to failure more than half of one order compared to conventional hot mix asphalt.

The work was performed under the Contract No. 36 dated 21 July 2016 "Improvement of standard and technical base of the road branch" with the Committee of Roads of the Ministry for Investments and Development of the Republic of Kazakhstan.

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ПОЛИМЕР ҚОСПАЛЫ ЫСТЫҚ АСФАЛЬТБЕТОННЫҢ ШАРШАУ СИПАТТАМАЛАРЫН БАҒАЛАУ

Аннотация. Мақалада кәдімгі ыстық асфальтбетон мен Kraton және Calprene полимерлері қосылған ыстық асфальтбетондарды төрт нүктелі июші аспабында 10 ^{0}C температурада 10 Гц жиілікпен күш түсіріп бақыланатын деформация режимінде сынау нәтижелері берілген. Фазалық бұрыштың өсуі және комплекстік модулдың кемуімен байланысты сейілген псевдодеформация энергиялары, сейілген толық псевдодеформация энергиясы анықталды. Сейілген деформация энергияларының күш циклдарының санына байланыстылығының графиктері көрсетілген. Күш циклдарының сыну саны мен тұрақты сынақ деформациясы арасындағы, күш циклдарының сыну саны мен сынуға дейінгі толық сейілген деформация энергиясы арасындағы корреляциялық байланыстар анықталды. Calprene полимері қосылған ыстық асфальтбетонның шаршау беріктігінің ең үлкен екендігі табылды.
Түйін сөздер: ыстық асфальтбетон, битум, полимер қоспалар, шаршау.

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ОЦЕНКА УСТАЛОСТНЫХ ХАРАКТЕРИСТИК ГОРЯЧЕГО АСФАЛЬТОБЕТОНА С ПОЛИМЕРНЫМИ ДОБАВКАМИ

Аннотация. Представлены результаты испытания традиционного горячего асфальтобетона и асфальтобетонов с полимерными добавками Kraton и Calprene на усталость в режиме контролируемой деформации на приборе четырехточечного изгиба при частоте нагружения 10 Гц и температуре 10 ^{0}C. Определены рассеянные энергии псевдодеформации, связанные с повышением фазового угла и понижением комплексного модуля, полная рассеянная энергия псевдодеформации. Построены графики зависимости рассеянных энергий деформации от числа циклов нагружения. Установлены корреляционные зависимости между числом циклов нагружения до разрушения и постоянной деформацией испытания, числом циклов нагружения до разрушения и полной рассеянной энергией деформации при разрушении. Было найдено, что горячий асфальтобетон с полимером Calprene имеет наибольшую усталостную прочность.
Ключевые слова: горячий асфальтобетон, битум, полимерные добавки, усталость.

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www:nauka-nanrk.kz

ISSN 2518-170X (Online), ISSN 2224-5278 (Print)

http://geolog-technical.kz/index.php/kz/

Верстка *Д. Н. Калкабековой*

Подписано в печать 15.02.2017.
Формат 70x881/8. Бумага офсетная. Печать – ризограф.
15,25 п.л. Тираж 300. Заказ 1.

Национальная академия наук РК
050010, Алматы, ул. Шевченко 28, т. 272-13-19, 272-13-18