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Investigating the Performance Characteristics of Asphaltic Concrete Containing Nano-Silica

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ABSTRACT: Using nano-technology materials in the asphalt pavement industry is new compared with Portland cement concrete. The main objective of this study is to investigate the effects of nano-silica modification on some properties of a penetration grade asphalt cement and a typical asphalt concrete. 60/70 penetration grade bitumen was modified with different percentages of nano-silica (i.e. 1, 3 and 5%, by weight) and was used for making the asphalt concrete specimens. After evaluating the basic properties of the modified binder, the asphalt concrete specimens were evaluated based on the stiffness and resistance against fatigue cracking, moisture damage and permanent deformation. The fatigue life of the modified mixtures was also calculated using an already developed regression model. The results showed that penetration grade and ductility increase and softening point decreases with increasing nano-silica content. Furthermore, results showed that the addition of nano-silica results in the increase of stiffness, tensile strength, resilient modulus, fatigue life and resistance against permanent deformation and moisture damage. The reduction of indirect tensile strength in wet the condition decreases with increasing nano-silica content. Dynamic creep test results showed that, the flow number of the control mixture and the mixture containing 1% of nano-silica is much lower than 10000 loading cycles. However, the mixtures containing 3 and 5% of nano-silica do not reach to the tertiary creep region after 10000 loading cycles.

Keywords: Asphalt Concrete, Dynamic Creep, Moisture Damage, Nano-Silica, Resilient Modulus.

INTRODUCTION

Asphaltic mixtures are used in the upper layers of flexible pavements and their main functions are to protect the underlying layers and sub-grade against detrimental effects of traffic loading and environmental conditions and provide a surface with a satisfactory riding quality. These materials are highly sensitive compared with the other materials used in pavement construction (Abtahi et al., 2009). They are exposed to high stresses imposed by traffic and detrimental effects of environment and prone to different types of distress such as thermal and fatigue cracking, rutting and moisture damage. Distress is the result of one or more factors, including magnitude and type of load, climatic conditions, material characteristics and material interactions. Different modes of

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distress in asphaltic pavements may be classified into the those corresponding to stability problems (e.g. rutting and fatigue cracking) and those corresponding to durability problems (against environmental effects, e.g. moisture damage, thermal cracking and aging). Improvement of the engineering properties of asphaltic layers in flexible pavements results in the increase of their life, which is environmentally and economically beneficial.

For many years, when the loading on pavements was less severe, different neat asphalts (unmodified binders) were combined to improve their properties. However, in recent years, due to the increase of traffic volume, use of heavier axle loads, new axle configurations and higher tire pressures, the demands on highway pavements and asphaltic layers have increased, requiring enhancement of the performance of existing asphaltic materials (Yusoff et al., 2014). In addition, developments in technology and production of new materials and advances in understanding of the behavior and characteristics of asphaltic binders have made it easier to examine the benefits of introducing new additives and modifiers into asphaltic materials. The modifiers that are available fall into various categories, such as naturally occurring materials, industrial by-products and waste materials, as well as carefully engineered products (Yosuff et al., 2014). Some of the more common categories include reclaimed rubber products, fillers, fibers, catalysts, polymers (natural and synthetic) and extenders, to name a few (Whiteoak and Read, 2005). A most common category of the materials used for asphalt modification is polymers, including thermoplastic elastomers and plastomers and thermosetting polymers (Dogan and Bayramli, 2009; Sadeque and Patil, 2013; Sengoz and Isikyakar, 2008; Samsonov and Gureev, 2013; Gama et al., 2016). Resistance against thermal and fatigue cracking and permanent deformation of asphaltic mixtures have been shown to be improved by polymer modification of the binder (Issacson and Zeng, 1998). Polymers suffer from some drawbacks including their comparatively higher cost, storage stability and compatibility with bitumen (Yusoff et al., 2014). These drawbacks have encouraged engineers and researchers to find some alternative materials to be used for asphalt modification.

In recent years, nanotechnology has become a promising and creative technique in the materials industry, and nano-materials have been widely applied in various fields across the world (Yao et al., 2012). The Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) defines nano-material as a material with one or more external dimensions, or an internal structure having one or more dimensions of the order of 100 nm or less, and which can exhibit novel characteristics compared to the same material without nano-scale features (SCENIHR, 2006). Many researchers have used nano-materials for cement, but nano-material modified asphalt is relatively new compared to modified concrete. Because of this very small size and huge surface area, nano-materials can achieve the same effect as ordinary material by adding a relatively small amount. There are various nano-materials, which have been or have the potential to be used to modify asphalt, such as nano-clay, nano-silica, nano-titanium, nano-hydrated lime, nano-sized plastic powders, or polymerised powders, nano-fibers, and nano-tubes, to name a few (Shafabakhsh et al., 2015; Yosuff et al., 2014; Shafabakhsh and Jafari Ani, 2015; Yao et al., 2012; Yusoff et al., 2014; Yuo et al., 2011; Khatak et al., 2012).

One of the nano-materials, which has been shown to be effective in improving the mechanical properties of the bitumen and asphaltic mixtures is Nano-clay (Taherkhani, 2016a; Taherkhani, 2016b; Ghile, 2005; Becker et al., 2002). Modification of asphaltic binder by a small nano-clay content has shown to decrease its temperature sensitivity and increase its stiffness and ductility. Nano-clay-modified asphalt has also been shown to be more resistant against ageing (Santagata et al., 2012). Jahromi and Khodaii (2009) found that the dynamic modulus of asphaltic binder increases and its phase angle decreases by nano-clay modification, leading to the increase of its resistance against permanent deformation. For example, it has been found that 2% (by weight of bitumen) of nano-clay in asphalt may increase the shear (complex) modulus by as much as 184% (You et al., 2011). This indicates that the rutting resistance of such asphalt is likely to have been improved. Nano-material has also been used for further improvement of SBS-modified asphalt binder properties (Polacco et al., 2008; Sureshkumar et al., 2010). Shafabakhsh and Jafari Ani (2015) used a combination of nano-titanium dioxide and nano-silica (TiO_2/SiO_2) for modification of penetration grade bitumen and found that the nano-particles boost the rheological properties and improve the toughness and viscosity of the bitumen. The use of modified bitumen in asphaltic mixtures containing steel slag aggregate showed that the resistance against rutting and fatigue cracking was improved. Several studies have been conducted on nano-calcium carbonate (Nano CaCO3) modified asphalt in China, as well. Based on the results of these studies, both rutting resistance and the toughness of asphalt were improved by adding nano CaCO3. The results show that adding nano-CaCO3 to asphalt makes a uniform mixture that is stable and improves the susceptibility to high temperatures (Han et al., 2011; Hao et al., 2012).

