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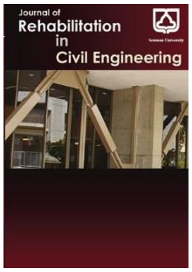

Estimation the Fatigue Number of Stone Mastic Asphalt Mixtures Modified with Nano SiO_2 and Nano TiO_2

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ABSTRACT

Asphalt modification/reinforcement has received considerable attention as viable solutions to enhance flexible pavement performance. This is mainly prompted by the unsatisfactory performance of traditional road materials exposed to dramatic increases and changes in traffic patterns. This paper presents the evaluation of fatigue behaviour of nano reinforced Stone Mastic Asphalt mixtures. Fatigue is one of the most important distresses in asphalt pavement structure due to repeated load of heavy traffic services which occur at intermediate temperatures. There are different test methods used throughout the world to measure fatigue resistance for asphalt concrete mixtures. In this study, indirect tensile fatigue test was conducted to estimate fatigue number of asphalt mixture with different contents of nano SiO_2 and Nano TiO_2. The results indicated that the addition of different percentages of nano particles is capable to improve the shear modulus of modified bitumen. Also, modified SMA mixtures had more resistance against fatigue cracking phenomena.

1. Introduction

Roads are considered as one of the most important elements of infrastructure. They play an essential role in our lives for the present and in the future. Thus, highway construction engineers must consider the primary user's requirements of safety as well as the economy. To achieve this goal, highway construction designers should take into account three fundamental requirements which include environmental factors, traffic flow, and asphalt concrete mixtures materials. In asphalt concrete (AC), bitumen as a binder serves two major functions in road pavement: first, to hold the aggregates firmly and, second, to act as a sealant against water. However, due to some distresses like fatigue failure, the performance and durability of bitumen are highly affected by changes with time in terms of its characteristics which can lead to the cracking of pavement [1].

The design of asphalt mixtures involves the selection of materials to obtain the good properties in the pavement. Hot mix asphalt (HMA) is designed to resist fatigue cracking, rutting, and cracking in low temperatures. These distresses reduce the serviceability of the HMA and elevate the maintenance costs [2].

However, the mechanical properties of HMA mixtures are deficient in resisting pavement distresses. Hence, the task of asphalt pavement researchers is to evaluate the different additives for modifying the bitumen and HMA mixtures [2].

Due to an increase in service, traffic density, axle loading, and low maintenance services, road structures have deteriorated and are therefore subjected to failure more rapidly. To minimize the damage of pavement such as resistance to rutting and fatigue cracking, asphalt needs to be modified with appropriate additives [3].

1.1. Stone Mastic Asphalt (SMA)

SMA mixture is gap-graded hot mix asphalt that is used in worldwide, where traffic volume is heavy. SMA was first developed in Germany during the mid-1960s [4] for providing more resistance to rutting phenomena on highway. SMA mixtures were widely used in the United State; however, the reports of researchers showed that the great possibility of this mixtures against rutting but ignored any potential fatigue resistance of SMA [5].

In recognition of its excellent performance a national standard was set in Germany in 1984. Since then, SMA has spread throughout Europe, North America, and Asia Pacific. Several individual countries in Europe now have a national standard for stone mastic asphalt, and CEN, the European standards body, is in the process of developing a European product standard. Today, SMA is widely employed in many countries in the world as an overlay or surface course to resist induced load and its popularity is increasing amongst road authorities and the asphalt industry. Due to the nature of SMA mixes (gap-graded) and the relatively large proportion of asphalt content, stabilization is required to inhibit drain down of asphalt.

1.2. Fatigue Cracking of Asphalt Mixtures

Fatigue is one of the most important distresses in asphalt pavement structure due to repeated load of heavy traffic services which occur at intermediate and low temperatures [6].

There are different test methods used throughout the world to measure fatigue resistance for asphalt concrete mixtures. Cracking is normally considered to be low temperature phenomena while permanent deformation is considered to be the predominant mode of failure at elevated temperatures. Cracking is mainly categorized into thermal cracking and load-associated fatigue cracking. Large temperature changes that occur in pavement usually result thermal cracking. This type of failure occurs when the thermally induced tensile stress, together with stresses caused by traffic, exceeds the tensile strength of the materials. It is often characterized by transverse cracking along the highway at certain intervals. Load-associated fatigue cracking is the phenomenon of fracture as a result of repeated or fluctuated stresses brought about by traffic loading. Traffic loads can cause a pavement structure to flex, and the maximum tensile strain will occur at the base of the bituminous layer. If this structure is inadequate for the imposed loading conditions, the tensile strength of the materials will be exceeded, and cracks are likely to initiate, which will be manifested as cracks on the surface of the pavement [5].

