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The fatigue behavior of SBS/nanosilica composite modified asphalt binder and mixture

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HIGHLIGHTS

- Modification of asphalt binder and asphalt mixture with SBS/nanosilica nanocomposite proposed.
- SBS/nanosilica nanocomposite produced binder with largely different properties.
- SBS/nanosilica nanocomposite increases the fatigue life of asphalt mixture significantly.
- SBS/nanosilica nanocomposite with 6% nanosilica and 5% SBS result in the best fatigue life.

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ABSTRACT

In this study, the effect of SBS polymer, nanosilica, and SBS/nanosilica nanocomposite on the fatigue life of asphalt binder and asphalt mixture was investigated. Linear amplitude sweep (LAS) test was used to evaluate the fatigue life of asphalt binder and a fatigue model was developed by the viscoelastic continuum damage model. The four-point flexural bending test at three strain levels was also used in asphalt mixtures. In addition, correlation equations were developed between the fatigue behavior of asphalt binder and asphalt mixtures. The results showed that the fatigue life of asphalt binder and asphalt mixture were increased significantly by adding SBS/nanosilica nanocomposite and experimental results indicated that the optimum content of nanosilica was 6%. In addition, a good correlation was observed between the fatigue life of asphalt binder and asphalt mixture.

1. Introduction

Damage to asphalt pavement caused by repeated stresses and strains due to traffic loads is considered fatigue and it is one of the main distress mechanisms in asphalt pavements [1]. Flexible pavement fatigue cracking is caused by horizontal tensile strain at the bottom of the asphalt layer [2]. According to experimental studies, fatigue cracking begins through the binder phase and spread to the whole mix [3]. As asphalt binder plays a key role in the fatigue behavior of asphalt mixture, many researchers investigated the use of additives in order to improve the asphalt binder properties in asphalt mixtures [4,5]. Polymers have the ability to increase asphalt binder stiffness at high temperatures and improve the asphalt binder ductility at low temperatures. In this way, they reduce the rutting at high temperatures and fatigue cracking at moderate and low temperatures. However, due to the poor compatibility of polymer with asphalt binder, when it is stored at high temperatures it tends to separate from asphalt binder. In addition, polymer properties are reduced after exposure to heat, oxygen, and UV rays [6]. When the SBS and asphalt binder are blended, as the molecular weights of the polymeric chains are higher or equal than those of asphaltenes, a phase separation may occur [7,8]. Therefore, many studies show that polymers could not be effective alone in the improvement of all pavement distress such as rutting, fatigue, moisture-induced damage and aging [9,10].

Increasing demand to access for asphalt mixtures with better properties, and some of the deficiencies observed in polymers, have led polymer nanocomposites to be considered as more powerful modifiers. Nanosilica is generally used in the preparation of polymeric nanocomposite blends due to the high reaction between silica material and the asphalt binder that results in a higher dispersion ability of nanosilica and polymers within the bitumen blend compared to other nanomaterials [11,12].

In recent years, various polymer nanocomposites have been used by researchers to improve the physical, rheological, and

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mechanical properties of asphalt binder and the performance of asphalt mixture. The nanoclay/SBS nanocomposite is one of them which increases the viscosity and complex modulus of asphalt binder modified with SBS and decreases the phase angle and improves the tensile strength and the fatigue life of the asphalt mixture [13,14]. Another nanocomposite is the combination of nanosilica and SBS. Ghasemi et al. (2012) investigated the potential benefits of nanosilica and SBS in SMA asphalt mixtures used in pavements. The results of these studies showed that modified asphalt mixtures with 5% SBS plus 2% nanosilica powder lead to the best results as this modification can increase physical and mechanical properties of asphalt binder and mixture [15].

Al-Hamali et al. (2015) evaluated the performance properties of modified asphalt binder with polymer mixed with nanosilica. As a result, the effect of nanosilica was evaluated on the stability of storage and physical and rheological properties. According to the results of DSR testing, the addition of nanosilica increases the complex modulus at low frequencies or high temperatures compared to asphalt binder with polymer, therefore, leading to higher resistance to rutting. In contrast, at low frequencies or moderate temperatures, the complex modulus was decreased, leading to fatigue performance improvement at temperatures below 40 °C [16].

Yousef et al. (2014) examined the performance properties (moisture sensitivity, resilient modulus and dynamic creep) of the asphalt mixture modified with nanosilica/SBS nanocomposite that based on the results distress due to moisture is reduced and the resistance of asphalt mixture and resistance to rutting are increased [17].

As seen in recent years, studies have been performed on polymer nanocomposites. but so far, the effect of SBS/nanosilica nanocomposite on the performance grade of asphalt binder, the fatigue life of asphalt binder and asphalt mixture and their relationship and comparison with the fatigue life of asphalt mixture with polymer and asphalt mixture with nanosilica have not been studied, that in order to achieve these goals, this study was carried out.

