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Investigating the Effects of Nanoclay and Nylon Fibers on the Mechanical Properties of Asphalt Concrete

Taherkhani, H.[1*]

[1] Assistant Professor, Civil Engineering Department, University of Zanjan, Zanjan, Iran.

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ABSTRACT: This paper describes the effects of reinforcement by randomly distributed nylon fibers and addition of nanoclay on some engineering properties of a typical asphalt concrete. The properties of asphalt concrete reinforced by different percentages of 25 mm nylon fibers have been compared with those of the mixtures containing different percentages of nanoclay and those in which both the fibers and nanoclay have been included. Engineering properties, including Marshall stability, resilient modulus, dynamic creep and fatigue life have been studied. Nylon fibers have been used in different percentages of 0.1, 0.2, 0.3 and 0.4% (by the weight of total mixture), and nanoclay has been used in 2, 4 and 7% (by the weight of bitumen). It is found that the addition of fibers is more effective than the nanoclay for increasing the resistance against fatigue cracking. However, nanoclay improves the resistance of the mixture against permanent deformation better than the nylon fibers. The results also show that the mixture reinforced by 0.4% of nylon fibers and containing 7% of nanoclay has the highest resilient modulus, Marshall stability and fatigue life. However, the mixture containing only 7% of nanoclay has the highest resistance against permanent deformation.

Keywords: Asphalt Concrete, Fatigue, Nanoclay, Nylon Fiber, Permanent Deformation.

INTRODUCTION

Similar to many countries around the world, most highways in Iran have asphaltic pavement. Due to the limited resources of crude oil and sustainable development concerns, it will be in favor of environment and economy to preserve the asphaltic layers for a longer time. One approach to increase the life span of asphaltic layers is improving their engineering properties. Similar to other pavement materials, asphalt mixtures are subjected to different distress mechanisms, which leads to its disintegration over time (Hashemi and Latifi Namin, 2012). However, asphalt mixtures are more sensitive than the other paving materials (Abtahi et al., 2009). Distresses are affected by different factors associated with loading, environment and material properties. The major modes of distress, which challenge the pavement engineers, are permanent deformation (rutting), fatigue cracking, thermal cracking and raveling. Improving the performance of asphalt pavements results in decrease of distresses, leading to the extension of pavement life and saving investments.

Over the last decades, the use of additives for improving the performance of asphalt

* Corresponding author E-mail: taherkhani.hasan@znu.ac.ir

concrete has been practiced by engineers and investigated by researchers. A common method for improving asphalt concrete performance is reinforcement. Reinforcement can be defined as incorporation of certain materials with some desired properties within other material which lack those properties (Maurer and Gerald, 1989). Use of fibers is one method of reinforcement, which can be used by randomly distribution of the fibers within the material or applying oriented fibrous materials, e.g. geo-synthetics family. Addition of fibers into asphalt concrete enhances its strength and fatigue characteristics, while adding ductility. Furthermore, fiber reinforcement of asphalt concrete can increase its dynamic modulus (Wu et al., 2007), resistance against moisture damage (Putman and Amirkhanian, 2004), creep compliance, resistance against permanent deformation (Chen et al., 2004), freeze-thaw (Echols, 1989), ageing and reflective cracking (Goel and Das, 2004). Fibers have also shown to be able to prevent the formation and propagation of cracks in asphalt concrete (Maurer and Gerald, 1989). Fibers have also shown to be able to prevent the formation and propagation of cracks in asphalt concrete (Maurer and Gerald, 1989). Fibers are also used in gap graded asphaltic mixtures, such as stone matrix asphalt, to prevent asphalt drain down (Hansen et al., 2000).

Some types of fibers are used for increasing the electrical conductivity of the asphalt mixtures, which is used for deicing and self-healing of micro cracks (Garcia et al., 2013; Wu et al., 2006). Asphaltic mixture is a self-healing material. Once the load causing the micro cracks is removed, the molecules on either side of each crack starts diffusing to the other end, and the micro cracks are healed during the rest period. On the pavements under heavy traffic, there is not enough rest period available to allow the occurrence of self-healing. One solution is to raise the temperature of the material by inducing electrical energy into conductive asphalt concrete, because the healing can be accelerated with increased temperature (Park et al., 2014). The addition of fibers with high energy absorbing capacity can increase the energy absorbing property of asphaltic mixtures which is beneficial for using as solar collector for heating adjacent buildings (Garcia et al., 2013; Wu et al., 2006). The thermal energy collected by asphaltic mixtures is harvested by circulating a fluid through it (Sheeba and Rohini, 2014).

