Available online at www.sciencedirect.com

ScienceDirect

International Journal of Pavement Research and Technology 10 (2017) 131–138

www.elsevier.com/locate/IJPRT

Laboratory evaluation of Nano Al_2O_3 effect on dynamic performance of stone mastic asphalt

Asadollah Chelovian, Gholamali Shafabakhsh *

Faculty of Civil Engineering, Semnan University, Semnan, Islamic Republic of Iran

Received 18 February 2016; received in revised form 13 August 2016; accepted 11 November 2016
Available online 17 November 2016

Abstract

A part of different countries' budget in the world annually is spent on the restoration and reconstruction of pavements damages. Hence, by increasing the quality of hot mix asphalt, the pavement researchers are constantly trying to improve the quality of hot mix asphalt, greatly reduce the incidence rate of damages in the roads and delay the incidence time as much as possible. Many studies show that the quality of hot mix asphalt can be improved by using additives. Nano Al_2O_3 is studied as an additive in this research and also, in order to improve the hot mix asphalt strength against the damages, the type of stone mastic asphalt is examined. Stone materials gradation used in this study is the average gradation proposed by Asphalt Pavement Regulation of Iran Roads (Publication 234) for stone mastic asphalt with a maximum aggregate nominal size of 20 mm. The bitumen consumed is bitumen 60–70 in Tehran Pasargad Oil Processing Complex. In order to prevent the draindown phenomenon in stone mastic asphalt which occurred according to the space between aggregates, the cellulose fibers with the amount of 0.3% hot mix asphalt weight are used to produce the hot mix asphalt. The effect of Nano Al_2O_3 additive on dynamic performance of stone mastic asphalt is investigated through dynamic creep test, wheel track test and indirect tensile fatigue test. Results show that addition of different percentages of Nano Al_2O_3 is capable to improve the dynamic performance of stone mastic asphalt, significantly.

Keywords: Stone mastic asphalt; Nano Al_2O_3; Rutting; Dynamic creep; Fatigue

1. Introduction

The asphalt concrete is one of the materials widely used for pavement of roads and airports. The researchers and engineers are constantly trying to improve the performance of asphalt pavements. The pavement of roads as the surfaces that are exposed to the frequent loadings of heavy axes should have enough strength against the fatigue, cracking, creep and skid resistance [1].

Hot mix asphalt in the pavement structure is used as a surface layer to distribute the stress caused by the loading and protect the unprotected bottom layers against water effect. Hot mix asphalt should be resistant against the weather effects and stand up against the permanent deformation and cracks caused by loading and environmental factors in order to be able to do both duties efficiently in pavement design lifetime [2].

1.1. Stone mastic asphalt

Stone mastic asphalt is gap-graded hot mix asphalt consisting of two parts of coarse aggregate and bitumen-filled mortar (bitumen mix, filler and stabilizing additives). This hot mix asphalt should have coarse aggregate

* Corresponding author.
E-mail address: Shafabakhsh@semnan.ac.ir (G. Shafabakhsh).
Peer review under responsibility of Chinese Society of Pavement Engineering.

http://dx.doi.org/10.1016/j.ijprt.2016.11.004
1996-6814/© 2016 Chinese Society of Pavement Engineering. Production and hosting by Elsevier B.V.

structure with stone on stone contact. In this type of hot mix asphalt, the stones are referred to the materials left on the 4.75 mm sieve, also 2.36 mm sieve can be used for this purpose [3].

Stone mastic asphalt is mainly used as binder course and the crowded roads with heavy axial load. This hot mix asphalt due to the use of high-grade and 100% crushed materials, relatively high consumption of the aggregates larger than 4.75 mm compared to the continuous-graded, with stone on stone contact structure which increases the strength and resistance of hot mix asphalt against rutting and permanent deformations and because of the relatively high consumption of bitumen, has reliability and higher durability.

Bitumen used in the stone mastic asphalt should be as the classified pure bitumen according to penetration degree, or functional or modified bitumen. The amount of consumed bitumen in these mixtures is at least 6% and usually more than the amount of bitumen in continuous-graded hot mix asphalts. The reason for the high consumption of bitumen in the mixtures is the gap-gradation and relatively large amount of filler. In order to prevent the phenomenon of separation or draindown, the stabilizing additives can be used. Any additives that can cause any improvement by promoting the properties of bitumen or bitumen mortar used in stone mastic asphalt in one or more of the following cases can be used [3]:

I. The permanent deformation.
II. Fatigue & Low Temperature Cracking.
III. Economic issues, particularly the reduction of required thickness to design.