Raad and Saboundjian investigated the fatigue life of asphalt concrete mixtures using the indirect tension fatigue test. During the indirect tension fatigue, the horizontal deformation was recorded as a function of load cycle. The test specimen was subjected to different levels of stress, in order, for a regression analysis on a range of values. This allowed the development of the fatigue relationship between the number of cycles at failure (N_f), and tensile strain (ε_t) on a log-log relationship. Fatigue life (N_f) of a specimen is number of cycles to failure for asphalt concrete mixtures. These models are created based on the relationship existing between stress, or strain, and fatigue life as are presented in the equations below:

$$\sigma = A.\, N_f^{\ n} \quad (1)$$

$$\varepsilon = a\, .\, N_f^{\ b} \quad (2)$$

Where N_f is the number of load cycles to failure, σ is the applied stress, ε is the strain, and A, n, a, and b are the regression coefficients (fatigue parameters) which are related to mixture properties.

1.3. Literature Review

Modarres et al. in a research surveyed the effect of using such waste plastic materials crashed by special crashing machines to 0.425 to 1.18mm particles and added to asphalt mix with different percentages (2, 4, 6, 8, and 10 of the weight percentage of tar). Then they analyzed fatigue behavior of asphalt mixes under ITFT test in two different temperatures of 5 and 20^{o}C. Results indicated that adding recycled bottles increases fatigue life of asphalt mixes in both temperatures. Meanwhile, quantities more than %10 of such materials have had profitable effects on fatigue behavior of asphalt mixes [6].

Moghaddasnejad et al. in 2014 used high-density polyethylene HDPE for enhancing fatigue of asphalt mixtures. ITFT Results in both temperatures of 15 and 20^{o}C represent higher fatigue of mixtures containing HDPE as compared to control mixtures. Results indicate that in temperature of 15^{o}C, fatigue life of mix containing HDPE in the dry state, are 1.6 times of control mix [7].

Suchismita et al. (2011) evaluated fatigue characteristics of stone matrix asphalt mixes in warm climate. This study presented the details of a laboratory study of stone mastic asphalt mixes, with emphasis on engineering characteristics under repeated load conditions. In this study, conventional binders namely locally used penetration grade bitumen 80/100 and 60/70, with locally available aggregates and cement as filler have been used. A non-conventional natural fiber, namely coconut fiber to the extent of 0.3% by weight, has been added to the mix to act as a stabiliser. It is observed that the natural fibres improve the resistance of SMA mixtures against fatigue [8].

Xiao et al. (2009) studied the fatigue behaviour of rubberized asphalt mixtures containing warm asphalt additives (WMA). Two kinds of binder, PG 64 to 22 binder and PG 64 to 22 + 10% - 40 mesh ambient rubber, with addition of Asphamin and Sasobit as two warm asphalt additives were utilized, also two different sources of aggregate were used in this study, one of them was a type of granite which predominantly contains quartz and potassium feldspar (Type A) and the other type was schist (Type B). The results showed that Aggregate A has the greatest fatigue life as compared to Type B. Moreover, regardless of aggregate sources the fatigue life of the mixtures made with crumb rubber and WMA additive is greater than the control mixtures [9].

Xu et al. (2010) investigated the effect of polyester, polyacrylonitrile, lignin and asbestos fibers with different percentages (0.00, 0.20, 0.35 and 0.50% by mass of mixture) on fatigue properties of asphalt concrete (AC) mixtures. They investigated that addition of fibers into mixture resulted in increment of fatigue life. As a result, fatigue life of AC with polymer fiber (polyacrylonitrile and polyesterfibers) was more than other mixtures [10].

The effect of carbon fiber with the percentage of 0.1, 0.2, 0.3, 0.4 and 0.5% by weight of mix on fatigue life of mixtures was also studied. ITFT test was conducted using constant repeated stress of 350 kPa with half sine pulse of 5 Hz frequency, 150 ms loading period and 50 ms rest period. It was illustrated that using carbon fiber showed great promise when the fatigue lives increased about 28.2, 37.2, and 44.4%, with the addition of 0.1, 0.2, and 0.3% carbon fiber, respectively [11].

1.4. Goal of Study

The objective of this study is to evaluate the effect of Nano SiO_2 and Nano TiO_2 on the SMA mixtures fatigue behaviour. To achieve this goal, SMA samples were made according to ASTM D 1559. After preparation, indirect tensile fatigue test (ITFT) was carried out on SMA mixtures modified with different content of Nano SiO_2 and TiO_2. The characteristics of all samples used in this study are summarized in table 1.

Table 1. Characteristics of all samples used in this study

Test	Bitumen or Asphalt sample	Temperature (^oC)	Stress (KPa)
DSR	Bitumen samples	40, 50, 60, 70	-
ITFT	Asphalt samples	5, 15, 25	150, 250, 350

2. Materials and Methods

2.1. Materials

Stone materials gradation used in this study is the average gradation proposed by [12] for stone mastic asphalt with maximum aggregate nominal size of 20 mm. The limits for this gradation are presented in Table 2. Calcium carbonate ($CaCO_3$) was used as a mineral filler and it was passed through the sieve No. 200. The bitumen consumed is bitumen 60-70 in Tehran Pasargad Oil Processing Complex and the basic properties are mentioned in Table 3. Also, Properties of nano SiO_2 and TiO_2 are shown in Table 4. These nano materials were provided from Notrino co. in I.R.Iran.