The objectives of this study are to:

(1) Laboratory evaluation of the effect of adding SBS/nanosilica nanocomposite on the fatigue life of asphalt binder using LAS test.
(2) Laboratory evaluation of the fatigue life of asphalt mixtures modified with SBS/nanosilica polymer nanocomposites in various percentages of nanosilica and determination of the optimal percentage of nanosilica result in the best fatigue life.
(3) The effect of adding SBS/nanosilica nanocomposite on fatigue life compared to adding nanosilica on fatigue life and SBS polymer on fatigue life.
(4) Evaluation of the effect of adding SBS/nanosilica nanocomposite on the performance grade of asphalt binder.
(5) The development of the prediction models of the fatigue behavior of asphalt binder and asphalt mixture and the evaluation of their correlation.
(6) The development of the prediction model of the fatigue life of asphalt mixture based on the fatigue life of asphalt binder.

2. Materials and methods

2.1. Materials

The aggregates used in this research were from Qazvin Abyek mine (Iran). The aggregation of these materials is for the construction of asphalt mixtures based on the fifth type of AASHTO continuous aggregate grading, which is shown in Table 1. The asphalt binder used in this research is the 60–70 asphalt binder prepared from Isfahan Refinery. The physical properties of asphalt binder are shown in Table 2.

2.2. Additives

In this study, two additives including SBS polymer and nanosilica and their combination were used to modify asphalt binder. SBS is a three-component polymer that increases asphalt binder stiffness at high temperatures and improves its flexibility at lower temperatures [18]. Its basic properties are according to Table 3. As in several papers the optimal percentage of SBS polymer was investigated to improve asphalt binder performance [19–22], the optimal percentage of SBS polymer was chosen as 5% by weight of asphalt binder.

The reason for using nanosilica is the low cost of production and high performance properties. Nanosilica has a high specific surface area, strong surface adsorption, good dispersion capability, high chemical purity and excellent strength [23]. In addition to these beneficial properties, nanosilica has the potential to be used as an asphalt binder modifier to improve the performance of asphalt mixtures. In this study, nanosilica was added to asphalt binder at 4, 6 and 8% by weight of asphalt binder. Its physical and chemical properties are shown in Table 4.

2.3. Sample preparation

A high shear mixer was used to add polymer and nanosilica to asphalt binder. First, the asphalt binder was heated alone to form a uniform liquid. Then, the SBS polymer was added to asphalt binder at 5% by weight of asphalt binder and finally, the nanosilica was added slowly to the mixture to the desired extent and mixed with asphalt binder at 3000 rpm at the temperature of 163 °C [24]. Then to evaluate the aging effect on modified asphalt binder, they were exposed to the RTFO- and PAV-aging processes.

Then, modified asphalt binder was added to aggregates to make asphalt mixtures and based on the Marshall mixing design process the optimum asphalt binder percentage was determined [25].

Table 2
Asphalt binder properties.

Softening point (°C)	Viscosity at 135 °C	Penetration at 25 °C	Flash Point (°C)
49.6	325	65	348

Table 3
SBS polymer base properties.

Molecular Weight	Tensile strength (MPa)	Special weight	Styrene to butadiene ratio	Structure
145,000	1.5	0.95	68.5–31.5	Linear

Table 4
Physical and chemical properties of nanosilica.

Shape	Particle size	Purity	Color	Physical state	Chemical formula	Chemical name
Spherical	20–40 nm	95 percent	White	Powdery	Sio_2	Nanosilica dioxide

Table 1
The aggregation used in the mix design.

Sieve size (mm)	3.4 in. (19)	1.2 in. (12.5)	Size 4 (4.75)	Size 8 (2.36)	Size 50 (0.3)	Size 200 (0.075)
Aggregation range (passing percent)	100	90–100	44–74	28–58	5–21	2–10
Used aggregation (passing percent)	100	95	59	43	13	6

3. Experimental design

3.1. Standard bitumen tests

Penetration tests were performed according to ASTM D5 standard and softening point test was conducted according to ASTM D36 standard on modified asphalt binder.

3.2. High and low temperature performance grading

Increasing $G^*/\mathrm{Sin}\ \delta$ eventually reducing the asphalt binder deformation during the loading. For non-aged asphalt binder $G^*/\mathrm{Sin}\ \delta > 1$ KPa and for the short term aged asphalt binder, $G^*/\mathrm{Sin}\ \delta > 2.2$ KPa (ASTM-D2872). Bending Beam Rheometer (BBR) test can be used to determine properties of asphalt binder at low temperature.

3.3. Linear amplitude sweep test

In asphalt binder fatigue testing, the Superpave specification parameter $G^*.\mathrm{Sin}\ \delta$ is usually used. This parameter is developed based on the dissipated energy in the linear viscoelastic range. Given that modified asphalt binder showed a better fatigue strength and its response entered into the nonlinear range, using this parameter in such asphalt binder type is not reliable. The time sweep test has been determined in NCHRP 9-10 report as an appropriate alternative method for modified asphalt binder. According to the definition of fatigue; that is, loss of material integrity due to repeated loading, the test is performed by the DSR subjected to a large number of loading on the sample with two types of constant stress and constant strain [26,27].