Another nano-material, which can be used for modification of asphaltic materials is nano-silica. Silica is an abundant compound worldwide that is largely employed in industries to produce silica gels, colloidal silica, and fumed silica, etc. (Yang and Tighe, 2013). Nano-silica particles have been used for reinforcing elastomeric polymers in industry (Chrissafis et al., 2008) and Portland cement concrete mixtures (Quercia and Brouwers, 2010). The advantages of nano-silica are its low cost of production and the high performance features (Lazzara and Milioto, 2010). Nano-silica has also a huge specific surface area, strong adsorption, good dispersal ability, high chemical purity and excellent stability (Yao et al., 2012). Use of 2-4% of nano-silica by weight of asphalt binder has been shown to reduce the rut depth by almost half (You et al., 2011; Yao et al., 2012).

Up until now, limited studies have been conducted for investigation of the nano-silica modified asphaltic mixtures. Therefore, this study aimed to investigate the performance of nano-silica modified asphaltic concrete and relate the results of the mixture with the effects on the binder.

RESEARCH METHODOLOGY

Materials

Aggregate and nano-silica are the materials which have been used in this study. 60/70 penetration grade bitumen produced by Pasargad refinery in Iran has been used as the binder in the mixtures. The properties of the bitumen used in this research are shown in Table 1. Siliceous coarse, fine and filler aggregates were collected from an asphalt plant in Zanjan Province in the north-west of Iran. In order to control the required specifications and use in mix design process, some basic properties of the aggregates were measured. The properties of the coarse, fine and filler fractions of the aggregate used in this study are shown in Table 2. A gradation test was also conducted on each fraction to determine the percentage of each in the mixture to achieve the target gradation. A dense gradation, with a maximum aggregate size of 19mm, used for binder and wearing courses of asphaltic pavements in Iran, was used as the target gradation of the mixtures in this study. Figure 1 shows the specification limits and the gradation of the mixtures used in this study. Figure 2 shows the nano-silica, and Table 3 and Table 4 shows the chemical composition and the properties of the nano-silica used in this research.

Table 1. Properties of the bitumen

Test	Standard	Results
Density at 15˚C	ASTM-D70	1.016
Penetration at 25˚C (0.1mm)	ASTM-D5	69
Softening Point (˚C)	ASTM-D36	49
Ductility at 25˚C (cm)	ASTM-D113	100
Solubility in Trichloroethylene (%)	ASTM-D2042	99.8
Flash Point (˚C)	ASTM-D92	308
Loss in weight after thin film oven test (%)	ASTM-D1754	0.03
Retained penetration after thin film oven test (%)	-	98
Ductility after thin film oven test (cm)	-	74
Viscosity at 120˚C (centistokes)	ASTM-D2170	810
Viscosity at 135˚C (centistokes)	ASTM-D2170	420
Viscosity at 150˚C (centistokes)	ASTM-D2170	232

Table 2. Properties of aggregate

Properties (tests) / Materials	Sand Equivalent (%) ASTM-D2419	Los Angeles Abrasion Test ASTM-C131	Plasticity Index AASTM-D4318	Angularity in one and two sides (%) ASTM-D5821	Moisture Absorption (%)	Density ASTM-C127,128 ,D854	Flakiness BS 812	Loss in Magnesium Sulfate Solution (%) ASTM-C88	Silicate content (%)	Fineness modulus of sand AASHTO-M6
Coarse aggregate	-	22	-	94/90	1.8	2.6	11	0.7		
Fine aggregate	58	-	N.P	-	2.5	2.6	-	0.9	55	3.7
Filler	-	-	N.P	-	-	2.79	-	-		

Table 3. Chemical composition of nano-silica

SiO_2 (%)	Ti (ppm)	Ca (ppm)	Na (ppm)	Fe (ppm)
>99	<120	<70	<50	<20

Table 4. Properties of nano-silica used in this study

True Density (gr/cm^3)	Bulk Density (gr/cm^3)	Color	SSA (m^2/g)	Particle Size (nm)	Purity (%)
2.4	0.1<	White	200	11-13	+99