Table 2. Gradation of aggregates used in the present study

Sieve(mm)	**19**	**12.5**	**9.5**	**4.75**	**2.36**	**0.075**
Lower–upper limits	100	90-100	50-80	20-35	16-24	8-11
Passing (%)	100	95	66	28	20	10

Table 3. Properties of asphalt binder used in this study

Test	Standard	Result
Penetration (100 g, 5 s, 15 ºC), 0.1 mm	ASTM D5-73	68
Ductility (15 ºC, 5 cm/min), cm	ASTM D113-79	102
Solubility in trichloroethylene, %	ASTM D1041-76	99.6
Softening point, ºC	ASTM D36-76	50
Flash point, ºC	ASTM D91-78	308
Loss of heating, %	ASTM D1754-78	0.2

Table 4. Properties of Nano Materials (SiO_2 & TiO_2) used in this study

Type	Purity %	Special Surface m^2/g	Diameter nm	Density g/cm^3
SiO_2	99.9	160	80	2.40
TiO_2	99.9	60	30	4.23

In order to achieve the objectives of this research, the homogeneous mixtures consisted of bitumen and Nano SiO_2 and TiO_2 is required. Achieving more favorable results is largely dependent on the mixture of bitumen and nanoparticles. Inappropriate mixture can prevent achieving good results. In this research, to evaluate the impact of Nano SiO_2 and TiO_2 on the fatigue behavior of SMA mixtures, different percentages of nanoparticles according to previous studies (0.3, 0.6, 0.9 and 1.2% by weight of bitumen), was added to the bitumen and mixing was performed with high speed mixer. In this study, the wet method was used to mix bitumen and Nano SiO_2 and TiO_2, so that first nano dispersed in the solvent. The selected solvent should have the ability to be solved in bitumen at low and moderate temperatures without the significant impact on the mechanical properties of bitumen with proper evaporation. For uniform dispersion of nano in bitumen, the solvent should have a low viscosity at room temperature. In this study, Kerosene was used as a solvent. For mixing, first the bitumen was heated to a temperature of 150 °C and with specified intervals, the nano-particles are slowly added to mechanical stirring bowl with 4000 rpm for 30 minutes and the mixing continued until the homogeneous mixture of bitumen and nano-particles was created [13].

2.2. SMA Samples

In this study, similar to many studies in the world performed on stone mastic asphalt, the Marshall method with 50 density hammer blows was used. In order to determine the optimum bitumen percentage in the stone mastic asphalt, the measure of mixing design is the voids percentage of the hot mix asphalts which the Iran Highway Asphalt Paving Code, No. 234 suggests the amount of 4% for it. Also, the percentage of voids in the mineral aggregate to the minimum limit of 17% is another item considered as the main measure to determine the percentage of optimum bitumen in the stone mastic asphalt mixtures. After producing the asphalt mixtures and by considering the above criteria, the optimum bitumen for control samples of stone mastic asphalt was calculated 6.6%. In results, the samples with different percentages of Nano TiO_2 and Nano SiO_2 and with 6.6% bitumen were made.

Due to the high bitumen contents in SMA mixtures, a stabilizing additive shall be used to help holding the bitumen on the aggregate. In results, using of stabilizing additives in SMA mixtures is necessary to prevent unacceptable drain down. In this study, 0.3% cellulose fiber plays stabilizing additive role in all SMA mixtures. Drain down values for unmodified SMA and Nano modified mixtures were tested according to AASHTO T305 and are shown in Table 5.

Also, the laboratory test used to estimate the fatigue behaviour of SMA mixtures modified with different content of Nano materials was Indirect Tensile Fatigue Test (ITFT) according to BS- EN12697-24.

2.3. Laboratory Tests

2.3.1. DSR Test

The dynamic shear rheometer (DSR) test was carried out according to ASTM D-7175 on bitumen samples to evaluate its viscoelastic behavior. In the DSR test, the value of the complex shear modulus (G*) and the phase angle (δ) of the tested bitumen are measured according to Equations (1) and (2) [14]. By measuring the complex shear modulus of the bitumen material, the total complex shear modulus value as well as its elastic and viscous components are determined. The phase angle is the time lag between the applied shear stress and the resulting shear strain converted into degrees.