According to AASHTO TP 101-12, this test is performed in two steps: the first step of frequency sweep followed by the second stage of amplitude sweep. In the first step, it is possible to determine parameter *B*. This parameter describes the properties of undamaged asphalt mixtures. This step includes imposing loads at strain level of 0.1% and the range from 0.2 to 30 Hz. The next step is the amplitude sweep step or strain in which parameter *A* can be determined by the viscoelastic continuum damage. At this stage, oscillatory shear loading is performed at a constant frequency of 10 Hz. As shown in Fig. 1, the strain increases stepwise from 0.1% to 30% in 310 s during 3100 cycles. This test is performed at the mid-temperature of asphalt [10] and it evaluates asphalt binder strength to fatigue according to its performance [28].

The results of linear amplitude sweep test are applicable in the context of viscoelastic continuum damage (VECD) model.

3.4. Four-point bending fatigue test

Four-point flexural bending fatigue test can be performed under two controlled stress and strain conditions. Failure under controlled stress condition can be easily defined, so that the samples are failed after a short time of crack initiation. But under controlled strain condition, failure is defined based on the time when the stiffness reaches to 50% of the initial stiffness. This criterion was used based on AASHTO T321 standard. In this study, the test was performed under controlled strain condition to evaluate the fatigue life of asphalt mixture. To study the fatigue life, three strain levels of 400, 700 and 1000 were considered in sinusoidal loading mode. To develop a better fatigue model, the test was performed according to the standard at a temperature of 20 °C and loading frequency was determined to be 10 Hz. Since, in practice, produced asphalt mixtures in the asphalt plant are under short-time aging and the fatigue phenomenon usually occurs when the asphalt mixture is in service for several years and long-term aging occurs, to investigate the effect of short- and long-term aging on the fatigue life of asphalt mixtures with these additives, the short- and long-term aging processes were performed according to AASHTO R30 standard on asphalt mixtures and then fatigue tests were conducted on them.

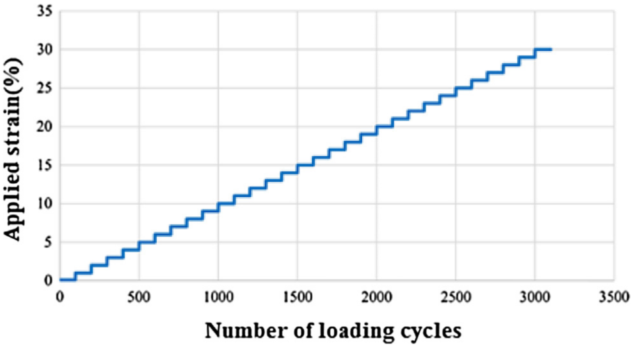

Fig. 1. Schematic loading of LAS test [28].

4. Results and discussion

4.1. Standard bitumen test

Penetration and softening point tests were performed on the unmodified and modified asphalt binder. The results indicate an increase in the softening point and a decrease in the penetration degree in the modified asphalt binder according to the following diagrams (see Figs. 2 and 3).

4.2. Determining the performance grading of asphalt binder at high temperature

The results of $G^*/\mathrm{Sin}\ \delta$ are as shown in Figs. 4 and 5. The results show that the base asphalt binder used in this research has a high performance grade 64 °C.

The results of $G^*/\mathrm{Sin}\ \delta$ at various temperatures showed that the above-mentioned additives increase the performance grade of asphalt binder at high temperature, so that nanosilica and SBS polymer increase one grade and nanosilica/SBS nanocomposite increase 2–3 grades, depending on the amount of additives, the results of which are summarized in the following Table 5.

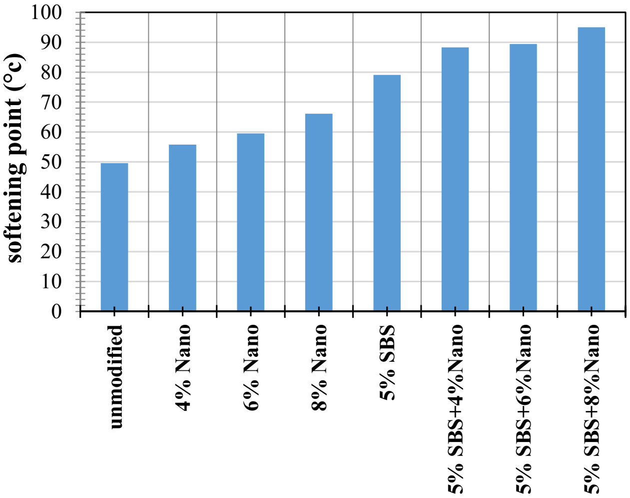

Fig. 2. Softening point of the unmodified and modified asphalt binder.