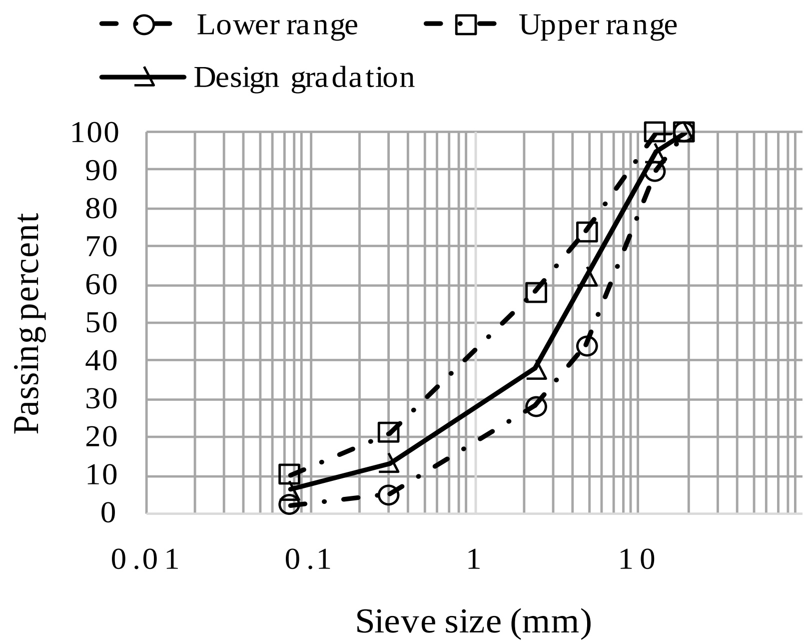


Fig. 1. Gradation of the mixtures and the specification limits

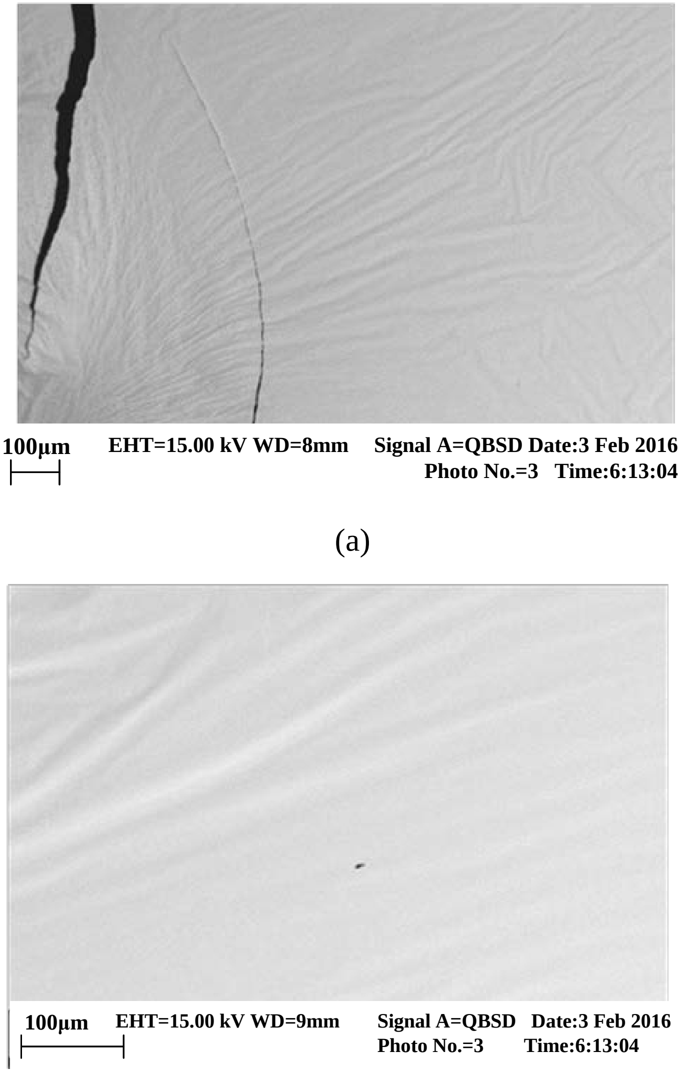
Fig. 2. Nano-silica particles

Research Plan

In this research, it was planned to study the effects of nano-silica on selected engineering properties of a bitumen and the asphaltic mixtures made with the modified binder. Different nano-silica contents of 1, 3 and ٥% (by the weight of binder) were added to a 60/70 Pen grade bitumen and the properties of penetration grade, softening point and ductility of the modified binders were evaluated. Using a typical aggregate gradation, asphalt concrete specimens were made using the control and nano-silica modified binders to investigate the Marshall properties, stiffness, resistance against moisture damage, permanent deformation and fatigue cracking. Moisture damage resistance was planned to be evaluated by measuring the Marshall stability and indirect tensile strength of moisture conditioned and dry specimens of the mixtures.

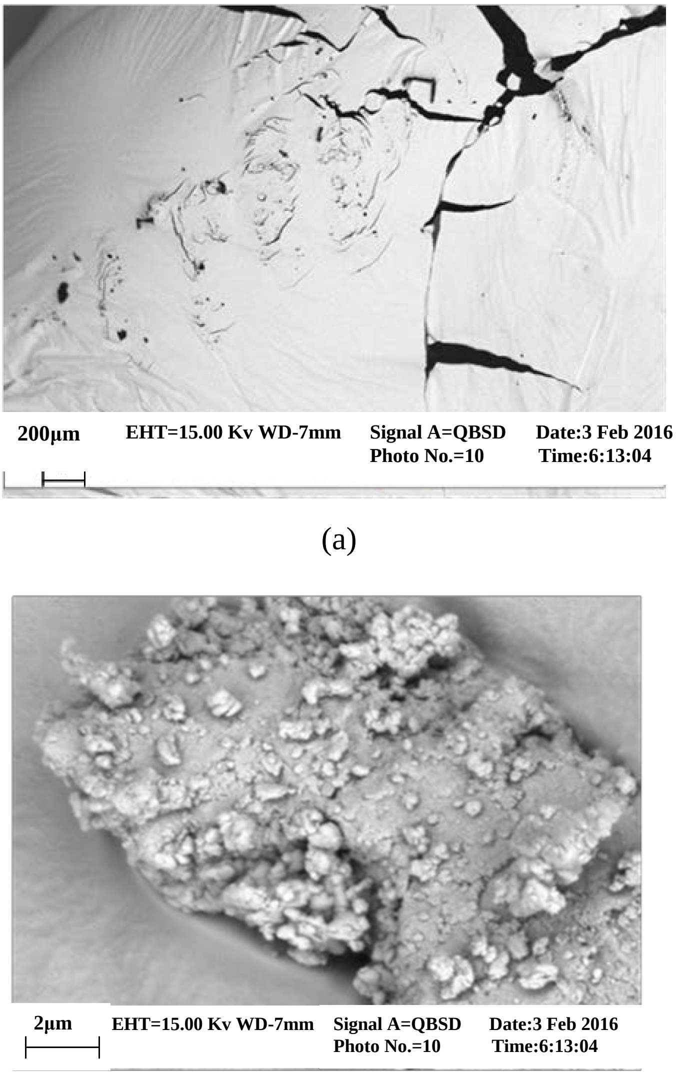
Mix Design and Specimen Fabrication

Nano-silica modified binders were made by the addition of nano-silica into the binder heated to a temperature of 160°C and mixed using a high shear mixer operating at a speed of 3000rpm for a duration of 1 hour. Effectiveness of mixing method for homogenous dispersion of nano-silica particles in binder was evaluated using Scanning electron microscopy (SEM). Figure 3 and 4 show, respectively, the SEM images of the unmodified bitumen and the binder modified with 3% of nano-silica. Nano-silica particles show a strong tendency for aggregation and formation of a random network of contacting particles, which is seen in Figure 4(b). In order to use the full potential of nano-silica as asphalt binder modifier, it is necessary to disperse these nano-particles in binder as much as possible. As is shown in SEM pictures, mixing procedure was a successful technique to mix nano-silica in asphalt cement and make a nano-silica–asphalt binder matrix. From Figure ٤ it can be concluded that some nano-silica particles are completely separated within the bulk of the binder and some are in a very small groups.