1.2. Damages of asphalt pavements

Pavements are usually affected by various factors which have effect on their life. Since a road is passing through different areas with different traffic volumes, traffic types and rainfall rates, therefore, the flaws and defects occur in different points of the road which will result in the road rapid damage in the case of lack of attention, evaluation and restoration.

Among the most important damages that occurred during the useful life of the pavement, the permanent deformations in the vehicles' wheel track (rutting) and the cracks caused by the fatigue can be mentioned. Since for restoration and reconstruction these flaws and defects, high costs should be spent, so the early prevention is usually more affordable. In order to avoid such damages, the pavement materials should be selected as they have adequate strength and stability [4].

Deep wheel track (rutting) is the permanent deformation of pavement layers that can be increased with the passage of time. Deep wheel track resulted from the deformation in one or several layers of the asphalt pavement. On the one side, there is a deformation that is limited to the surface layer which is called "surface rutting", while in another side, there is a deformation in which the main part of the deformation occurred in the sub base layer and is called the structural rutting [5]. A view of the deep wheel track is shown in Fig. 1.

Evaluation of asphalt concrete mixtures in order to protect them against the phenomenon of wheel track rutting has become an important research field in recent years. This type of damage occurs as a result of consolidation and compaction of hot mix asphalt after the construction and development of plastic deformation caused by the passage of vehicle wheels over time [6].

The cracks caused by fatigue usually occur where the asphalt pavement is affected by the frequent affected loading. Cracking is directly related to the increased tensile strain under the asphalt layer and begins when the strain passes the threshold limit. Despite the efforts taken, determining the amount of this threshold limit has not been successful. The fatigue process includes three steps:

I. Start of damage with fatigue cracks.
II. Cracks growth in the uncracked areas to the pavement component weakening step.
III. Final and sudden failure of pavement component.

Fatigue lifetime of a sample or component is the number of repetitions required for the sample failure and depends on many variables such as stress value, stress direction, the waveform and oscillation, the weather conditions and construction conditions. Small changes in the sample position might cause significant changes in the structure fatigue behavior and this is complicated the scientific and mathematical prediction of this phenomenon. Hence, the designers use their experiences on practical samples more than laboratory studies. However, the laboratory studies are essential to understand the material behavior and these tests can result in a design measure.

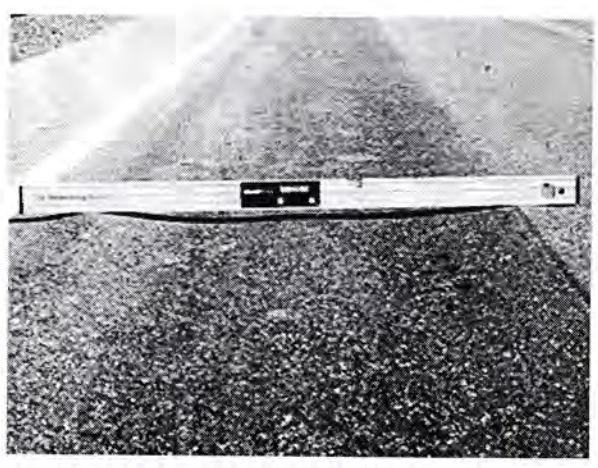

Fig. 1. A view of the rutting occurrence in asphalt pavement.

1.3. Methods to deal with damages

In recent years, in order to increase the flexibility of pavements as well as their increased strength against destructive factors such as fatigue and permanent deformations, the additives with the potential to improve the mechanical properties of asphalt pavements are used to produce the hot mix asphalt [7]. The pavement performance improvement is possible using two methods:

- Performance improvement using modified bitumen.
- Performance improvement using hot mix asphalt modification.

In recent years, the increasing cost of restoration and reconstruction of pavements of roads and airports which is caused by the increased amount and frequency of traffic loads applied to the pavements, has led to the comprehensive studies in using the additives to produce the hot mix asphalt to enhance their ability against the dynamic loads. The low strength of pavements against dynamic loads and their short life service is one of the main problems in the protection and maintenance of roads [8].

1.4. The purpose of research

This study aimed to evaluate the effects of using Nano Al_2O_3 in the stone mastic asphalt, to present the proper solutions to increase the asphalt pavement strength against the dynamic loads and therefore, preventing the rutting and fatigue in them.

2. Previous studies

Many studies in Iran and other countries have been conducted on the application of nano-materials to improve the performance of bitumen, hot mix asphalt and stone mastic asphalt, of which some are mentioned in the following.

