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Research Article

FATIGUE BEHAVIOR OF HOT MIX ASPHALT MODIFIED WITH NANO AL_2O_3 – AN EXPERIMENTAL STUDY

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ABSTRACT
Nanotechnology is one of the most important research areas and is presented in the vast fields of knowledge such as road construction industry has been surrounded. This paper has focused on the potential benefits of nano particles for modification of asphalt mixtures. Nano Al_2O_3 due to its unique properties can improve the dynamic characteristics of hot mix asphalt. Fatigue life of asphaltic samples is determined with indirect tensile fatigue tests by using of UTM. The results show that fatigue life of modified asphalt mixtures in compare with conventional mix is significantly increased. Beside, based on experimental results and numerical analyses, a new model is presented for prediction the fatigue behavior of asphalt mixtures modified with nano Al_2O_3. This model can completely characterized the fatigue performance of modified asphalt under dynamic loading conditions and different temperatures.

Keywords: asphalt mixture, nano Al_2O_3, fatigue life, final strains.

INTRODUCTION

Asphalt pavements must undergo heavy loads and unfavorable environmental conditions for an acceptable period of time. Bitumen is used in road pavements as the binder of aggregates in a great extent all around the world. Cracking is one of the most considerable performance limitations of unmodified and pure asphalt pavements [1].

It is impossible to construct an asphalt pavement that does not experience cracking after being used for a certain period of time. Crack propagation is an unavoidable problem, which is of concern for more than two million miles of US roadways constructed with asphalt concrete pavements. The fatigue related cracking of asphalt concrete pavements is caused by the successive tensile strain induced by traffic loading, which according to structural analysis will be at maximum value under the bitumen layer. The cracks propagate upward, and weaken the pavement structure gradually [2].

Reflective cracking develops whenever an existing crack in the old pavement layer beneath the current one reflects in the upper layer [3]. The excessively increasing cost of the repair and rehabilitation of highway and airport pavements has lead to comprehensive research on the use of additives in HMAs to increase their strength and life durability against dynamic loads. The pavements weakness in the case of dynamic loads and their short performance life are the major concern regarding their repair and maintenance. The relationship between the bending strain at the bottom of an asphalt layer and the occurrence of fatigue cracking in that layer is shown in Eq. (1):

$$N_f = K_1 \varepsilon_t^{K_2} \quad (1)$$

where: N_f – is the number of load cycles to fatigue failure,
k_1 and k_2 – are constants,
ε_t – is the tensile strain due to bending at the bottom of the HMA.

Fatigue damage of asphalt pavement is a complex phenomenon that is a result from repeated bending that causes micro-damage to the asphalt pavement. Fatigue characteristics of asphalt mixes are usually determined from laboratory tests. The fatigue behavior of a specific mix is defined by relationship described in Eqs. (2) and (3).

$$N_f = A.W^z \quad (2)$$

$$N_f = K_f (1/\varepsilon_t)^{K_2} (1/s)^{K_3} \quad (3)$$

where: N_f – is the fatigue life,
ε_t – is the tensile strain,
S – is the initial mix stiffness,
W – is the cumulative dissipated energy to failure,
K_f, K_2, K_3, A, z – are experimentally determined coefficients.

The fatigue life of an asphalt specimen was related to the tensile strain developed in the loaded specimen. Even under different temperature and loading rate conditions, the life time still appeared to have a unique relationship with tensile strain (ε_t). This 'law' can be expressed as a simple Eq. (4).

$$N_f = A(\varepsilon_t)^n \quad (4)$$

where: N_f – is the number of load applications to failure,
A and n – are experimentally determined coefficients.

Another fatigue cracking model (derived with laboratory specimens subjected to displacement controlled four point bending fatigue tests) is represented by Eq. (5).

$$N_c = 0.0685(1/\varepsilon_t)^{5.671}(E_1)^{-2.363} \quad (5)$$

where: N_c – is the number of load repetitions that contribute to failure by fatigue cracking,
ε_t – is the horizontal tensile strains at the bottom of the asphalt layer, and
E_1 – is the elasticity modulus [4].

LITERATURE REVIEW

Nanotechnology is one of the important research areas and is presented in the vast fields of knowledge such as road construction industry has been surrounded. Of benefits use of the nanotechnology can to increase quality materials, save conserving energy and to consequently it save economic and improved physical and mechanical properties of materials in road construction and road building is sustainable and environmentally friendly. Surface to volume ratio of nano materials is one of the important properties of materials produced at the nano scale.