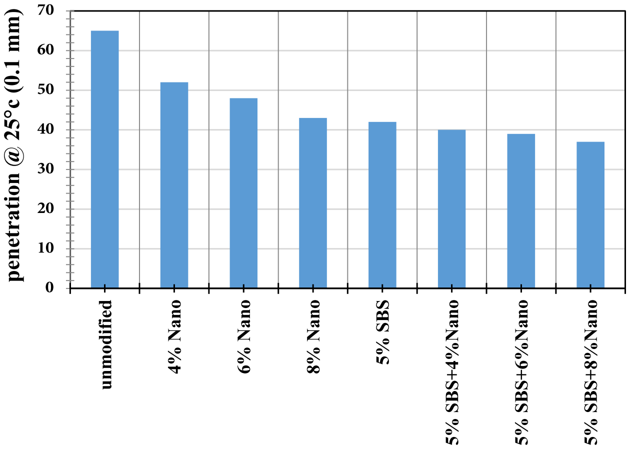

Fig. 3. Penetration of unmodified and modified asphalt binder.

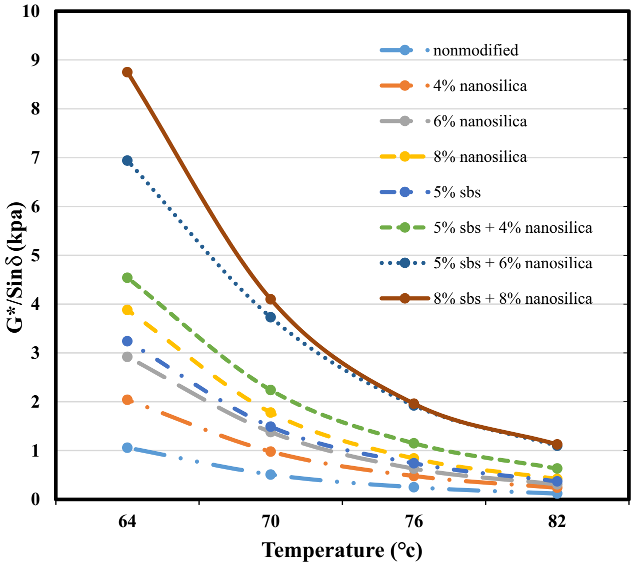

Fig. 4. G^*/Sind at non-aged state.

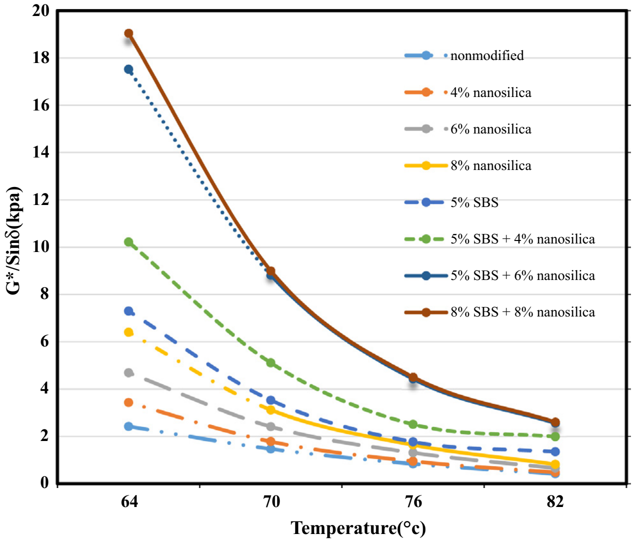

Fig. 5. G^*/Sind at short-term aged state.

Table 5
High temperature performance grade of the studied asphalt binders.

Type of asphalt binder	High temperature performance
60/70	64
60/70 + 4% nanosilica	64
60/70 + 6% nanosilica	70
60/70 + 8% nanosilica	70
60/70 + 5% SBS	70
60/70 + 4% nanosilica + 5% SBS	76
60/70 + 6% nanosilica + 5% SBS	82
60/70 + 8% nanosilica + 5% SBS	82

4.3. Determining the performance grading of asphalt binder at low temperature

In order to evaluate the binder rheological properties at low temperature, BBR test were used. The experimental result of m (60 s) are shown in Table 6. According to the results, the performance grade of the base asphalt binder is at low temperature −22 °C. In all states, the modification of the base asphalt binder with nanosilica at low temperature reduces one degree the performance grade and it reaches to −16 °C, but other additives do not affect the performance grade of asphalt binder at low temperatures.

4.4. LAS test

4.4.1. Fatigue life of modified asphalt binder (short term aging)

The full details of the damage properties and the fatigue behavior of asphalt binder with various additives are given in Table 7. The greater the severity of damage is at the failure moment, the greater the material strength to fatigue is [3]. As seen, fatigue models were obtained for all samples based on VECD analysis.