Where G* is the complex shear modulus and δ is the phase angle (^{o}); ε_{max} is the maximum shear strain; γ_{max} the maximum resulting shear strain; t the time lag (s); and f is the loading frequency.

$$G^* = \varepsilon_{\max} / \gamma_{\max} \quad (1)$$

$$\delta = 360 \times t \times f \quad (2)$$

In this study, The DSR test was conducted at a frequency of 10 rad/s (1.59 Hz) and four test temperatures: 40, 50, 60, and 70 ^{o}C at 10 ^{o}C increments. The complex shear modulus (G*) value and the phase angle (δ) value were obtained for all the nano contents at the four test temperatures. Figure 1 show the DSR test apparatus.

2.3.2. Indirect Tensile Fatigue Test (ITFT)

Fatigue test procedure is used to rank the bituminous mixture resistance to fatigue as well as being a guide to evaluate the relative performance of asphalt aggregate mixture and obtaining data and input for estimating the structural behaviour in the road. During the fatigue test, stiffness modulus value decreases as indicated in Figure 2. Three phases were distinguished:

(i) Phase I: initially there is a rapid diminution of the modulus value.

(ii) Phase II: modulus variation is approximately linear.

(iii) Phase III: rapid decrease of the modulus value.

Table 5. Variation of drain down with different Nano contents

Sample Type	Drain down (%)	
	Bitumen- Nano SiO_2	Bitumen- Nano TiO_2
Control , 0% Nano	6.5	6.5
0.3% Nano	5.1	5.2
0.6% Nano	3.9	4.1
0.9% Nano	2.7	2.9
1.2% Nano	1.1	1.4

Figure 1. The DSR test apparatus

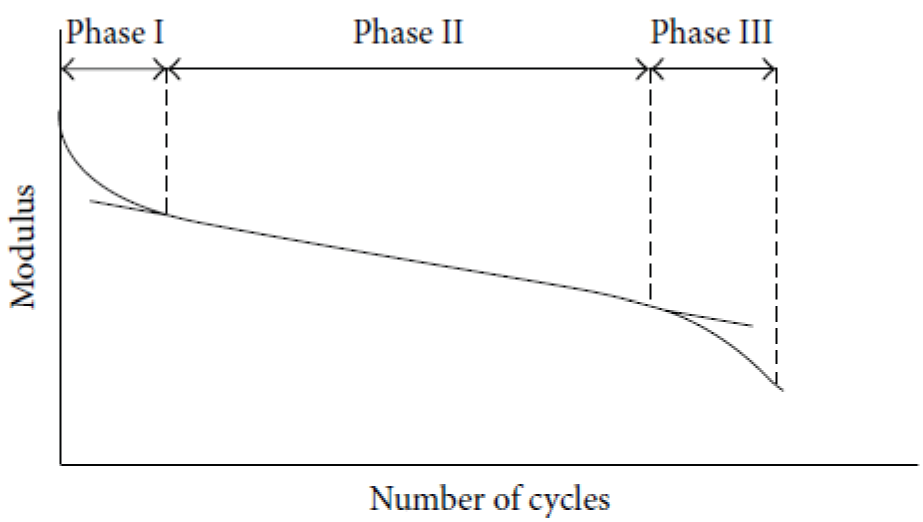

Figure 2. The three phases of fatigue test [10]

Damage is defined as any loss of strength that takes place in a specimen during a test. The fatigue life is defined as the number of load cycling application (cycles) resulting in either disintegration or a permanent vertical deformation [15].

In this study, the ITFT test was carried out according to the procedure described by the British Standard, BS- EN12697. The UTM apparatus was used to determine the resistance of the mixtures to failure under repeated loading. A series of specimens with diameter 100 and height 40 mm were manufactured from each mix. The loads were applied using havesine waveform loads with 500 ms repetition time and 100 ms pulse width at temperatures of 5, 15 and 25^{o}C until the failure point of the specimen [15]. Figure 3 show the samples for ITFT in this study.

Figure 3. ITFT test samples in this study

3. Results and Discussions

3.1. DSR Test Results on the Bitumen

The G* values obtained for the unmodified and modified bitumens at the different temperatures were plotted with the Nano contents as shown in Figures 4 and 5. According to the results, with addition of different percentages of Nano SiO_2 and Nano TiO_2, the amount of G* is increased. This can be due to the improved bitumen elastic and viscoelastic behavior at different temperatures with the addition of different percentages of nano materials. When the Nano SiO_2 and Nano TiO_2 particles at nano-scale added to the bitumen particles with high surface to volume ratio, it strengthens the bond between bitumen particles and creates an appropriate cover. The cover can prevent the viscous nature of bitumen at high temperatures and delay the withdrawal from the elastic behavior to the viscous area. What has been said can be summarized in the increased amount of G*.

According to the results, the increasing amount of G* in all the Nano SiO_2 percentages used in this study is maintained and show that the compatibility between Nano SiO_2 particles and bitumen with the increased percentages has been still maintained and its addition would improve the bitumen rheology. This is not true about Nano TiO_2 and with addition of 1.2% Nano TiO_2, the amount of G* is decreased. This can be justified so that the compatibility between Nano TiO_2 particles and bitumen with the excessive increased Nano, is removed and nanoparticles by being among the constituent particles of bitumen causes an excessive increase in them and change the nature of bitumen and its rheological behavior. As a result, it is predicted that among the percentages used in this study, 1.2% for Nano SiO_2 and 0.9% for Nano TiO_2 create the best performance.