Ghasemi et al. in a study modified the stone mastic asphalt using nano-SiO_2 powder. They used 5% nano to produce hot mix asphalt and used Marshall Method as the pattern to produce the samples and mix design. The results showed that stone mastic asphalt modified with 1% nano-SiO_2 has the best performance against dynamic loads [9].

Yen and Chen in a study examined the effect of nano-titanium oxide on the properties of hot mix asphalt at high temperatures. The results show that addition of this nano to hot mix asphalt can increase their strength against the rutting phenomenon, therefore, the final and permanent strain of hot mix asphalt is lower compared to the control mixtures [10].

Tanzadeh et al. in another study examined the effect of nano-titanium oxide on the rutting performance of hot mix asphalt. Their study aimed to examine the effect of this nano on the improvement of bitumen properties and finally the hot mix asphalts. Hence, they used the results of wheel truck test. The results showed that using nano-TiO_2 in bitumen and then using the modified bitumen to produce the hot mix asphalts have decreased the rut depth in these mixtures compared to the control mixtures [11].

Khodadai et al. in this study have examined the effect of adding nano-clay on the long-term performance of hot mix asphalt. Results of indirect tensile test performed on asphalt cylindrical samples in stresses of 200, 300, 400 and 500 kPa were chosen as the comparison measure between the control and modified samples. The results show that the addition of 1% nano-clay increase the lifetime of hot mix asphalts [12].

3. Materials and methods

3.1. The used materials

Stone material gradation used in this study is the average gradation proposed by Asphalt Pavement Regulation of Iran Roads (Publication 234) for stone mastic asphalt with maximum aggregate nominal size of 20 mm. The limits for this gradation are presented in Table 1. The bitumen consumed is bitumen 60–70 in Tehran Pasargad Oil Processing Complex and the basic properties are mentioned in Table 2.

In order to prevent the draindown phenomenon in stone mastic asphalt which occurred according to the space between aggregates, the cellulose fibers with the amount of 0.3% hot mix asphalt weight used to produce the hot mix asphalt. Table 3 shows the properties of Nano Al_2O_3 used in this study. Nano Al_2O_3 is produced from Notrino Company. Fig. 2 also shows the nano used in this research.

3.2. Method for producing bitumen composite

In this study, in order to produce the homogeneous bitumen mix, the wet mixing method with auxiliary kerosene solvent has been used. At first, the amount of particular bitumen is heated to reach the 150 °C until it is melt. Then, it is put in a high shear mixer at a speed of 4000 rpm. Gradually, the amounts of 0.3, 0.6, 0.9 and 1.2% Nano Al_2O_3 dissolved in kerosene solvent and the obtained composite was added to bitumen and after 15 min. of mixing by the homogenizer and cooling the composite, the required modified bitumen was prepared to produce the asphalt samples (see Table 4).

Table 1
Stone materials gradation used in this study for stone mastic asphalt.

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

Table 2
Bitumen 60–70 properties used to produce the samples.

Solubility %	Loss of heating %	Flash point °C	Ductility cm	Softening point °C	Penetration 0.1 mm
99.6	0.2	308	102	50	68

Table 3
Properties of Nano Al_2O_3 used in this study.

Specification	Result
Molecular formula	Al_2O_3
Color	White
Particle size (nm)	80
Specific gravity (g/cm^3)	0.90
Solubility (%)	99.0

Fig. 2. Nano Al_2O_3 used in this study.

Table 4
Equations used for determining the Marshall Method computational quantities for stone mastic asphalt.

VMA	$\mathrm{VMA} = 100 - \frac{G_{mb} \times p_s}{G_{sb}}$
V_a	$V_a = 100 \times \frac{(G_{mm} - G_{mb})}{G_{mm}}$

G_{mb}: Real specific weight of asphalt sample.
P_s: Percentage of stone materials compared to the total weight of hot mix asphalt.
G_{sb}: Real specific weight of stone materials mix.
G_{mm}: Real specific weight of maximum hot mix asphalt.

3.3. Program and method for stone mastic asphalt samples

AASHTO proposed the superpave method and rotary compressor device to produce the stone mastic asphalt. But due to lack of access to this device in all areas, by modeling many studies conducted in this field, Marshall Method according to ASTM D1552 standard also has been used to produce the stone mastic asphalt. With the difference that according to suggestion of Publication 234, the number of compressor beats is considered equal to 50 beats, and also in order to determine the percentage of optimum bitumen instead of considering Marshall strength measures and the flow and specific weight of mixtures, only the percentage of empty space of hot mix asphalt and stone materials have been determined as measure. These two measures are defined according to Fig. 4.