The result shows that nano materials modification can improve mechanical behavior properties of mixture, such as indirect tensile strength, creep, and fatigue resistance [5]. Golestani et al. (2012) evaluated Performance of modified asphalts binder by nano composite. The results showed that nano composite could improve the physical properties, rheological behaviors and the stability of the bitumen [6].

Ghasemi et al. (2012) evaluated the potential benefits of nano-SiO_2 powder and SBS for the asphalt mixtures used on pavements. The results of this investigation indicated that the asphalt mixture modified by 5% SBS plus 2% nano SiO_2 powder could give the best results in the tests carried out in the current study [7]. Goh et al. (2011) found that, addition of nanoclay and carbon microfiber improved the mixture's moisture susceptibility performance and decreased the moisture damage potential [8].

Ghaffarpour et al. (2010) carried out comparative rheological tests on bitumens and mechanical tests on asphalt mixtures containing unmodified and nanoclay modified bitumen. Results showed that nanoclay could improve properties such as stability, resilient modulus, and indirect tensile strength [9]. Vandeven et al. (2008) investigated nanotechnology effects on the adhesion of asphalt mixtures. Two different types of nanoclay were used to modify bitumen. In the first case, Viscosity of modified bitumen in comparison to original bitumen (70-100) did not change after the addition of 6% (by weight) of nano-clay, although improved its short-term and long-term hardening. In the second case, Nanoclay increased viscosity of bitumen. Therefore, it was concluded that this type of modifier was appropriate to use in asphalt mixtures to prevent water penetration [10].

Khodadadi et al. (2007) investigated Nanoclay additive effect on long-term performance of asphalt pavement. Indirect tensile test was conducted on cylindrical specimens made of standard and modified bitumen at the stress levels of 200, 300, 400 and 500 kPa. The results showed that the addition of 2% nanoclay increased the fatigue life of the asphalt pavement [11].

Many researches were carried out on bitumens modified with Nano materials. By adding these materials to bitumen, because the bonds that are formed between the material and bitumen, Properties of bitumen are improved. It is expected that modification of bitumen with Nano materials improve the mechanical properties of asphalt mixtures including increase of stiffness modulus, increase of strength against stripping, increase of strength against moisture damage, Prevention of cracks and increase of resistance against creep compliance.

The purpose of this research is to investigate the fatigue life of HMA mixtures containing Nano Al_2O_3 as a bitumen modifier. In the current study, nano Al_2O_3 modified bitumen is prepared by mixing nano Al_2O_3 into the bitumen. The properties of the modified bitumen is evaluated by using the conventional test methods. The effects of nano Al_2O_3 on the properties of modified asphalt mixtures are investigated. For this purpose, indirect tensile fatigue (ITF) test is done on the conventional and modified asphalt mixtures.

MATERIALS AND METHODS

The aggregates used in this study were graded using the continuous type IV scale of the AASHTO standard, which is presented in Table 1. The 60/70 penetration bitumen was obtained from Isfahan Mineral Oil Refinery, Isfahan, Iran. Table 2 shows the physical properties of the bitumen. Also, Properties of nano Al_2O_3 are shown in Table 3.

Empirical rheological tests on bitumen

The modification of bitumen with nano $Al_2O_3$was performed at nano scale level by thermodynamic driving force. To determine the optimum content of Nano Al_2O_3, The physical properties of the modified bitumen (such as softening point, penetration and ductility) were measured based on ASTM D36, ASTM D5 and ASTMD113, respectively.

Table 1. Gradation of aggregates used in the present study

Sieve(mm)	19	12.5	4.75	2.36	0.3	0.075
Lower–upper limits	100	90–100	44–74	28–58	5–21	2–10
Passing (%)	100	95	59	43	13	6