Other types of additives have also been used for improving the mechanical properties of bitumen and asphalt concrete, which are usually added to the bitumen. Polymers are among the most commonly used materials in recent years for improving the performance of bitumen (Alatas and Yilmaz, 2013; Dogan and Bayramli, 2009; Sadeque and Patil, 2013; Sengoz and Isikyakar, 2008; Samsonov and Ureev, 2013; Gama et al., 2016). Different types of polymers, including plastics and elastomers are among the widely used polymers. They have shown to improve the resistance of bitumen against fatigue cracking, permanent deformation and low temperature cracking (Issacson and Zeng, 1998). Polymers have been reported to suffer from some limitations including the price, compatibility with bitumen and stability during storage. Due to these limitations, the use of nano scale non organic materials have attracted the attention of engineers and researchers for improving the mechanical properties of bitumen and asphaltic mixtures (Liu et al., 2003; Ghafarpour Jahromi et. al., 2012; Shafabakhsh et al., 2015; Mohammad Yosuff et al., 2015; Shafabakhsh and Jafari Ani, 2015). Nanoclay is among the nano materials which its effects on the properties of bitumen and asphaltic mixtures have been investigated and showed to improve the rheological properties of bitumen and mechanical properties of the mixtures (Ghile, 2005; Becker et al., 2002).

Sufficient documents can be found in literature, which have investigated the properties of fiber reinforced asphaltic mixtures. However, the research on the asphalt concrete reinforced by nylon fibers is limited. In addition, few research studies have been conducted on the properties of asphalt concrete containing nanoclay. It is worthy to compare the effects of nanoclay and nylon fibers on the properties of asphalt concrete. Therefore, in this research, the effects of nylon fibers on the mechanical properties of a typical asphalt concrete have been compared with the asphalt concrete containing nanoclay. In addition, the effects of using both the nylon fiber and nanoclay, simultaneously, in the asphalt concrete are investigated.

MATERIALS

The materials used in this research include aggregate, asphalt cement, nanoclay and nylon fibers. Siliceous aggregates have been used in this study, which were obtained from a local quarry in Zanjan, a city in northwest of Iran. They were washed, dried and sieved to be used for making the specimens. The gradation of binder course asphalt concrete, specified in national code was used for making the mixtures. Figure 1 shows the upper and lower limits of the gradation specified in Code 234 (Iran Asphalt Pavement Roads, 2012), and the gradation of the mixture used in this research. Table 1 shows some of the properties of the aggregates used in this research.

The asphalt cement used in this research was a 60/70 penetration grade bitumen supplied by Tabriz refinery. Table 2 shows the properties of the bitumen used for making specimens. The fibers (Figure 2a), used for reinforcing the mixtures were supplied by Middle East Dorochem Co. These fibers are made of nylon, which is referred to a group of plastics known as polyamides. Different types of nylon are available with different chemical compositions. The fibers used in this research are made of nylon 6. This type of nylon is very tough with good thermal and chemical resistance. Table 3 shows the physical and mechanical properties of the fibers. The fibers were cut in 25mm, which is the maximum aggregate size of the mixtures, and used for reinforcement.

Nanoclays are nano-particles of layered mineral silicates. Nanoclay type Cloisite 20A (Figure 2b) supplied by Rockwood company was used in this research, which its properties are shown in Table 4.

Table 1. Aggregates properties

Properties (tests) / Materials	Sand Equivalent (%) ASTM-D2419	Los Angeles Abrasion Test ASTM-C131	Plasticity Index AASTM-D4318	Angularity in Two Sides (%) ASTM-D5821	Moisture Absorption (%)	Density ASTM-C127,128, D854	Flakiness BS 812	Loss in Magnesium Sulfate Solution (%) ASTM-C88
Coarse Aggregate	-	21	-	85	1.6	2.607	12	1
Fine Aggregate	53	-	N.P	-	2	2.593	-	1
Filler	-	-	N.P	-	-	2.72	-	-