As seen, there are many differences in the fatigue life of asphalt binder with various additives. Nanosilica increases the fatigue life of asphalt binder. SBS polymer has also a positive effect and its effect is more than nanosilica, but SBS/nanosilica nanocomposite has a significant effect on the fatigue life and not only increases the fatigue life several times higher than the unmodified asphalt binder, but also increases it considerably compared to asphalt binder with only SBS polymer or nanosilica. Among nanocomposites, the nanocomposite with 5% SBS and 6% nanosilica has the best fatigue life.

4.4.2. Fatigue life of modified asphalt binder (long term aging)

The values of the fatigue life of asphalt binder with additives that were involved with long-term aging by PAV testing are shown in Table 8. As observed, with an increase in the strain rate due to long-term aging, the fatigue life is decreased more severely.

4.5. Fatigue life analysis of asphalt mixtures

Table 9 shows the full details of the results of fatigue life as well as the fatigue life model of asphalt mixtures tested in different strain levels in a short-term aged.

As observed in Table 9, with an increase in strain level the fatigue life decreases because the increase of strain level increases the applied stress to the mixture. This increase contributes to the advancement of destructive processes, such as the growth of capillary cracks and the failure of the bond between asphalt binder and aggregates resulting in a rapid reduction in the stiffness of mixtures and reaching the failure conditions. Among all asphalt mixtures in this study, the fatigue life of asphalt mixtures with SBS/nanosilica nanocomposite is more than others so that the

Table 6
BBR test results.

Type of asphalt binder	Temperature	m (60S)	Temperature	m (60S)
60/70	−6	0.383	−12	0.317
60/70 + 4% nanosilica	−6	0.363	−12	0.298
60/70 + 6% nanosilica	−6	0.349	−12	0.284
60/70 + 8% nanosilica	−6	0.325	−12	0.271
60/70 + 5% SBS	−6	0.406	−12	0.347
60/70 + 4% nanosilica + 5% SBS	−6	0.347	−12	0.332
60/70 + 6% nanosilica + 5% SBS	−6	0.386	−12	0.324
60/70 + 8% nanosilica + 5% SBS	−6	0.379	−12	0.309

Table 7
Damage properties and the fatigue behavior of asphalt binder (short-term aging).

Sample	D_f	Fatigue life in strain		Damage level	Damage model
		5%	2.5%		
Unmodified asphalt binder	42	1426	15,043	0.504	$N_f = 3.388 \times 10^5 (\gamma_{\max})^{-3.399}$
5% SBS	56	3955	80,321	0.630	$N_f = 4.300 \times 10^6 (\gamma_{\max})^{-4.344}$
4% nano	47	1698	17,541	0.543	$N_f = 3.842 \times 10^5 (\gamma_{\max})^{-3.368}$
6% nano	44	1593	17,394	0.537	$N_f = 4.101 \times 10^5 (\gamma_{\max})^{-3.449}$
8% nano	42	1300	16,996	0.522	$N_f = 5.085 \times 10^5 (\gamma_{\max})^{-3.709}$
4% nano + 5% SBS	137	19,153	258,781	0.826	$N_f = 8.084 \times 10^6 (\gamma_{\max})^{-3.756}$
6% nano + 5% SBS	144	29,980	496,201	0.833	$N_f = 2.027 \times 10^7 (\gamma_{\max})^{-4.049}$
8% nano + 5% SBS	134	19,250	270,009	0.798	$N_f = 8.863 \times 10^6 (\gamma_{\max})^{-3.810}$

Table 8
Fatigue life at strain levels of 2.5 and 5% (long-term aging).

Fatigue life at strain level	Unmodified	4% nanosilica	6% nanosilica	8% nanosilica	5% SBS	4% nano + 5% SBS	6% nano + 5% SBS	8% nano + 5% SBS
2.5%	13,137	18,143	16,760	12,361	21,589	96,063	123,130	61,224
5%	959	1179	1117	559	803	5021	5848	2936

Table 9
The fatigue life of asphalt mixtures at various strain levels (short-term aging).

Sample	$\varepsilon \times (10^{-6})$	N_f	Fatigue Model	R^2
Control	400	15,030	$N_f = 6 \times 10^9 (\varepsilon)^{-2.158}$	0.9943
	700	3985		
	1000	2121		
5% SBS	400	73,905	$N_f = 3 \times 10^{12} (\varepsilon)^{-2.942}$	0.9954
	700	16,499		
	1000	4874		
4% Nano	400	17,729	$N_f = 4 \times 10^9 (\varepsilon)^{-2.065}$	0.9833
	700	4579		
	1000	2757		
6% Nano	400	20,633	$N_f = 1 \times 10^9 (\varepsilon)^{-1.823}$	0.927
	700	5110		
	1000	4124		
8% Nano	400	55,973	$N_f = 5 \times 10^{11} (\varepsilon)^{-2.682}$	1
	700	12,354		
	1000	4802		
4% Nano + 5%SBS	400	116,619	$N_f = 2 \times 10^{13} (\varepsilon)^{-3.101}$	0.9449
	700	35,662		
	1000	6235		
6% Nano + 5%SBS	400	383,334	$N_f = 1 \times 10^{15} (\varepsilon)^{-3.641}$	0.9165
	700	112,069		
	1000	11,989		
8% Nano + 5%SBS	400	250,500	$N_f = 1 \times 10^{15} (\varepsilon)^{-3.722}$	0.9692
	700	50,805		
	1000	7656		