3.2. ITFT Test Results

Figures 6 and 7 show the final strain versus fatigue life of samples at different stresses of 150, 250 and 350KPa, and temperatures of 5, 15 and 25°C, respectively. The fatigue life in the indirect tensile fatigue test is defined as the number of the tolerable cycles of an asphalt sample to the crack incidence.

As the results show, the number of cycles of SMA samples at lower temperatures and stresses is higher.

For example, ratio of control samples N_f (without nano content) at the lowest temperature and stress (5°C and 150 KPa) and the highest temperature and stress (25°C and 350 KPa) is equal to 25, that shows the great impact of temperature and stress on the fatigue life of SMA mixtures. In fact, the lower temperature and stress is equivalent to the greater life time of SMA mixtures. But two above parameters (temperature and stress) cannot be changed by the road construction engineers, what is achievable is finding a way that even at higher temperatures and stresses can also prevents the excessive loss of mixtures life time.

In order to obtain representation of the fatigue life, the regression equation for each mixture along with the regression parameters for various stress and temperature values are illustrated in Table 6. The basic fatigue life model confirms the aforementioned effects of nanoparticles content, stress and temperature levels on fatigue life. By having looked at fatigue model coefficients, some guidance may be provided. As strong evidence, the high R^2 values are reasonably indicative of good models accuracy.

Meaning, the fatigue life is higher for the mixtures reinforced with nanoparticles as compared with original mixture (without nanoparticles). The relationship obtained is rational in that lower fatigue life as the stress levels are increased. Also, table 5 indicates the variation of cyclic loading on the specimens containing varying percentages of nanoparticle modifiers. As the loading cycles are increased, the rate of tensile strain generation for both reinforced and non-reinforced specimens is found to be increased. However, the number of cycles to failure is different for asphalt samples which contain various percentages of nanoparticles. Reinforced samples tend to have longer fatigue life compared with non-reinforced samples. From Table 6, the behaviour model for asphalt samples containing various percentages of nanoparticles and the respective correlation coefficients are presented as well. It is observed that deviation from the optimum nanoparticles content decreases the fatigue life of reinforced asphalt samples. The Nano-asphalt deters tensile and vertical cracks from being effortlessly formed by horizontal tensile stresses and stops them from propagating.

It can be seen from results that the number of cycles to failure is not the same for SMA samples that contain various percentages of Nano materials. Modified samples tend to have longer fatigue life compared with the conventional samples. This is due to presence of Nano that improves viscoelastic property of bitumen and absorbs the amount of energy which is produced by repetitive loads, and postpones crack initiation and propagation in the mixtures. The presence of Nano causes SMA samples to sustain higher fatigue life. Nano SiO_2 and and Nano TiO_2 cause SMA samples to resist creep-caused-cracks and reduces the generation and propagation rate of micro-cracks.

The results show that using 1.2% Nano SiO_2 and 0.9% Nano TiO_2 obtained the highest number of cycles for SMA mixtures at all the temperatures and stresses. Therefore, it can be expected that the possibility of crack incidence and start of fatigue phenomenon in the modified mixtures with 1.2% Nano SiO_2 or 0.9% Nano TiO_2 is significantly lower compared to the control samples.