Publication 234 suggests that the percentage of stone mastic asphalt void space should be equal to 4% and the percentage of hot mix asphalt void space should be at least 17%. By considering two above measures, the amount of optimum bitumen for different samples used in this study is equal to the values in Table 5.

3.4. Tests

3.4.1. Dynamic creep test

Frequent axial load test is used to determine the effect of hot mix asphalt different variables in the amount of strength against the permanent deformation. In this test, the load is applied as axial to the samples and permanent deformation is continuously measured by two sensors. This test is performed based on British Standard DD226 [13]. The test was conducted on two stresses of 350 and 500 kPa at temperatures of 40, 50 and 60 °C. The reason to choose these temperatures and stresses is that the creep and permanent deformations occurred in the asphalt at the above temperatures and stresses. In order to compare the results between different samples, this test has been performed for 3600 cycles. The results are in the form of strain or final permanent deformation which is studied and calculated for different samples.

3.4.2. Wheel track test

Wheel track test used to determine the strength of hot mix asphalts against the permanent deformations at the critical temperature and under the loading similar to what is applied in the roads to the pavement surface. Wheel track test, using sweep move of loaded wheel on the asphalt samples, determines the rutting potential of asphalt pavements. This is done by measuring the rut depth created in

Table 5
Results of optimum bitumen percentage for different samples of the study.

Sample type	Optimum binder content (%)
Control, 0% Nano Al_2O_3	6.60
0.3% Nano Al_2O_3	6.80
0.6% Nano Al_2O_3	6.90
0.9% Nano Al_2O_3	7.00
1.2% Nano Al_2O_3	7.20

the sample along the wheel movement by the rut meter at the specified intervals. In this study, the samples with dimensions of 50 × 300 × 300 mm have been used. In order to perform the test, the samples should be placed in the test machine and after the necessary adjustments through the software in the computer connected to the device, the test is started. In this research, the wheel track test was performed at 40, 50 and 60 °C and the applied load is selected equal to the 500 and 700 N.

3.4.3. Indirect tensile fatigue test (BS 1962-3518)

ITFT test is performed on samples with dimensions of 100 mm and thickness of 40 mm affected by the frequent loadings with 1 Hz pulses to rupture the sample. The rupture is determined by measuring the amount of sample vertical deformation. The kind of loading in the fatigue test is performed as linear and along the axis of the sample diameters. Relationships and parameters related to fatigue, including fatigue life and the number of cycles required for the failure caused by the fatigue is determined by fatigue test using the indirect tensile method. The fatigue test also ends when the vertical crack is created as a result of indirect tensile strain repeat in the center of the sample. The range of stress application in the fatigue test is 50–1000 kPa. Fatigue lifetime of a sample or component is the number of repetitions required for the sample failure and depends on many variables such as stress value, stress direction, the waveform and oscillation, the weather conditions and construction conditions. In this study, the fatigue test is performed at three temperatures of 5, 15 and 25 °C and three stresses of 150, 250 and 350 kPa to compare the effect of different percentages of Nano Al_2O_3 on fatigue life of stone mastic asphalt at different temperatures and stresses [14].

4. Results and analysis

4.1. Dynamic creep test results

Dynamic creep test results have been shown in Figs. 3–5. The final strain shown in the vertical axis of diagrams is studied as the main output of the dynamic creep test. This strain is in fact the amount of strain remained after 3600 loading cycles (about 2 h) in the sample. Also, it should be noted that the remaining strain is the equivalent of permanent deformation or the same rutting in the mixtures. The samples where the final strain occurred are more susceptible to rutting.

Results show that with addition of Nano Al_2O_3 at all temperatures and stresses, the final strain is reduced. For example, at the temperature of 40 °C and stress of 350 kPa, the amount of final strain of stone mastic asphalt samples modified with 0.6% Nano Al_2O_3 is approximately 20% lower than the samples without additives. At this temperature and stress, the samples containing 0.6% additives have the lowest amount of strain and with addition of more Nano Al_2O_3, the final strain increased again. Results at the

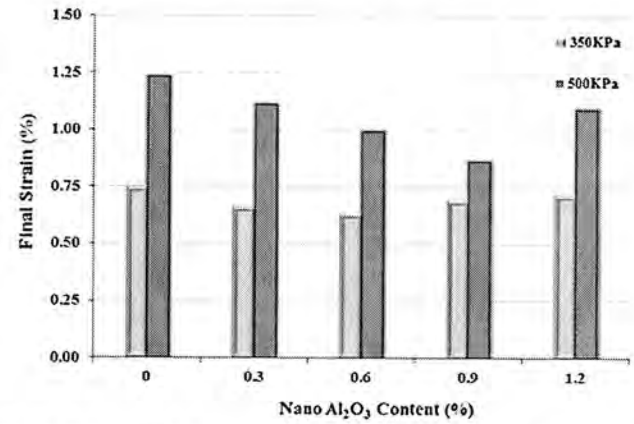

Fig. 3. Permanent deformation of the samples vs Nano Al_2O_3 percentage at 40 °C.