(b)

Fig. 3. SEM images of unmodified asphalt binder; a) 100_ magnification; b) 500_ magnification



(a)

(b)

Fig. 4. SEM images of modified asphalt binder with nano-silica; a) 100_ magnification; b) 20,000_ magnification

The optimum binder content of the control mix (without nano-silica) was determined using Marshall mix design method, which was found to be 5.3%. The same binder content was used for making the nano-silica modified mixtures. The air voids content of the mixtures was checked to within the range of 3 to 5%. The volumetric properties of the mixtures are shown in Table 5. ASTM D1559 standard method was followed for making the specimens used in this study. Cylindrical specimens, measuring 101.6 mm in diameter and approximately 67 mm high were made from each mixture. The required aggregate for each specimen was weighed and placed in an oven set at 172 ˚C for 4 hours, and the bitumen was also heated at 150 ˚C. Then, using a laboratory mixer, the heated aggregate and binder were mixed thoroughly until obtaining a mixture with aggregate particles uniformly coated with asphalt. Then, the hot mixture was poured into the mold and compacted using Marshall Compactor with 75 blows to either side. After 24 hours, the specimens were removed from the molds and stored in room temperature until using them in tests.

Table 5. Binder content and volumetric properties of the mixtures

Nano-silica Content (%)	Bitumen Content (%)	Air Voids Content (%)	Voids in Mineral Aggregate (VMA) (%)	Voids Filled with Asphalt (VFA)
0	5.3	4.15	16.3	74.65
1	5.3	4.38	15.95	72.95
3	5.3	4.64	15.74	70.38
5	5.3	4.93	15.43	66.58

Tests on Asphalt Binder

ASTM-D36, ASTM-D36 and ASTM-D5 standard methods were followed for measuring the standard penetration grade, softening point and ductility, respectively, of the control and nano-silica modified binders.

Marshall Tests

Marshall tests were conducted for measuring the Marshall stability and flow of the mixtures following the ASTM D1559 standard method. Before putting the specimens in loading frame, they were placed in a water tank set at 60 ˚C for 30 minutes. Using a Marshall test set up the specimens were loaded at a constant rate of 50.8 mm/min, and the force required for breaking the specimen and the diametrical deformation along the loading direction were measured as the Marshall stability, and flow, respectively. By dividing the Marshall stability to the Marshall flow, the Marshall Quotient (MQ) of the mixtures was calculated, which is commonly used as an indicator for resistance of asphaltic mixtures against permanent deformation (Ameri et al., 2013). The Marshall test was also used for evaluating the resistance against moisture damage of the mixtures. To this end, 6 specimens of each mixture were made with an air void content at 4 ± 1%, and divided into two groups. After placing the specimens for 30 min in a water tank set at 60 °C, the Marshall stability of the specimens in group one was measured, and the average for 3 replicates was used as the unconditioned Marshall stability (MS_u). The Marshall stability of the specimens in second group was measured after submerging them in a water tank, set at 60 ˚C, for 24 hours, and the average of 3 specimens was used as the Marshall stability of conditioned specimens (MS_c). The Marshall Stability Ratio (MSR) was calculated using Eq. (1).

$$MSR = \frac{MS_c}{MS_u} \times 100 \tag{1}$$

Iran Highway Asphalt Paving code 234 (IHAP, 2012) requires a minimum MSR value of 80% for asphaltic mixtures.

Indirect Tensile Strength Tests

One of the main properties of asphaltic mixtures is the tensile strength, which is related to the strength against cracking and permanent deformation. A mixture with a higher tensile strength is more resistant against cracking and permanent deformation. The resistance against moisture damage is described using the indirect tensile strength of asphaltic specimens after undergoing a specified conditioning in moisture compared with that of unconditioned specimens. In this research, following AASHTO T283 standard method, the Indirect Tensile Strength (ITS) test was conducted on dry and conditioned specimens at 25 ˚C. From each mixture, 6 specimens were made with an air voids content of 7 ± 0.5%. They were divided into two groups. The indirect tensile strength (ITS) of one group was measured in dry condition, for which the specimens were placed in plastic bags and submerged in a water tank set at 25 ˚C. The indirect tensile strength of the specimens in group 2 was measured after conditioning them according to the AASHTO T283 standard method. According to this standard, first, the specimens were saturated at 70 to 80% using a vacuum pump and were placed in a plastic bag containing 10 ± 0.5 ml of water. Then, they were placed in a freezer set at -18 ˚C for 16 hours, after which they were placed in a Marshall water bath set at 60 ˚C for 24 hours. Later, they were placed in a water tank set at 25 ˚C for 2 hours. The indirect tensile strength of the dry and conditioned specimens was measured by placing them in a ITS frame and loading using the Marshall test set up at a rate of 50.8 mm/min until failure. The required force for breaking the specimen was measured and the indirect tensile strength was calculated using Eq. (2).

$$ITS = \frac{2000P}{\pi t D} \tag{2}$$

where ITS is the indirect tensile strength in kPa, P is the maximum applied load for breaking the specimen in N, D is the specimen diameter in mm, and t is the thickness of the specimen in mm.

The average of 3 specimens in each group was calculated and used as the dry or conditioned indirect tensile strength of the mixture. For each mixture, the tensile strength ratio (TSR) was calculated using Eq. (3).

$$TSR = 100\left(\frac{ITS_w}{ITS_d}\right) \tag{3}$$

where ITS_w and ITS_d are the indirect tensile strength of dry and conditioned specimens, respectively.

Resilient Modulus Test

The resilient modulus test was conducted on the specimens at 25 °C, using a UTM-10 and according to the ASTM D4123-95 standard method. Resilient modulus of asphalt concrete is defined as the ratio of deviatoric stress to the recoverable strain of a specimen under cyclic loading. Cylindrical specimens 100 mm in diameter and approximately 40 mm in thickness were cut from Marshall compacted specimens and used in the tests. In this test, 5 cycles of haversine load with an amplitude of approximately 15% of tensile strength at a frequency of 0.5 Hz, with 500 ms of loading time and 1500 ms of rest duration were applied on each specimen. The resilient modulus of the specimens has been determined by the software connected to the test set up using Eq. (4). The modulus was determined for each cycle and the average of 5 cycles was used as the resilient modulus of the mixture.

$$M_r = P(0.27 + \nu)/(t \times \Delta t) \tag{4}$$

where M_r is the resilient modulus (MPa), P is the vertical load applied on the specimen (N), t is the thickness of the specimen (mm), Δt is the horizontal deformation across the diameter (mm) and υ is the Poisson ratio of asphalt concrete.