fatigue life of these asphalt mixtures is much more than that of the asphalt mixtures with nanosilica and without additive and it is between 2 and 5 times more than the fatigue life of asphalt mixtures with SBS polymer. Among nanocomposite asphalt mixtures, the asphalt mixture with 5% SBS and 6% nanosilica has the highest fatigue life and then the asphalt mixture with 5% SBS and 8%

nanosilica and the asphalt mixture with 5% polymer are ranked the next highest and 4% nanosilica has the lowest fatigue life. After nanocomposites, the asphalt mixture with SBS polymer has the highest fatigue life. Among the asphalt mixtures with nanosilica, the asphalt mixture with 8% nanosilica has the highest fatigue life and after that asphalt mixture with 6% nanosilica and finally asphalt mixture with 4% nanosilica are ranked. The results of the fatigue life of asphalt binder due to the linear amplitude sweep test are consistent with the results of the fatigue life of asphalt mixture due to the four-point bending fatigue test.

4.5.1. The effect of long-term aging on fatigue life reduction severity

As observed in Fig. 6, fatigue life decreases as a result of long-term aging. At low strain levels, the fatigue life reduction severity due to long-term aging is almost the same in asphalt mixtures with various asphalt binder, but at high strain levels in which damage occurs due to traffic loads and the resulted fatigue, the fatigue life reduction severity due to long-term aging is lower in asphalt mixtures made with SBS/nanosilica nanocomposites than that of in binder mixtures made with base asphalt.

4.5.2. Changes in cumulative dissipated energy in different strains

Fig. 7 shows the accumulated dissipated energy of different asphalt binder. The more dissipated energy is, the more energy materials absorb. Therefore, cracking in the asphalt will be less and fatigue life will increase. According to the following diagram, the amount of dissipated energy also confirms the better performance of the asphalt binder with SBS/nanosilica nanocomposite.

4.6. The prediction model of the fatigue life of asphalt mixture based on that of asphalt binder

Models were obtained for the samples according to Table 10 based on the fitting results of the fatigue life of asphalt mixture of different samples with corresponding fatigue life of asphalt binder. As observed, in all samples, the prediction model accurately correlates the fatigue life of asphalt mixture to that of asphalt binder and the values of R^2 in all samples are above 0.9.

To create a prediction model for the fatigue life of asphalt mixture based on that of asphalt binder, the model will be proportional to the line fitted to the results according to the following equation, and the diagram will be according to Fig. 8.

$$(N_f)_M = 0.3448(N_f)_B \quad R^2 = 0.8658$$

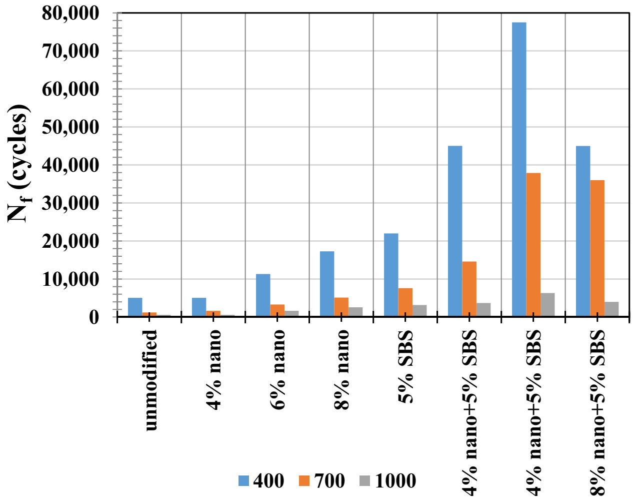

Fig. 6. The fatigue life of asphalt mixtures under long-term aging.