Indirect tensile fatigue (ITF) test

In this study, the resistance to fatigue cracking of modified asphalt concrete mixtures by different nano Al_2O_3 was evaluated by using ITF test. To determine the optimum content of Nano Al_2O_3, The fatigue life of the samples was determined by the Indirect Tensile Method using a UTM apparatus. Specimens were prepared with nano Al_2O_3 of 0, 2, 5, and 8%. The fatigue life of the specimens was identified by using the indirect tensile test of the ITF test method on samples with 100 mm diameter and 40 mm thickness. Specimen preparation and compaction were conducted in accordance with ASTM D1559. Loading was accomplished by applying repeated loads at a frequency of 1 Hz until the failure point of the specimen. The failure was also characterized by measuring the vertical deformation of the samples. Fatigue life tests are usually carried out through two methods: loading with constant stress and loading with constant strain. In the constant stress test, the strain increases with the number of pulses of loading, while in the constant strain test, the stress decreases with the number of pulses of loading. By maintaining a certain tensile strain for each level of stress, the relation between the tensile strain and the number of cycles related to the failure can be determined. In this study, fatigue life tests were performed at 5, 25 and 40^{o}C, with constant stresses of 250 and 400 KPa. The program for the prepared samples and the experimental tests is described in Table 4. In order to eliminate possible error, number of sample replicates that were tested per test condition were 3 times.

The relationship between number of cycles to failure and tensile strain for each percent of nano was established. A linear relationship was recorded when numbered cycles to failure is plotted against the strain in the logarithmic scale and

Table 2. Properties of bitumen used in this study

Test	Standard	Result	Specification limit
Penetration (100 g, 5 s, 25 ºC), 0.1 mm	ASTM D5-73	68	60–70
Ductility (25 ºC, 5 cm/min), cm	ASTM D113-79	102	Min 100
Solubility in trichloroethylene, %	ASTM D2042-76	99.5	Min 99
Softening point, ºC	ASTM D36-76	51	49–56
Flash point, ºC	ASTM D92-78	250	Min 232
Loss of heating, %	ASTM D1754-78	0.2	Max 0.8

Table 3. Properties of nano zinc oxide used in this study

Specification	Result
Molecular formula	Al_2O_3
Color	white
Particle size (nm)	80
Specific gravity (gr/cm³)	0.90
Solubility (%)	99.0

Table 4. Program for specimen preparation and testing

Parameter	Levels
Percentage of Nano Al_2O_3	(0, 2 , 5, 8)%
Test temperatures	(5, 25, 40) °C
Type of gradations	Topka
Stress (KPa)	250 and 400

the fatigue life prediction equations were developed. By using a regression analyses, the fatigue equations were developed which are in the form of Wohler's fatigue prediction model according to eq. 1 [12].

Empirical rheological tests results on bitumen

The results of penetration, softening point, and ductility tests are presented in figures 1-3. It can be seen from figures 1-3 that adding percentages of nano Al_2O_3 has positive effect on the rheological properties of bitumen.

Results show that the viscosity of bitumen is increased by adding the nano Al_2O_3. Subsequently, penetration of modified bitumen is decreased. Moreover, by decreasing temperature sensitivity of modified bitumen due to adding nano Al_2O_3, the softening point of bitumen is improved. It is