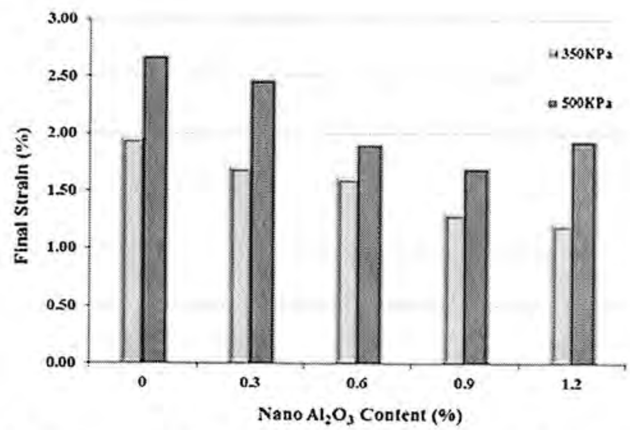

Fig. 4. Permanent deformation of the samples vs Nano Al_2O_3 percentage at 50 °C.

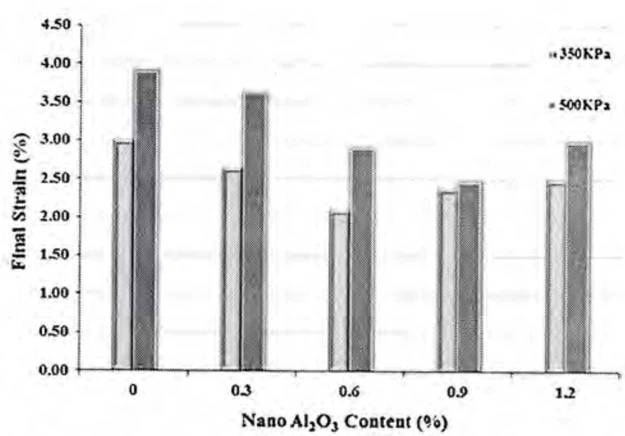

Fig. 5. Permanent deformation of the samples vs Nano Al_2O_3 percentage at 60 °C.

temperature of 40 °C and stress of 500 kPa is that the decreasing trend of control samples final strain is continued to 0.9% additive and at this percentage, the approximately 20% decrease in final strain can be seen.

At the temperature of 50 °C and stress of 350 kPa, the decreasing trend of final strain is continued with addition of different percentages of Nano Al_2O_3, so that in the sample containing 1.2% Nano Al_2O_3, the amount of final strain is approximately 17% lower than the control samples. The decreasing trend at this temperature and stress of 500 kPa is continued to the sample containing 0.9% nano and then the amount of final strain is increased again. The percentage of optimum Nano Al_2O_3 at this temperature and stress is 0.9 where about 29% decrease can be seen in the final strain.

At the temperature of 60 °C and stress of 350 kPa, 0.6% nano has achieved the best performance for hot mix asphalts. The amount of final strain at this temperature and stress is about 29% lower than the control sample. Also, at the stress of 500 kPa and at a temperature of 60 °C, the optimum nano percentage is equal to 0.9% and the amount of decrease is 26% compared to the control samples.

The results show that the addition of Nano Al_2O_3 can decrease the final strain and permanent deformation of stone mastic asphalt. The decrease is in the range of 17–29% that due to the addition of 0.3–1.2% Nano Al_2O_3, it could be an amazing amount. Bitumen modification with different Nano Al_2O_3 percentages and using new bitumen mortar to produce hot mix asphalt has led to the increased adhesion and mortar maintenance in mix, therefore, the hot mix asphalt performance is improved in terms of creep and permanent deformations. Bitumen behavior is viscoelastic which is a time function behavior. Bitumen composite and stone materials which are known as hot mix asphalt, at the medium temperatures are as viscoelastic and at high temperatures are as visco-elasto-plastic. This means that hot mix asphalts are susceptible to permanent deformation. The results show that Nano Al_2O_3 can decrease the rutting potential in bitumen, as a result, using this bitumen mortar can decrease the permanent deformation in SMA mixtures.