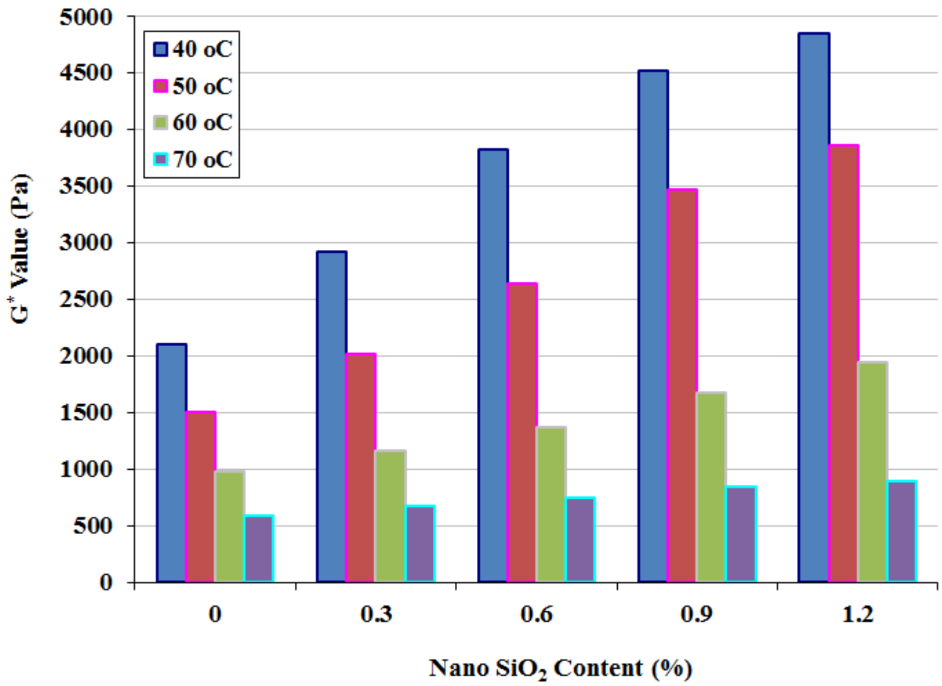

Figure 4. G* value versus Nano SiO_2 content at different temperatures

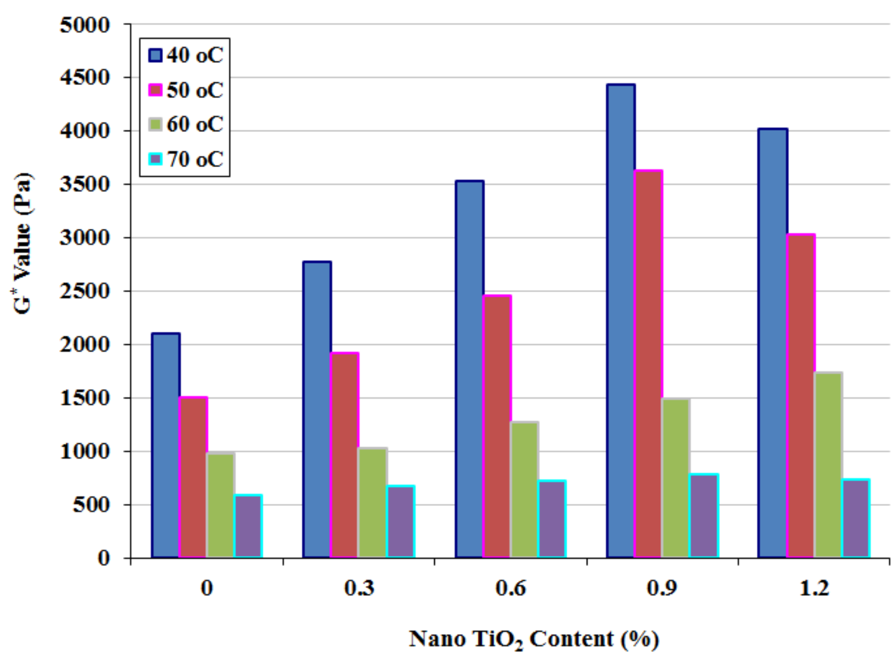

Figure 5. G* value versus Nano TiO_2 content at different temperatures