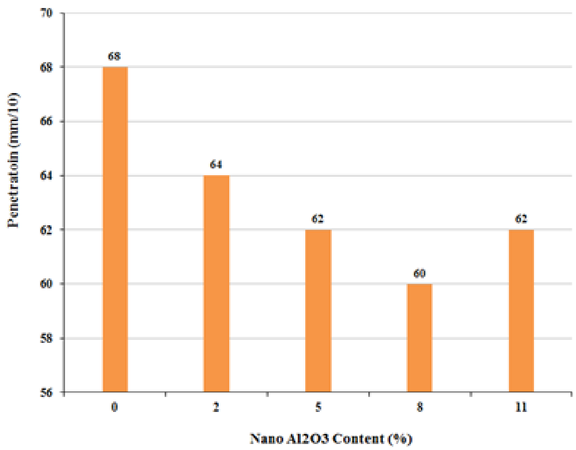

Fig. 1. Penetration test results on unmodified and modified bitumen

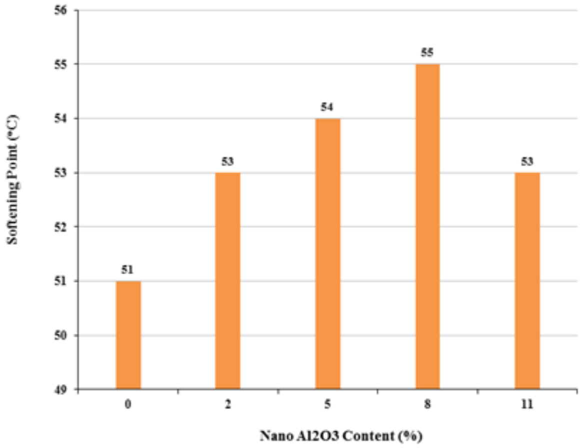

Fig. 2. Softening point test results on unmodified and modified bitumen

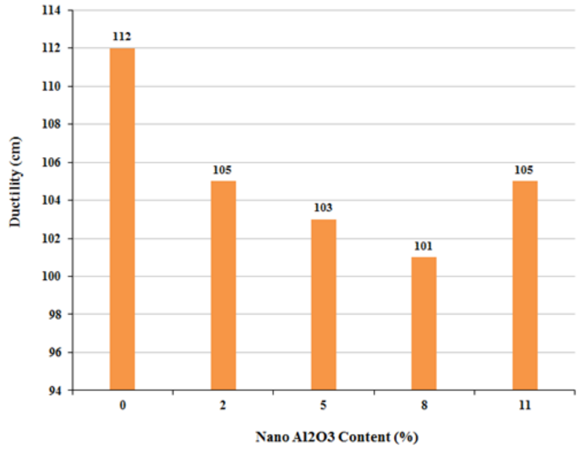

Fig. 3. Ductility test results on unmodified and modified bitumen

illustrated in figure 3 that ductility is significantly increased by improvement of modified bitumen stiffness in comparison to conventional bitumen.

The results obtained by the penetration, softening point, and ductility tests for bitumen show that 8% nano Al_2O_3 as modifier of bitumen is an optimal content. In 11% nano Al_2O_3, penetration is increased, however, softening point and ductility are decreased. As a result, to evaluate the effect of nano Al_2O_3 on the fatigue life of asphalt mixtures, the samples were made with modified bitumen by percentages of 2%, 5% and 8% nano Al_2O_3.

Indirect tensile fatigue (ITF) test

Figures 4 and 5 show the number of cycles needed for failure of asphalt concrete specimens, given with variation of the temperature, nano $Al_2O_3$and two levels of stress. It can be seen that asphalt concrete specimens containing nano Al_2O_3 show considerably better fatigue

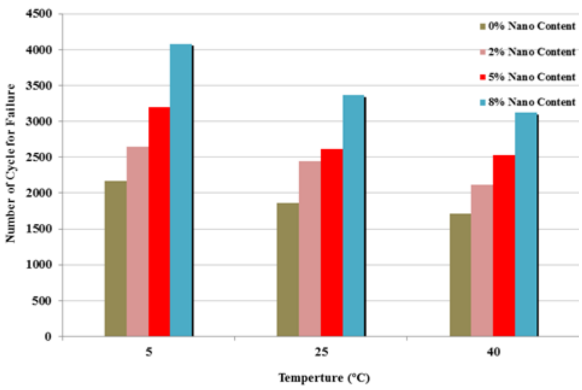

Fig. 4. Number of cycles for failure vs. temperature at a stress level of 250 kPa

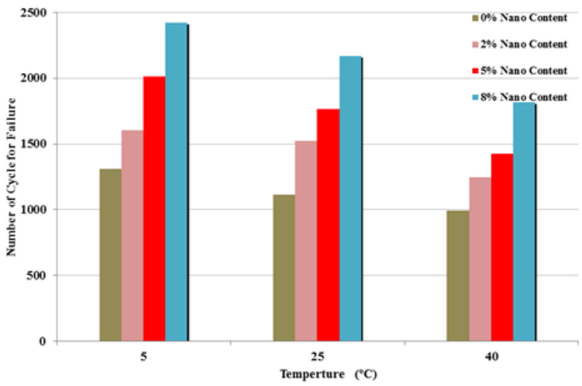

Fig. 5. Number of cycles for failure vs. temperature at a stress level of 400 kPa

performance than conventional HMAs. For example at 25 °C and 250 KPa, the fatigue life of 2%, 5% and 8% nano modified asphalt mixtures are 1.31 times, 1.40 times and 1.80 times (compared with the control mixture), respectively. This increase in fatigue life is caused due to better cohesion and adhesion among bitumen modified with nano Al_2O_3 and stone aggregates. It will also minimize the relative displacement of the stone aggregates and increase the fatigue life of the samples by slowing down cracking and crack propagation. Furthermore, figures 4 and 5 show that the fatigue life of the specimens modified with nano $Al_2O_3$is decreased with increasing of temperature. The reason for this behavior is the high sensitivity of bitumen in HMA to temperature. This confirms the previous researches on this issue.