Dynamic Creep Tests

Different types of test are available for evaluation of the permanent deformation behavior of asphaltic mixtures. A common test method is the uniaxial dynamic creep test. In this study, dynamic creep tests were conducted on cylindrical specimens using a UTM-10 machine, according to the EN 12697-25 standard method. Table 6 shows the tests conditions. For each test, the specimen was placed inside the temperature controlled cabinet two hours before commencing the test, to ensure that it was uniformly at the test temperature. The test is controlled by software installed on a PC connected to the test set up. The tests were continued for 10000 loading cycles. During the testing period, the vertical deformation and stress level were monitored by the equipment software. Before starting the dynamic creep tests, to ensure that the loading plate is seated on the specimen, a static load with a magnitude of about 10% of the deviatoric stress was applied for 10 min.

Table 6. Creep test conditions utilized in this study

Stress level (kPa)	Frequency (Hz)	Loading Time (sec)	Rest Time (sec)	Number of Cycles	Temperature (˚C)
200	0.5	1 ± 0.05	1 ± 0.05	10000	50

RESULTS AND DISCUSSION

Binder Tests Results

Figures 5 and 6 show, respectively, the penetration grade and softening point of the binders. As can be seen, the penetration grade decreases and the softening point increases with increasing nano-silica content. Decrease of the penetration grade is an indication of increasing the stiffness at intermediate temperatures, and the increase of the softening point is an indication of a decrease of temperature sensitivity, which in turn, increases the resistance against cracking at low temperatures and permanent deformation at high temperatures. These results are thought to be partly due to the absorption of asphalt light volatiles by the nano-silica, and that the nano-silica particles are stiffer than the asphalt, which results in an increase in the stiffness of modified asphalt. The mechanism needs more investigation.

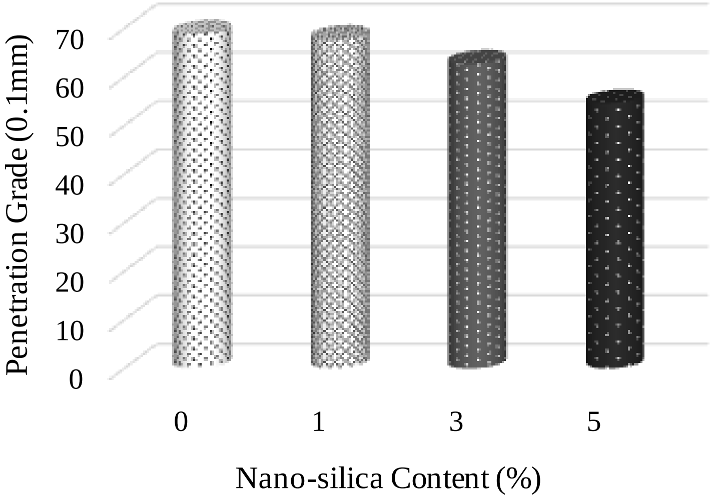


Fig. 5. Penetration test results

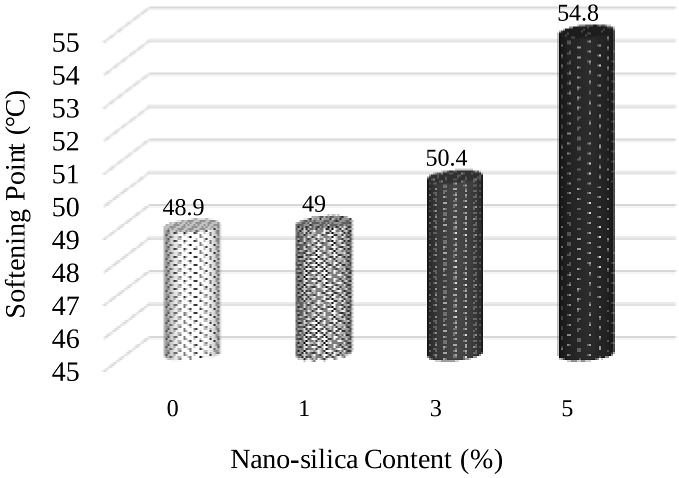


Fig. 6. Softening point test results

Penetration Index (PI) is an indication of temperature sensitivity and stiffness of an asphalt cement. The temperature sensitivity of asphaltic binder decreases and its stiffness increases with increasing penetration index. Lower temperature sensitivity is an indication of higher resistance against permanent deformation and thermal cracking (Ghasemi and Marandi, 2013). Penetration index of the control and modified bitumen was determined using Eq. (5) (Read and Whiteoak, 2005).

$$PI = \frac{1952 - 500log(Pen25) - 20SP}{50log(Pen25) - SP - 120} \qquad (5)$$

where *Pen 25* is the penetration grade at 25 ˚C in 0.1 mm, and *SP* is the softening point in °C. Figure 7 shows the PI of the binders containing different nano-silica contents. As can be seen, PI increases with increasing nano-silica content, indicating that the resistance against thermal cracking and permanent deformation increases with increasing nano-silica content in the bitumen.

Ductility is used to show the adhesion and cohesion of bitumen. Figure 8 shows the ductility of the control and nano-silica modified bitumen. As can be seen, the ductility decreases with increasing nano-silica content, which confirms the result of previous studies (Fini et al., 2015). The reduction of ductility is attributed to the absorption of the volatiles by nano-silica particles in the bitumen and the increase of stiffness resulting from nano-silica modification.