Another important point obtained from the above results is the impact of temperature on the amount of dynamic creep. The increased temperature causes enhancement in the plastic properties of hot mix asphalt and in these conditions, the risk of rutting increases. For example, at the stress of 350 kPa, the amount of permanent deformation of stone mastic asphalt samples without additives at a temperature of 60 °C is approximately 1.5 times as the strain at a temperature of 50 °C, and 4 times as the strain at a temperature of 40 °C. As it clear, the difference in permanent strain at the various temperatures is too high and shows that the samples have greater potential for rutting at higher temperatures. Many studies attributed the reason for high sensitivity of hot mix asphalt to the temperature to the bitumen and suggest that high thermal sensitivity of bitumen caused these results. Results show that modifying the bitumen with Nano Al_2O_3 has significantly reduced its thermal sensitivity and the asphalt samples containing Nano Al_2O_3 have proper performance than the control samples at high temperatures.

Results show that at different temperatures and stresses, the percentages of 0.6%, 0.9% and 1.2% Nano Al_2O_3 are the optimum percentages. But at the time of comparing the amount of final strain reduction for the above percentages at the various temperatures and stresses, this amount of reduction is compared economically, concluding that in dynamic creep test the percentage of 0.6% additives among different percentages is the optimum technical and economic percentage.

4.2. Wheel track test results

Figs. 6 and 7 show the wheel track test results on the modified stone mastic asphalt samples with various percentages of Nano Al_2O_3 at loading forces of 500 and 700 N. Results show that by increasing the Nano Al_2O_3 percentage, the amount of rut depth is gradually decreased. The reason for the above reduction can be found at adding Nano Al_2O_3 to bitumen and mix. Addition of the nanoparticles to the bitumen due to the high specific surface can play the reinforcing factor in the bitumen particles and increase the strength of bitumen particles to each other. The above factor can increase the viscosity and adhesion of bitumen and improve the functional behavior of bitumen and decrease its sensitivity to the rutting. Certainly, using this bitumen to produce the hot mix asphalt can be the main reason to improve the amount of rut depth in the modified stone mastic asphalt compared to the control samples. Because, the researchers attribute the reason of hot mix asphalt behaviors to the bitumen used in it. However, the consuming amount is low and is about 6–7% of the total weight of the mix.

Comparison shows that addition of more than 0.6% Nano Al_2O_3 to bitumen and then using the bitumen to produce hot mix asphalt at all the above temperatures and forces increase the rut depth compared to the samples containing 0.6% nano. The increase can be justified that Nano Al_2O_3 in the bitumen could only be useful as an additive and its excessive addition led to negative results, because the distance between the particles is gradually increased

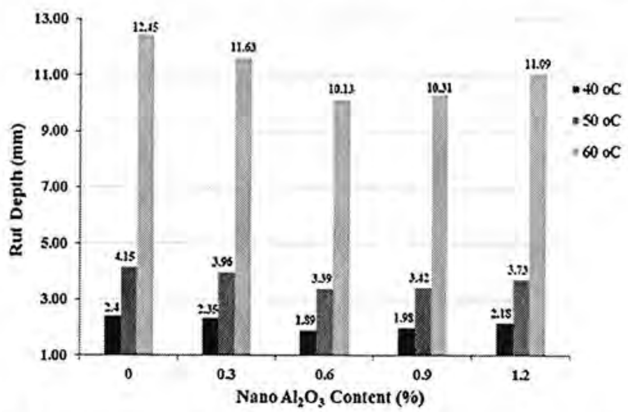

Fig. 6. Rut depth of the samples vs Nano Al_2O_3 percentage at loading forces of 500 N.

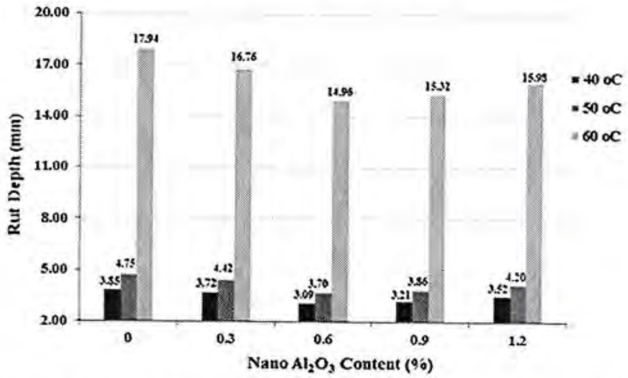

Fig. 7. Rut depth of the samples vs Nano Al_2O_3 percentage at loading forces of 700 N.

and the amount of nano is enhanced. The increased distance of bitumen particles has decreased their strength, so that with the smallest force, the cohesion and adhesion between the particles is ruptured and the bitumen does not have the former adhesion capability.