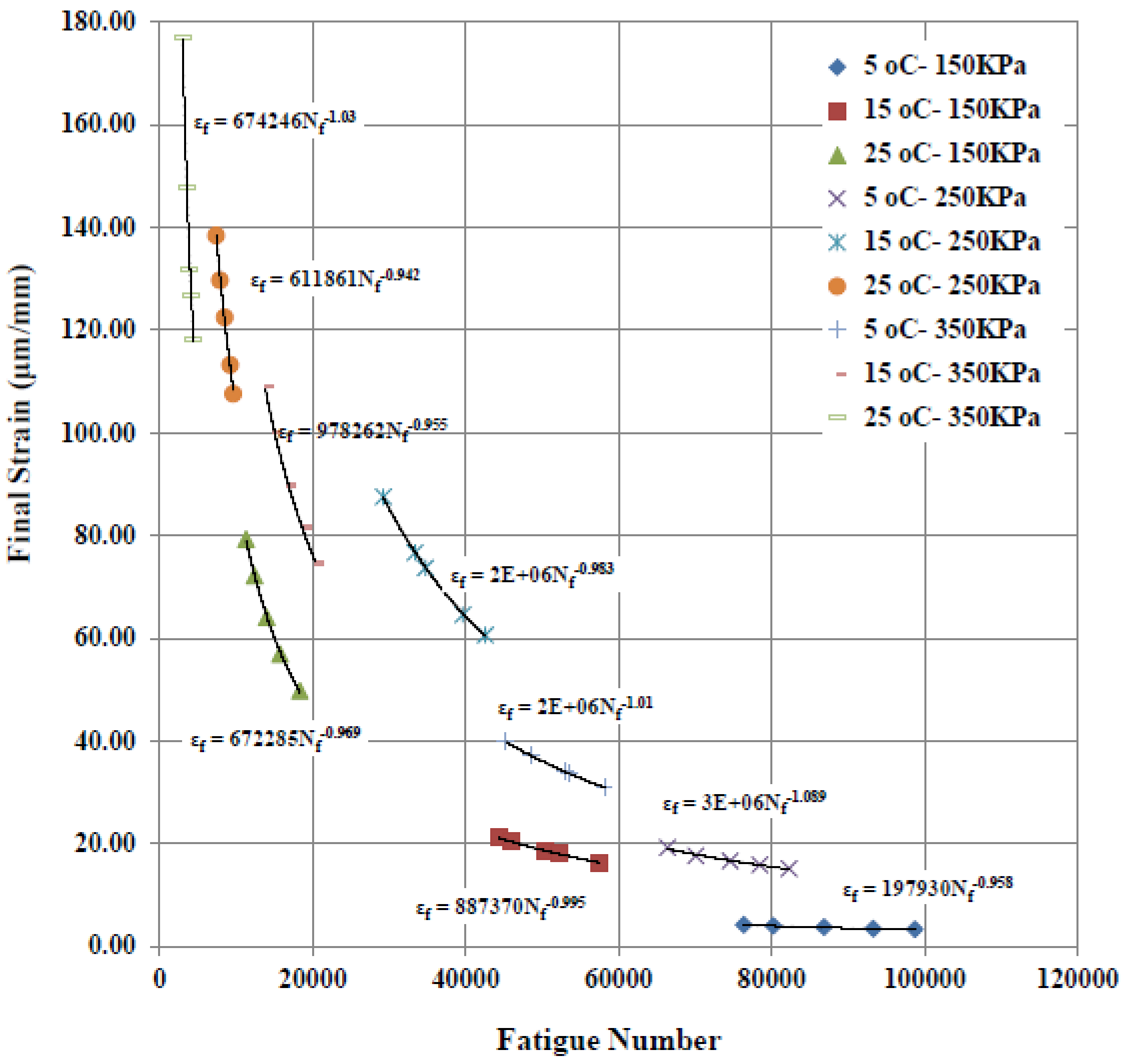

Figure 6. Final strain versus number of load cycle for Nano SiO_2 modified mixtures

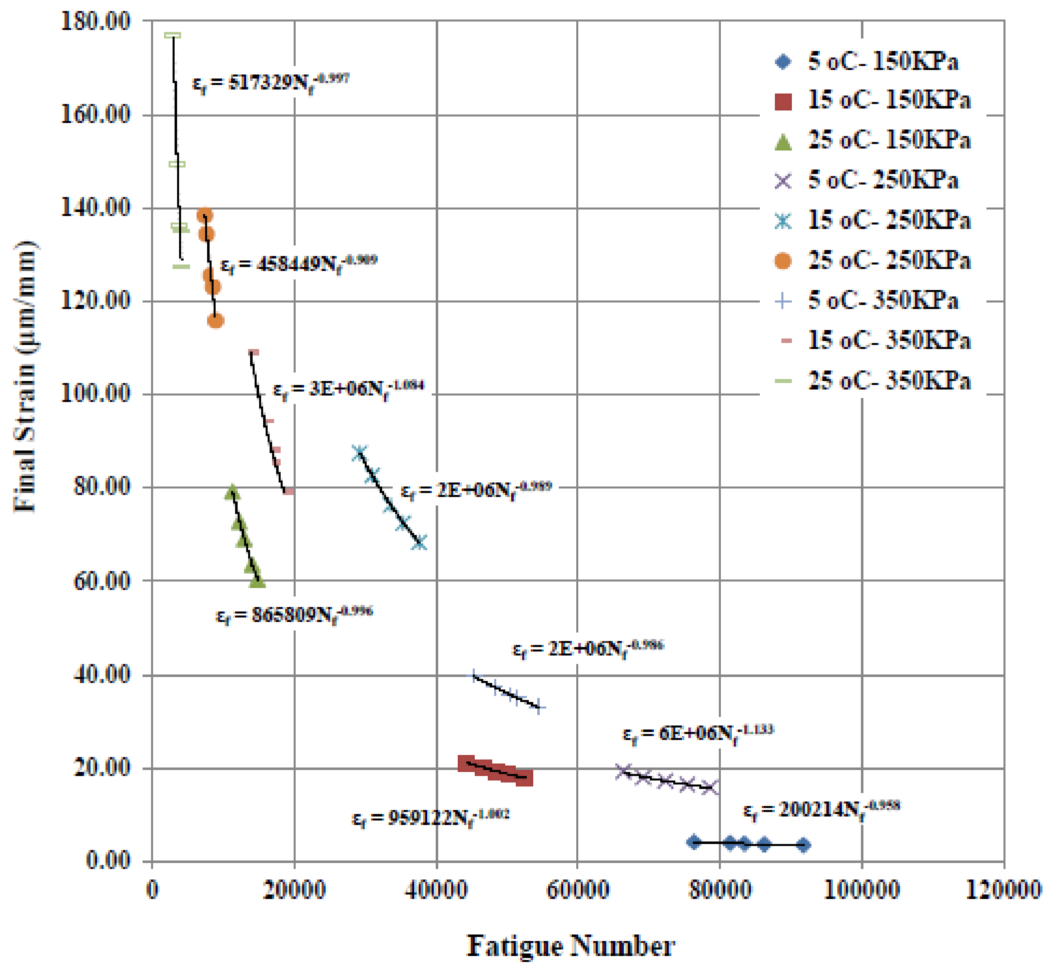

Figure 7. Final strain versus number of load cycle for Nano TiO_2 modified mixtures