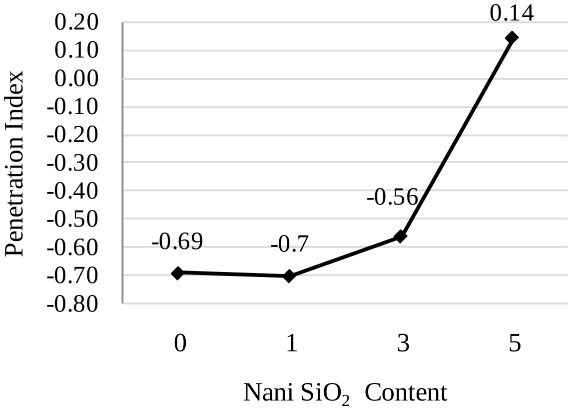


Fig. 7. Penetration Index of unmodified and modified binders

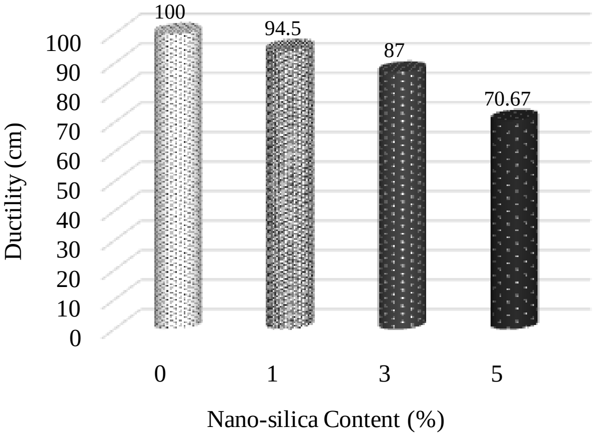


Fig. 8. Ductility test results of the binders

Marshall Tests Results

Variation of the Marshall stability with nano-silica content in shown in Figure 9, in which, the Marshall stability for each mixture has been obtained by averaging that for 3 specimens. As can be seen, Marshall stability increases with increasing nano-silica content. Iranian Highways Asphalt Pavements code (IHAP, 2012) requires a minimum Marshall stability of 8 kN for application in highways with heavy traffic (more than 10^7 ESAL). As can be seen in Figure 9, all of the mixtures satisfy the requirement. Figure 10 shows the flow of the mixtures containing different nano-silica contents. Flow of asphaltic mixture is an indication of its ductility. Very low flow is not desirable, as it makes the mixture prone to cracking, and, very high flow makes it prone to permanent deformation. Therefore, a minimum and a maximum flow is required by the specifications. From the results in Figure 10, it can be inferred that flow decreases with increasing nano-silica content. IHAP (2012) requires a minimum and a maximum flow of 2 and 3.5 mm, respectively, for asphalt concrete to be used in pavement layers of highways with heavy traffic. The results of Marshall quotient, which have been determined by dividing the Marshall stability by flow, are presented in Figure 11. Marshall quotient is usually used as an indication of resistance against permanent deformation of asphaltic mixtures (Zoorob and Suparma, 2000). From the results in Figure 11, it can be said that the Marshall quotient of the mixtures containing 1, 3 and 5% of nano-silica is 22, 40 and 55%, respectively, higher than the MQ of the control mixture. Therefore, these results are consistent with previous studies (Zafari et al., 2014; Sadeghpour Galooyak, 2015; Yusoff et al., 2014), which found that nano-silica modification improves the resistance of asphaltic mixtures against permanent deformation. The increase in the stiffness of asphalt concrete by nano-silica modification can be related to the high surface area of nano-silica particles and their interaction with the binder by increasing asphalt absorption and making it stiffer.