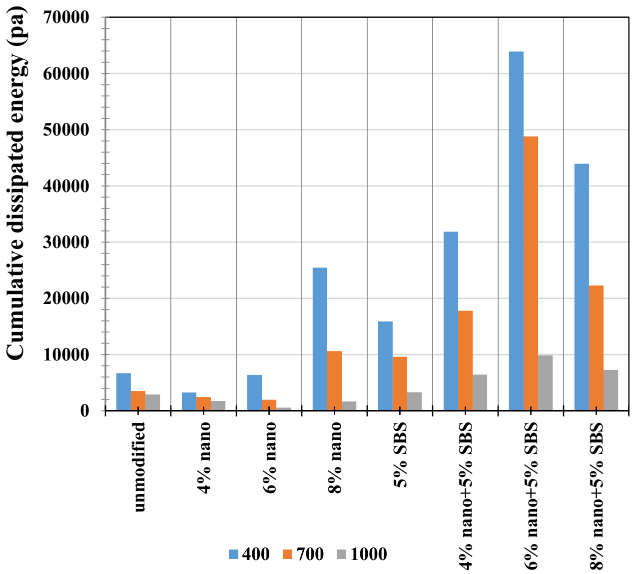

Fig. 7. Cumulative dissipated energy in different strain rates.

Table 10
Correlation equations that correlate the fatigue behavior of asphalt binder and that of asphalt mixture.

Sample	Regression equation	R^2
Unmodified	$(N_f)_M = 0.5146(N_f)_B$	0.8752
5% SBS	$(N_f)_M = 0.3866(N_f)_B$	0.8292
4% Nano	$(N_f)_M = 0.5221(N_f)_B$	0.8843
6% Nano	$(N_f)_M = 0.6023(N_f)_B$	0.8305
8% Nano	$(N_f)_M = 1.5765(N_f)_B$	0.8967
4% Nano + 5%SBS	$(N_f)_M = 0.2188(N_f)_B$	0.8154
6% Nano + 5%SBS	$(N_f)_M = 0.3485(N_f)_B$	0.8193
8% Nano + 5%SBS	$(N_f)_M = 0.4333(N_f)_B$	0.9089

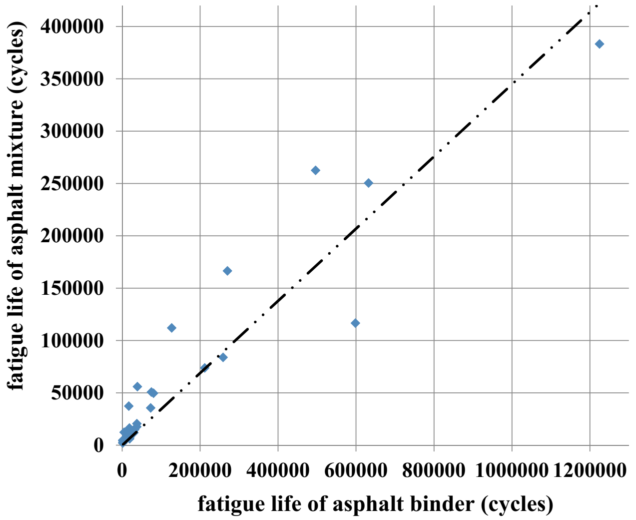

Fig. 8. Prediction model of the fatigue life of asphalt mixture based on that of asphalt binder.

5. Results

- SBS/nanosilica nanocomposite reduces penetration of asphalt binder and increases the softening point.
- SBS/nanosilica nanocomposite improves the high grade of asphalt binder 2–3 grades, but does not change the low grade of asphalt binder.

- SBS/nanosilica nanocomposite increases significantly the fatigue life of asphalt binder and asphalt mixture so that its effect is several times more than the effect of nanosilica on the increase of fatigue life and is 2–5 times more than the effect of SBS polymer on the increase of the fatigue life.
- SBS/nanosilica nanocomposite with 6% nanosilica and 5% SBS result in the best fatigue life.
- Asphalt mixture with SBS/nanosilica nanocomposite have the most dissipated energy, which confirms the better performance of this type of asphalt mixture compared to other asphalt mixtures used.
- There is a good correlation between the fatigue life of asphalt binder and asphalt mixture, so that the fatigue life of asphalt mixture based on the fatigue life of asphalt binder can be easily obtained by equations.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

References

[1] I.L. Al-Qadi, S. Diefenderfer, A. Loulizi, Fatigue Life characterization of superpave mixtures at the virginia smart road, Virginia Transportation Research Council, 2005.

[2] Y.H. Huang, Pavement Analysis and Design, Englewood Cliffs, New Jersey, 1993.

[3] F. Safaei, J.S. Lee, L.A.H.D. Nascimento, C. Hintz, Y.R. Kim, Implications of warm-mix asphalt on longterm oxidative ageing and fatigue performance of asphalt binders and mixtures, Road Mater. Pavement Des. 15 (sup1) (2014) 45–61.

[4] M.J. Khattak, A. Khattab, H.R. Rizvi, Characterization of carbon nano-fiber modified hot mix asphalt mixtures, Constr. Build. Mater. 40 (2013) 738–745.

[5] B.W. Tsai, C.L. Monismith, M. Dunning, N. Gibson, J. D'Angelo, R. Leahy, G. King, D. Christensen, D. Anderson, R. Davis, D. Jones, Influence of asphalt binder properties on the fatigue performance of asphalt concrete pavements, J. Assoc. Asphalt Paving Technol. 74 (2005) 733–789.