Results show that at different temperatures and loading forces, the amount of rut depth of asphalt samples containing 0.6% Nano Al_2O_3 is about 16–24% lower than the amount of rut depth in the control samples. Therefore, it can be said that addition of Nano Al_2O_3 to asphalt mixtures causes the improvement to the amount of 20% in rut depth.

4.3. Indirect tensile fatigue test results

Figs. 8–10 represent the fatigue life of stone mastic asphalt per various percentages of Nano Al_2O_3 at different temperatures. 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 a result, the above figures represent the number of cycles per various Nano Al_2O_3 percentages.

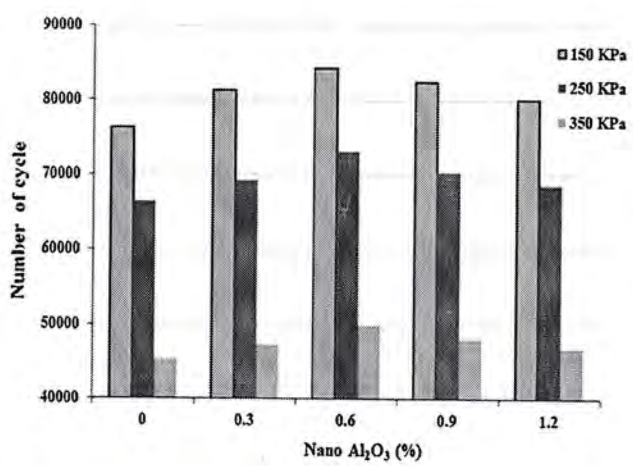

Fig. 8. Fatigue life of the SMA samples vs Nano Al_2O_3 percentage at 5 °C.

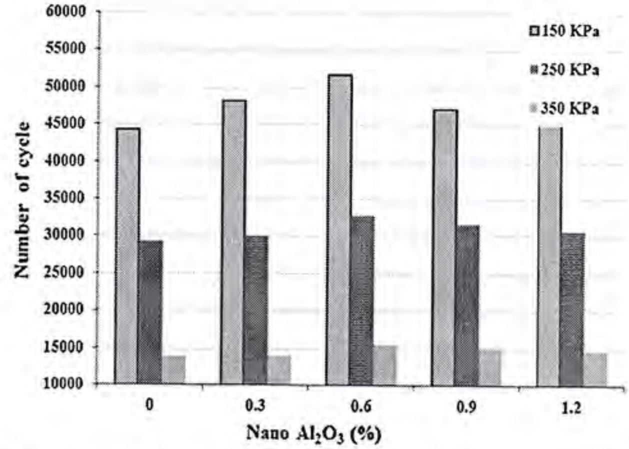

Fig. 9. Fatigue life of the SMA samples vs Nano Al_2O_3 percentage at 15 °C.

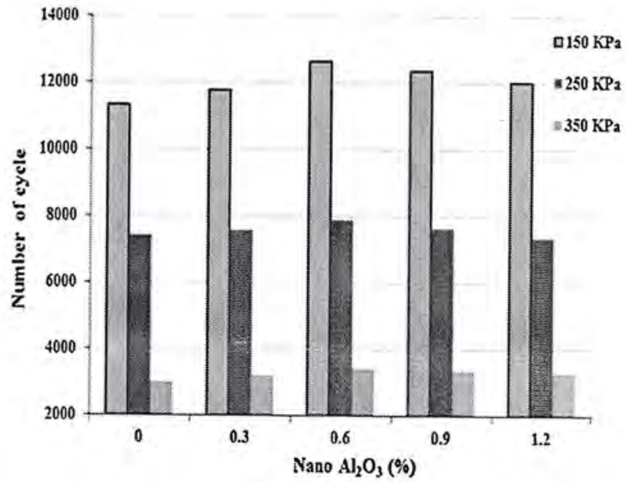

Fig. 10. Fatigue life of the SMA samples vs Nano Al_2O_3 percentage at 25 °C.

As the results show, the number of the tolerable loading cycles of SMA samples at lower temperatures and stresses is higher. For example, the number of tolerable cycles of control samples (without nano percentage) at the lowest temperature and stress which are 5 °C and 150 kPa and the highest temperature and stress which are 25 °C and 350 kPa is equal to 25, that shows the great impact of temperature and stress on the fatigue life of hot mix asphalts and in fact the lower temperature and stress is equivalent to the greater lifetime of hot mix asphalt. 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 lifetime.