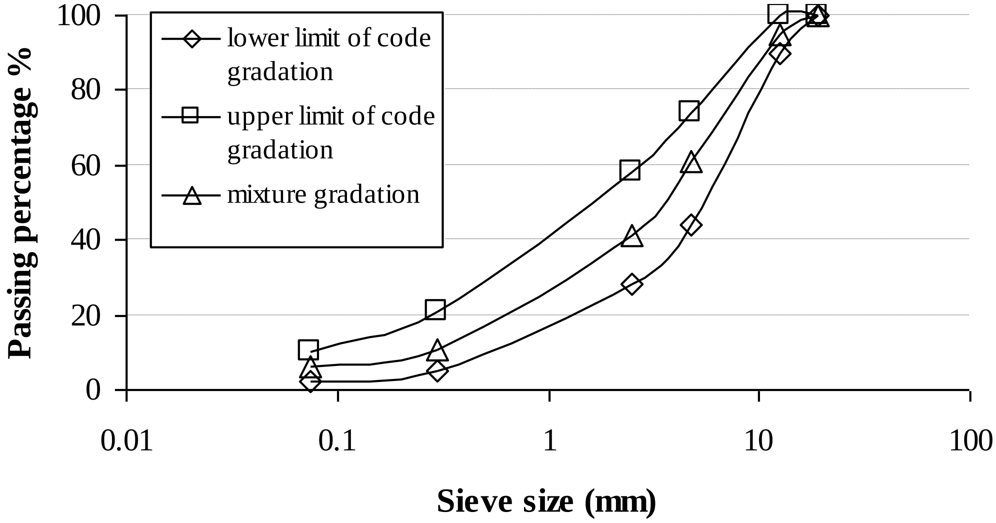

Fig. 1. Gradation of the mixture aggregates

Table 2. Properties of the bitumen used in this research

Test	Standard	Results
Density in 15˚C	ASTM-D70	1.016
Penetration in 25˚C (0.1mm)	ASTM-D5	66
Softening Point (˚C)	ASTM-D36	49.1
Ductility in 25˚C (cm)	ASTM-D113	150
Solubility in Trichloroethylene (%)	ASTM-D2042	99.8
Flash Point (˚C)	ASTM-D92	298
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)	-	94

Table 3. Properties of the fibers used in this research

Property	Original Length (mm)	Density (gr/cm^3)	Tensile Strength (MPa)	Melting Point (˚C)	Elastic Modulus (MPa)	Moisture Absorption (%)
Value	50	2.8	700	200	3670	0.01-0.02

Table 4. Properties of nanoclay Cloisite 20A

Property	Value
Base	Moontmorilonite
Concentration of modifier	95 meq in 100 gr of clay
Moisture content	< 25
Loss percent in ignition	38%
Organic Modifier	2M2HT (Dimethyl Dihydrogennated Tallow Quantemary Ammunium)
Anion	Chloride
Color	White
Density (gr/cm^3)	1.77
Particles Size	
10% finer than	2 μm
50% finer than	6 μm
90% finer than	13 μm

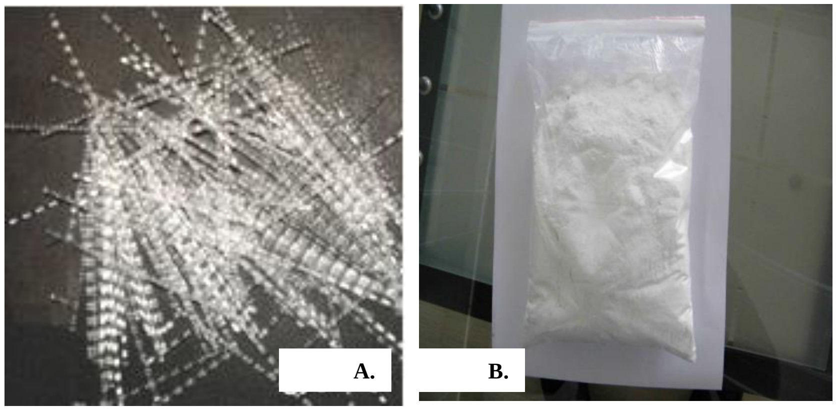

Fig. 2. A. Nylon fibers. B. Nanoclay

Experiments Plan

In addition to the control mixture, which is the mixture without reinforcing fibers and nanoclay, three types of mixtures have been used in this experimental investigation, all with the same aggregate and bitumen type as those of the control mixture. One with different percentages of nanoclay added to the bitumen, without any reinforcing fiber, one with different percentages of nylon fibers reinforcement, and one in which both the fibers and nanoclay have been used simultaneously. Table 5 shows the denotations used for these mixtures and the amount of additives in each mixture. In Table 5, the percentages of the fibers are by the weight of total mixture, and those of the nanoclay are by the weight of bitumen.