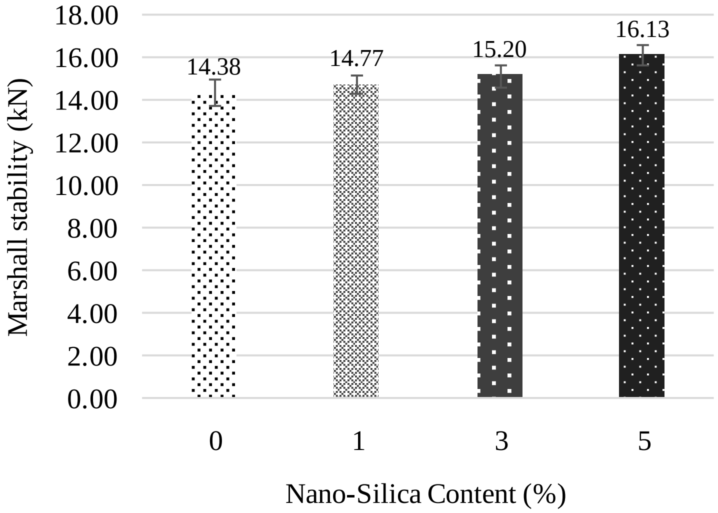


Fig. 9. Marshall stability versus nano-silica content

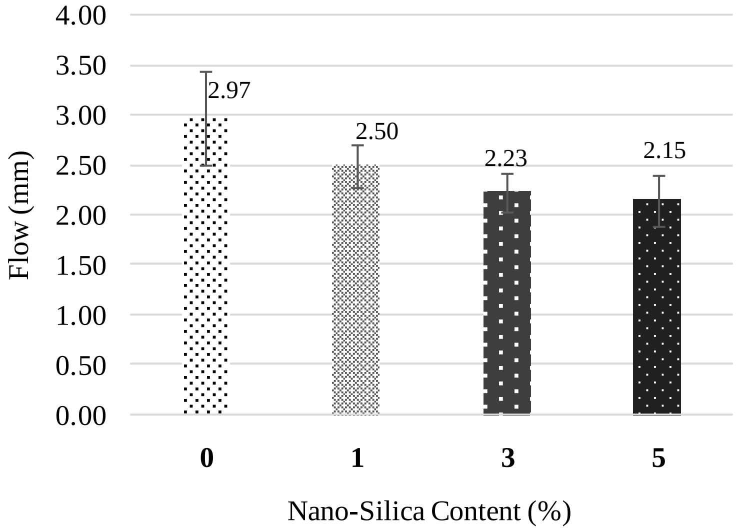


Fig. 10. Flow versus nano-silica content

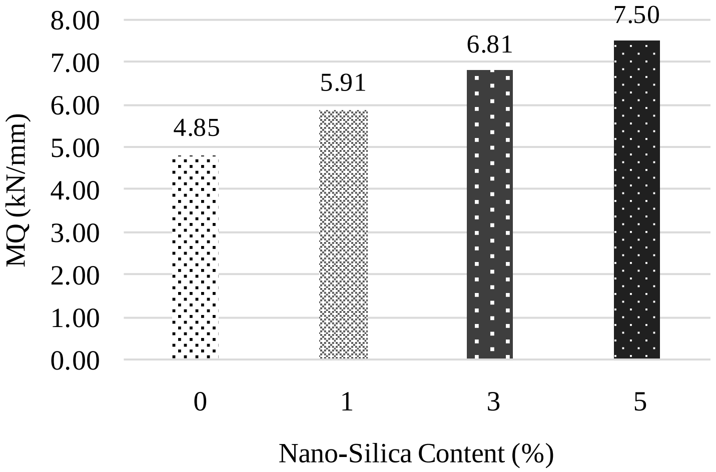


Fig. 11. Marshall quotient versus nano-silica content

Indirect Tensile Strength Tests Results

One of the main properties of asphaltic mixtures is their tensile strength, which is related to the resistance against thermal and fatigue cracking. Fatigue cracking of asphaltic mixtures occurs predominantly at intermediate temperatures. Figure 12 shows the dry and conditioned indirect tensile strength (ITS) of mixtures containing different percentages of nano-silica. As can be seen, under both dry and wet conditions, nano-silica modification has resulted improvement in ITS, indicating that nano-silica modification improves the resistance of asphaltic mixtures against fatigue cracking. The percentages of loss in ITS by conditioning have also been presented in Figure 12. As can be seen, the difference between the ITS of unconditioned and conditioned mixtures decreases with increasing nano-silica content. The ratio of the indirect tensile strength of conditioned and unconditioned specimens, known as tensile strength ratio (TSR), is used as an indication of resistance against moisture damage. A minimum TSR value is specified to ensure resistance against moisture damage. Figure 13 shows the TSR of the mixtures containing different percentages of nano-silica. As can be seen, TSR increases with increasing nano-silica content. Based on the values presented in Figure 13, the TSR of the mixtures containing 1, 3 and 5% of nano-silica, is, respectively, 18, 36 and 71% higher than that of the base mixture. The improvement of resistance against moisture damage can be related to the increase of binder stiffness by the addition of nano-silica. In general, the higher the stiffness of the binder the more difficult to lose its adhesion to the aggregate surface (Hamedi et al., 2015). Based on the specifications of asphaltic concrete in Iran (IHAP, 2012), the minimum TSR value is specified to be 75%. It can be seen that, although the base mixture and the mixtures containing 1 and 3% of nano-silica have a TSR value lower than that required by specifications, modification of the mixture by 5% of nano-silica results in a mixture which satisfies the requirement.

Figure 14 shows the Marshall stability ratio (MSR) of the mixtures. As can be seen, the trend is the same as that of TSR, with an increase of resistance against moisture damage with increasing nano-silica content. The results also show that the MSR values are higher than the TSR values, which is due to the lower air voids content of the mixtures used for Marshall stability than those used in the indirect tensile strength tests. As mentioned earlier, the specimens used in Marshall tests had an air voids content of 4 ± 1%, while those used in indirect tensile strength had an air voids content of 7 ± 0.5%. The higher air voids content allows more moisture to penetrate in the mixture and causes more damage in the mixture.

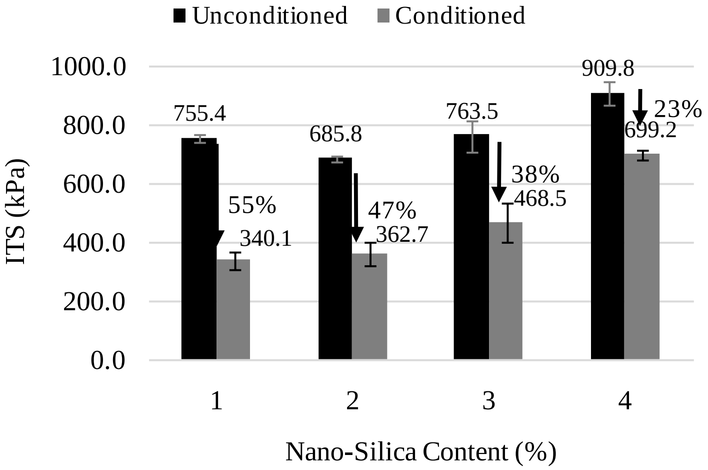


Fig. 12. Marshall quotient versus nano-silica content

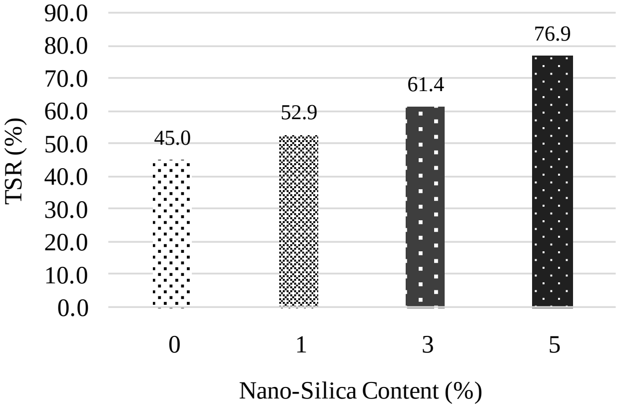


Fig. 13. TSR of the mixtures

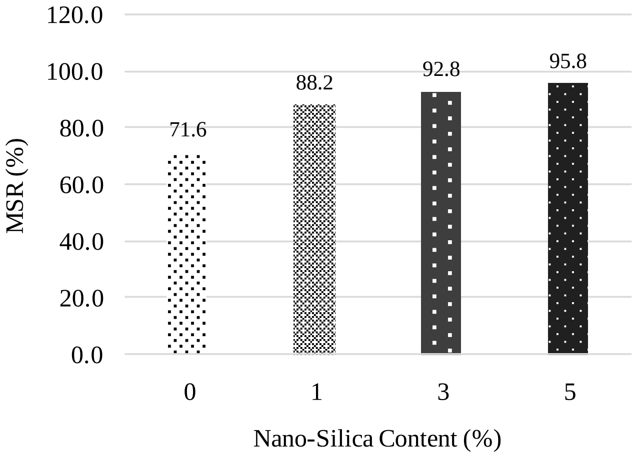


Fig. 14. MSR of the mixtures

Resilient Modulus Test Results

Figure 15 shows the variation of resilient modulus at 20 °C with nano-silica content. As can be seen, the resilient modulus increases with increasing nano-silica content, which the trend is consistent with that for Marshall quotient (Figure 11). From the results in Figure 15, it can be said that the resilient modulus of the mixture containing 5% of nano-silica is approximately 49% higher than that of the control mixture made by unmodified asphaltic binder. The improvement of resilient modulus is beneficial for resistance against permanent deformation at high temperatures and under heavy loadings. The increase of stiffness can also result in a reduction of asphaltic layer thickness, which may reduce the cost of pavement. As mentioned earlier, the high surface area of nano-silica particles results in more interaction with the binder and more absorption of the oils in the asphalt cement leading to a higher stiffness.