Figures 6 and 7 show the ratio of increment cycles needed for failure of asphalt concrete specimens modified with different nano Al_2O_3 to conventional samples, given with variation of the temperature, nano Al_2O_3 and two levels of stress.

For instance, the fatigue life of specimens containing 2, 5, and 8% nano Al_2O_3 at 5 °C and 250 KPa are 22, 47, and 93% longer, respectively, than those of conventional HMAs at the same temperature and stress. Also, it can be seen fatigue life of modified specimens with 8% nano Al_2O_3 at the worth case test conditions (40°C and 400KPa) are 75% longer, respectively, than those of conventional HMAs at the same temperature and stress. Results show specimens containing 8% nano Al_2O_3 at all of temperatures and stresses have better fatigue life.

The relationship between fatigue life and final strain of samples according equation 1 are given in table 5. The results show the usual linear relationship between the logarithm of fatigue life (number of applied load repetitions until failure) and the applied initial tensile strain. It can be observed that the values of "K1" and "K2" are all increased when nano contents are added and increased, which results in an increase in the cycle numbers to failure for asphalt mixtures. It can be concluded that the use of nano Al_2O_3 have much influence on the decrease of tensile strain and improvement the fatigue life of the asphalt mixtures.

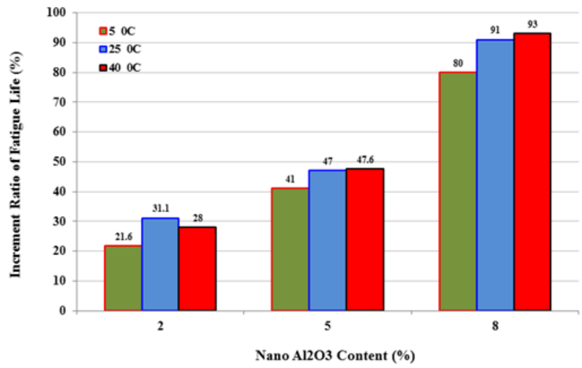

Fig. 6. Increment ratio of fatigue life vs. different content nano Al_2O_3 at a stress level of 250 kPa

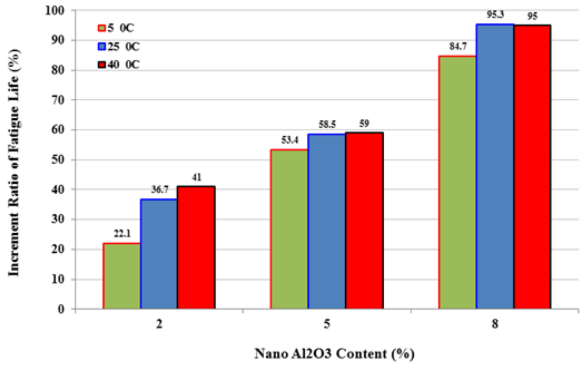

Fig. 7. Increment ratio of fatigue life vs. different content nano Al_2O_3 at a stress level of 400 kPa

CONCLUSIONS

The main goals of the present research were to characterize the rheological and mechanical properties of nano Al_2O_3 modified bitumen and mixtures. Adding modifiers to the pure bitumen improved the viscosity behavior of the bitumen and changed its rheological properties. The modifier included nano Al_2O_3 and had different levels of (decreasing or increasing) influence on the rheological properties of bitumen from the same source. After laboratory tests were conducted on the bitumen and mixtures with different modifier content and the data were analyzed and the results were compared, the following conclusions were made:

1. Adding nano Al_2O_3 to the mixtures improves the adhesion and cohesion of bitumen. Therefore, it provides more reasonable mixtures than the conventional ones.
2. The fatigue life of the mixtures increased with the increase of the nano Al_2O_3 content in the conventional mixtures.
3. By increasing the temperature, fatigue life of all specimens decreases. This behavior results from high sensitivity of bitumen in asphalt mixtures to temperature.
4. By increasing nano Al_2O_3 content, sensitivity of bitumen in asphalt mixtures to temperature is decreased.
5. Better cohesion and adhesion among bitumen modified with nano Al_2O_3 and stone aggregates will minimize the relative displacement of the stone aggregates and increase the fatigue life of the samples by slowing down the initial cracking and crack propagation.

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