4. Conclusion

The aim of this study was to evaluate the effects of adding Nano SiO_2 and Nano TiO_2 as modifier additive on the Fatigue behavior of SMA mixtures and estimating the fatigue number of stone mastic asphalt mixtures modified with these modifiers. Comparison of results for conventional and modified SMA mixtures showed that specimens containing Nano materials have noticeably better performance. In addition:

- According to the results, with addition of different percentages of Nano SiO_2 and Nano TiO_2, the amount of G* is increased.
- The results of this research suggest the using of Nano materials to increase fatigue life of SMA mixtures. Results show that Nano-SMA mixtures have

considerably higher fatigue lives in comparison with control mixtures.

- The results show that using 1.2% of Nano SiO_2 and 0.9% of Nano TiO_2 obtained the highest number of cycles for SMA mixtures at all the temperatures and stresses. Therefore, it can be expected that the possibility of crack incidence and start of fatigue phenomenon in the modified mixtures with 1.2% Nano SiO_2 or 0.9% Nano TiO_2 is significantly lower compared to the control samples.

REFERENCES

[1] Moghaddam, T.B., Karim, M.R., and Mahrez, A. (2011). “A review on fatigue and rutting performance of asphalt mixes”, Scientific Research and Essays, Vol. 6(4), pp. 670-682.

[2] Arabani, M., Jamshidi, R., Sadeghnejad, M. (2014). “Using of 2D finite element modeling to predict the glasphalt mixture rutting behavior”, Construction and Building Materials, Vol. 68, pp. 183-191.

[3] Ghasemi, M., Marandi, S.M., Tahmooresi, M., Kamali, J., and Taherzade, R. (2011). “Modification of Stone Matrix Asphalt with Nano-SiO2”, Journal of Basic and Applied Scientific Research, Vol. 1(1), pp. 1338-1344.

[4] Brown, E., Hemant, M. (1993). “Evaluation of Laboratory properties of SMA mixture”, Tech. Rep. 93-5, National Center for Asphalt Technology, Auburn University.

[5] Ratnasamy, M., Bujang, B. (2006). “Laboratory diameteral fatigue performance of SMA with cellulose oil palm fiber”, American Journal of Applied Sciences, Vol. 3(9), pp. 2005–2010.

[6] Modarres, A., Hamedi, H. (2014). “Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes”, Materials and Design, Vol. 61, pp. 8–15.

[7] Moghadasnejad, F., Azarhoosh, A., Hamedi, G.H. (2014). “Effect of high density polyethylene on the fatigue and rutting performance of hot mix asphalt– a laboratory study”, Road Materials and Pavement Design, Vol. 15, pp. 746-756.

[8] Suchismita, A., Panda, M., Chattaraj, U., Gaspar, L. (2011). “Fatigue Characteristics of Stone Matrix Asphalt Mixes in Warm Climate”, Acta Technica Jaurinensis Vol. 4(3), pp. 123-129.

[9] Xiao, F., Zhao, P., Amirkhanian, S.N. (2009). “Fatigue behavior of rubberized asphalt concrete mixtures containing warm asphalt additives”, Construction and Building Materials, 23, p.p. 3144-3151.

[10] Shafabakhsh, G.H., Mirabdolazi, S.M., Sadeghnejad, M. (2014). “Evaluation the effect of nano-TiO2 on the rutting and fatigue behavior of asphalt mixtures”, Construction and Building Materials, Vol. 54, pp. 566–571.

[11] Jahromi, S., Khodaii, A. (2008). “Carbon fiber reinforced asphalt concrete”, Arabian Journal for Science and Engineering, Vol. 33, pp. 355–64.

[12] Iran Highway Asphalt Paving Code, No. 234, 2011.

[13] Mashaan, N., Asim, H., Koting, S, and Karim, M. (2013). “Performance Evaluation of Crumb Rubber Modified Stone Mastic Asphalt Pavement in Malaysia”, Advances in Materials Science and Engineering, pp. 25-32.

[14] Ghaffarpour, S., Ahmadi, N. (2011). “Engineering Properties of Nanoclay Modified Asphalt Concrete Mixtures”, International Journal of Earth Sciences and Engineering, Vol. 4(6), pp. 941–944.

[15] Yan, J., Ni, F., Yang, M., and Li, J. (2010). “An experimental study on fatigue properties of emulsion and foam cold recycled mixes”, Construction and Building Materials, Vol. 24, pp. 2151–2156.