The fatigue life of the mixtures under different tensile stresses of 200, 250 and 300kPa was calculated using the model developed by Mansoorian (2006), as shown in Eq. (6).

$$\begin{aligned}Log\ N_f &= 3.527 - \\ &3.959\,Log\ (\sigma_t) + \\ &2.417\,Log\ (M_r) + 0.022VFA\end{aligned} \quad (6)$$

where N_f is the fatigue life, σ_t is the tensile stress, M_r is the resilient modulus and *VFA* is the voids filled with asphalt.

Figure 16 shows the predicted fatigue life of the mixtures made with the binders modified by different nano-silica contents.

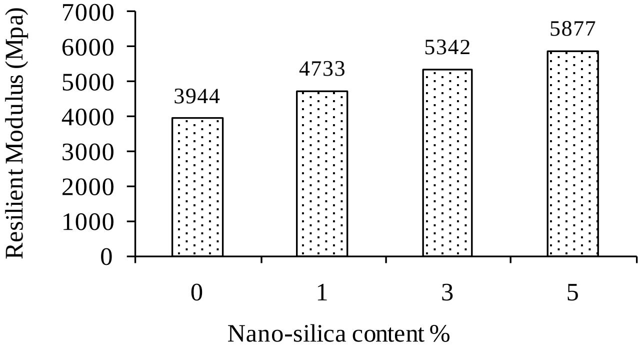


Fig. 15. Resilient modulus tests results

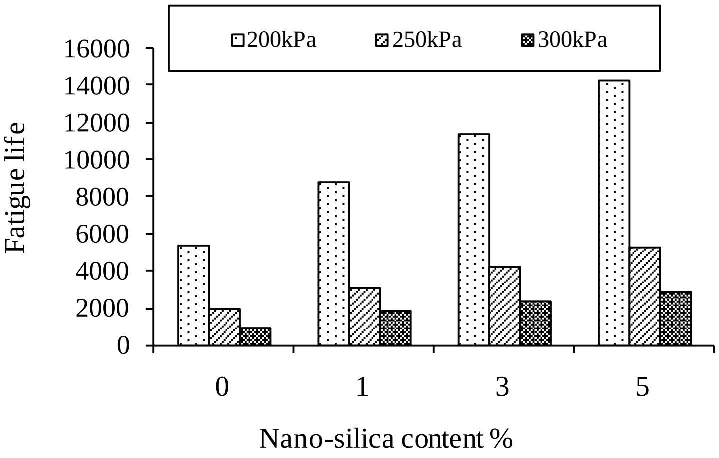


Fig. 16. Fatigue life of different mixtures

As can be seen, the fatigue life of the mixtures increases with increasing nano-silica content. The values of fatigue life at different stress levels show that the fatigue life of the mixture containing 5% of nano-silica is predicted to be approximately 160% higher than the control mixture.

Dynamic Creep Test Results

Figure 17 shows the dynamic creep test results on the control and nano-silica modified mixtures subjected to a stress level of 200kPa at a temperature of 50˚C, where the accumulated vertical strain is plotted against the number of cycles. As can be seen, the accumulated vertical strain of the mixtures decreases with increasing nano-silica content, indicating that the resistance against permanent deformation increases by using nano-modified binder in the mixture. Utilizing the algorithm developed by Zhou et al. (2004) the flow number and the creep strain slope (CSS), which is the steady state strain rate in the secondary creep region and the number of cycles at the beginning of the secondary creep region were also determined, and are presented in Table 7. As can be seen, the number of cycles at the beginning of the secondary creep region and the flow number increase with increasing nano-silica content of the mixtures. As the majority of the time-dependent strain occurring in the first region is recoverable after removing the stress, this is in favor of resistance against permanent deformation. It can also be seen that, after 10000 loading cycles, the mixtures containing 3 and 5% of nano-silica remain in the secondary creep region, while the control mixture lies in the tertiary creep region, in which the failure is accelerated. These results show that nano-silica modification improves the resistance against permanent deformation. The results in Table 7 also show that the steady state strain rate in the secondary creep region (CSS) decreases with increasing nano-silica content. Over the range of nano-silica contents used in this research, the optimum nano-silica content for achieving the highest resistance against permanent deformation is 5%.

Table 7. The creep curve parameters of the mixtures in different conditions

Nano-Silica content %	Number of Load Cycles at First Stage	Flow Number	Creep Strain Slope (CSS)
0	4200	5700	0.7175
1	4000	6500	0.6574
3	8400	n	0.273
5	n	n	n

n: Not found at the end of 10000 load cycle.

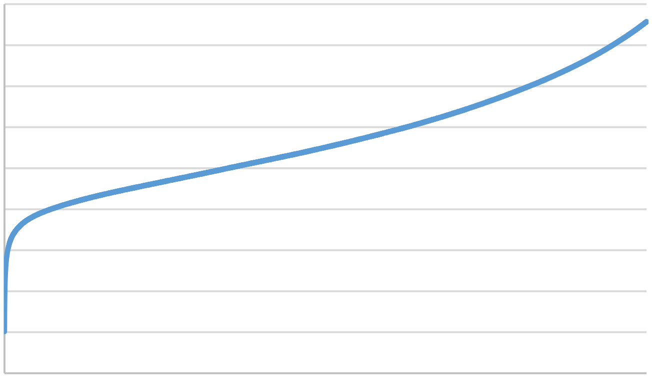


Fig. 17. Creep curves of the mixtures subjected to 200 kPa at 50 ˚C

CONCLUSIONS

In this study an asphaltic binder was modified with different percentages of nano-silica contents and some engineering properties of the binder and the asphaltic concrete made by modified binders were evaluated. The main conclusions drawn from this study are presented as follow.

- The resistance against low temperature and permanent deformation of asphaltic binder can be improved by nano-silica modification.
- Nano-silica modification decreases the ductility of bitumen.
- The Marshall stability and Marshall quotient of asphalt concrete increase with increasing nano-silica content in the modified asphalt used in the mixtures.
- Nano-silica modification improves the indirect tensile strength of asphalt concrete.
- The resistance against moisture damage can be improved by the use of nano-silica in the mixture, with increasing the resistance with increasing nano-silica content.
- The stiffness of asphaltic concrete increases with increasing nano-silica content.
- The resistance against fatigue cracking of asphaltic concrete increases with increasing nano-silica content.

Based on the dynamic creep tests conducted on the mixtures, it can be resulted that nano-silica modification improves the resistance of asphalt concrete against permanent deformation.

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