[6] J. Yu et al., Effect of montmorillonite on properties of styrene butadiene-styrene copolymer modified asphalt binder, Polym. Eng. Sci. 47 (9) (2007) 1289–1295.

[7] B. Golestani, F. Moghadas Nejad, S. Sadeghpour Galooyak, Performance evaluation of linear and nonlinear nanocomposite modified asphalts, Constr. Build. Mater. 35 (2012) 197–203.

[8] S.S. Galooyak, B. Dabir, A.E. Nazarbeygi, A. Moeini, Rheological properties and storage stability of bitumen/SBS/montmorillonite composites, Constr. Build. Mater. 24 (3) (2010) 300–307.

[9] J.S. Chen, M.C. Liao, M.S. Shiah, Asphalt modified by styrene-butadiene-styrene triblock copolymer: Morphology and model, J. Mater. Civ. Eng. 14 (3) (2002) 224–229.

[10] A. Kavussi, P. Barghabany, Investigating fatigue behavior of nanoclay and nano hydrated lime modified asphalt binder using LAS test, J. Mater. Civ. Eng. 28 (3) (2015) 04015136.

[11] P.C. LeBaron, Z. Wang, T.J. Pinnavaia, Polymer-layered silicate nanocomposites: an overview, Appl. Clay Sci. 15 (1999) 11–29.

[12] S.S. Ray, M. Okamoto, Polymer/layered silicate nanocomposites: a review from preparation to processing, Prog. Polym. Sci. 28 (2003) 1539–1641.

[13] F. Khodari, Longer Fatigue Life for Asphalt Pavement Using (SBS@Clay) Nanocomposite, Int. J. Curr. Eng. Technol. 5 (2) (2015).

[14] M. Arabani, A.K. Haghi, R. Tanzadeh, Laboratory evaluation of nanoclay composite effects on mechanical properties of aged asphalt mixture, Polym. Res. J. 8 (4) (2014).

[15] M. Ghasemi, Seyed M. Marandi, M. Tahmooresi, R.J. Kamali, R. Taherzade, Modification of stone matrix asphalt with nano SiO_2, J. Basic Appl. Sci. Res. (2012) 1338–1344.

[16] D. Alhamali, J. Wu, Q. Liu, Physical and rheological properties of polymer modified asphalt binder with nanosilica particles, Arab. J. Sci. Eng. (2015).

[17] N. Yusoff, A. Abozed Saleh, H. Alattug, The effects of moisture susceptibility and ageing conditions on nano-silica/polymer-modified asphalt mixtures, Constr. Build. Mater. 72 (2014) 139–147.

[18] G.M. Hrdlicka, V. Tandon, J. Prozzi, A. Smit, Y. Yildrim, Evaluation of binder tests for identifying rutting and cracking potential of modified asphalt binders, Center for Transportation Infrastructure Systems, Research Report 0-4824-1, 2007.

[19] J.S. Chen, M.C. Liao, C.H. Lin, Determination of polymer content in modified asphalt binder materials and structures, 36 (2003) pp. 594–598.

[20] A. Khodaii, A. Mehrara, Evaluation of permanent deformation of unmodified and SBS modified asphalt mixtures using dynamic creep test, Constr. Build. Mater. 23 (2009) 2586–2592.

[21] S. Tayfur, H. Ozen, A. Aksoy, Investigation of rutting performance of asphalt mixtures containing polymer modifiers, Constr. Build. Mater. 21 (2007) 328–337.

[22] S.F. Kalyoncougl, M. Tigdemir, A model for dynamic creep valuation of SBS modified HMA mixtures, Constr. Build. Mater. 25 (2011) 859–866.

[23] S. Sadeghpoor, M. Palassi, A. Goli, Performance evaluation of nano-silica modified asphalt binder, Int. J. Transport. Eng. 3 (1) (2015).

[24] D.I. Alhamali et al., The effects of nano silica particles on the physical properties and storage stability of polymer-modified asphalt binder, J. Civ. Eng. Res. 5 (4A) (2015) 11–16.

[25] A.F. Mirhosseini et al., Evaluating fatigue behavior of asphalt binders and mixes containing date seed ash, J. Civ. Eng. Manage. 23 (8) (2017) 1164–1175.

[26] H.U. Bahia, D.I. Hanson, M. Zeng, H. Zhai, M.A. Khatri, R.M. Anderson, Characterization of modified asphalt binders in superpave mix design, No. Project 9-10, 2001.

[27] C. Hintz, H. Bahia, Understanding mechanisms leading to asphalt binder fatigue in the dynamic shear rheometer, Road Mater. Pavement Des. (sup2) (2013) 231–251.

[28] C. Hintz, R. Velasquez, C. Johnson, H. Bahia, Modification and validation of linear amplitude sweep test for binder fatigue specification, Transport. Res. Record: J. Transport. Res. Board 2207 (2011) 99–106.