The results suggest the using of Nano Al_2O_3 for this reason. The results show that using 0.6% Nano Al_2O_3 at all the temperatures and stresses obtained the highest number of tolerable cycles for SMA mixtures. The results show that at various temperatures and stresses, the number of tolerable cycles of modified mixtures is 10–20% more than the control mixtures. Therefore, it can be expected that the possibility of crack incidence and start of fatigue phenomenon in the modified mixtures with 0.6% Nano Al_2O_3 is significantly lower compared to the control samples.

5. Conclusion

In this study, in order to evaluate the effect on Nano Al_2O_3 on dynamic performance of stone mastic asphalt, the various percentages of Nano Al_2O_3 have been used and their impact on the performance of hot mix asphalt have been evaluated by the results of dynamic creep test, wheel track test and indirect tensile fatigue test. The most important results of this laboratory research is as following:

- The results show that with addition of Nano Al_2O_3 at all the temperatures and stresses, the final strain is decreased. The decrease is in the range of 17–29% that due to the addition of 0.3–1.2% Nano Al_2O_3, it could be an amazing amount.
- The results show that Nano Al_2O_3 can decrease the rutting potential in bitumen, as a result, using this bitumen mortar can decrease the permanent deformation in SMA mixtures.
- Results show that at different temperatures and stresses, the percentages of 0.6%, 0.9% and 1.2% Nano Al_2O_3 are the optimum percentages. But after comparing the results at the above percentages and by considering the economic aspect, it is concluded that 0.6% additive is the optimum technical and economical percentage among the percentages used in this study.

References

[1] Y.H. Huang, Pavement Analysis and Design, Prentice Hall, University of Kentucky, USA, 1993.
[2] B.V. Kok, N. Kuloglu, The effects of different binders on mechanical properties of hot mix asphalt, Int. J. Sci. Technol. 2 (1) (2007) 41–48.
[3] Iran Highway Asphalt Paving Code, No. 234, 2011
[4] A.K. Haghi, M. Arabani, M. Shakeri, M. Haj jafari, B. Mobasher, Strength modification of asphalt pavement using waste tires, in: 7th International Fracture Conference, University of Kocaeli, Kocaeli, Turkey, 2005.
[5] A. Laurinavicius, R. Oginskas, Experimental Research on the Development of Rutting in Asphalt Concrete Pavements Reinforced with Geosynthetic Materials, Dept. of Roads, Vilnius Gediminas Technical University, 2006.
[6] J.M. Matthews, C.L. Monismith, Effects of Aggregate Gradation on the Creep Response of Asphalt Mixtures and Pavement Rutting Estimates, ASTM Special Technical Publication, No 1147, ASTM, Philadelphia, PA, 2003, pp. 329–343.
[7] C. Richardson, Asphalt Construction for Pavements and Highways, BiblioBazaar, 2008.
[8] S. Ghafarpoor, B. Andalibizade, S. Vossough, Engineering properties of nanoclay modified asphalt concrete mixtures, Arab. J. Sci. Eng. 35 (2010), Number 1B.
[9] M. Ghasemi, S.M. Marandi, M. Tahmooresi, J. Kamali, R. Taherzade, Modification of stone matrix asphalt with nano-SiO_2, J. Basic Appl. Sci. Res. 1 (1) (2011) 1338–1344.
[10] C.H. Fang, R. Yu, S.H. Liu, Y. Li, Nanomaterials applied in asphalt modification: a review, J. Mater. Sci. Technol. 29 (7) (2013) 589–594.
[11] J. Tanzadeh, F. Vahedi, P. Kheiry, R. Tanzadeh, Laboratory study on the effect of Nano TiO_2 on rutting performance of asphalt pavements, Adv. Mater. Res. (2012) 622–623
[12] A. Khodadadi, M. Kokabi, Effect of nanoclay on long-term behavior of asphalt concrete pavement, in: 1st Congress of Nanomaterials, University of Kashan, I.R. Iran, 2007.
[13] British Standard Insitution. 1995. Test Method for Determining the creep Compliance of Asphalt Material Using the Indirect Tensile Test Device. DD185.
[14] G.H. Shafabakhsh, S.M. Mirabdolazimi, M. Sadeghnejad, Evaluation the effect of nano-TiO_2 on the rutting and fatigue behavior of asphalt mixtures, Constr. Build. Mater. 24 (2013) 566–571.