Mix Design and Fabrication of Specimens

The optimum binder content of the control mixture was determined using Marshall design method, according to ASTM D1559 standard method, which was 5.5%. The mixtures containing nanoclay were made by the same optimum binder content of the control mixture. By evaluating the volumetric properties of the fiber reinforced mixtures, the optimum binder content of the mixtures containing 0.1, 0.2, 0.3 and 0.4% of nylon fibers was determined to be 5.6, 5.7, 5.8 and 5.9%, respectively. The optimum binder content of the mixtures containing nylon fibers was selected for the mixtures containing nanoclay and the same amount of nylon fibers.

The specimens required for testing were made using Marshall method, according to ASTM D1559. For the mixtures containing nanoclay, the required amount of naoclay was added to the bitumen heated at 155˚C and were mixed using a high shear mixer at 5000rpm for 30 minutes. For making the specimens reinforced by fibers, after trying different methods, the required amount of fibers were first mixed with the hot aggregate, and then mixed with hot bitumen at a temperature between 150 to 160 ˚C, by laboratory mixer. For making the mixtures containing both the fibers and nanoclay; first the nanoclay was mixed with hot bitumen at about 155˚C using a high shear mixer and, then, was mixed with the mixture of hot aggregate and fibers at a temperature between 150 to 160 ˚C. The melting point of the fibers is 200 ˚C, indicating that the fibers do not melt during the mixing process. The visual inspection also showed that the fibers did not melt after mixing with the hot aggregate and bitumen. However, more sophisticated methods such as DSC (Differential Scanning Calorimetry) analysis can be used for this purpose. The mixtures were placed in the Marshall compactor mold and compacted by the automatic compacter at 75 blows on each side. After 24 hours, the specimens were removed from the mold and used for testing.

Table 5. Mixtures used in this research

Mixture Denotation	Percentage of Nylon Fibers (%)	Percentage of Nanoclay (%)
Control	0	0
2% NC	0	2
4% NC	0	4
7% NC	0	7
0.1% NF	0.1	0
0.2% NF	0.2	0
0.3% NF	0.3	0
0.4% NF	0.4	0
0.3% NF - 4% NC	0.3	4
0.3% NF - 7% NC	0.3	7
0.4% NF - 4% NC	0.4	4
0.4% NF - 7% NC	0.4	7

EXPERIMENTS

Marshall Tests

ASTM D1559 standard method was followed for conducting Marshall tests on the specimen. The specimens were placed in a water tank, set at 60 ˚C, for 30 minutes, after which, were loaded using the Marshall test set up, at a constant rate of 50.8mm/min. The Marshall stability was recorded as the force required for breaking the specimen, and the diametrical deformation of the specimen at failure was measured as flow. The ratio of Marshall stability to flow was computed as Marshall quotient, which is usually used as an indicator for the strength against permanent deformation.

Following ASTM D2726 standard method, the bulk density of the compacted mixtures was measured before using them in Marshall tests. The maximum theoretical density of the mixtures was also measured according to ASTM D2041 standard method. The air voids content of the mixtures (V_a), the voids in mineral aggregates (VMA), and the voids filled with asphalt (VFA), were determined using the equations presented in Asphalt Institute Manual (Asphalt Institute, 1997).

Resilient Modulus Test

Resilient modulus of asphalt concrete is defined as the ratio of deviator stress to the recoverable strain of a specimen under cyclic loading. cylindrical specimens measuring 100mm in diameter and approximately 40mm in thickness were obtained from Marshall compacted specimens and used in the tests. Resilient modulus test was conducted according to ASTM D4123-95 standard method and using UTM 14 at 25 ˚C. In this test, 5 cycles of haversine load with the amplitude of approximately 15% of tensile strength at a frequency of 0.5 Hz, 500 ms of loading time and 1500 ms of resting time 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. (2). The modulus was determined for each cycle and the average of 5 cycles was used as the resilient modulus of the mixture.

$$M_r = P(0.27+\nu)/(t \times \Delta t) \quad (1)$$

in which M_r: is the resilient modulus (MPa), *P*: is the vertical load applied on the specimen (N), *t*: is the thickness of specimen (mm), Δt: is the horizontal deformation along the thickness (mm), and υ: is the Poisson's ratio of asphalt concrete.

Dynamic Creep Tests

Dynamic creep test was conducted on the mixtures to evaluate the resistance of the mixtures against permanent deformation. The tests were conducted at 50 ˚C on cylindrical specimens, 100 mm in diameter and 50mm in height, according to Australian AS2891.12.1-1995 standard test method. Haversine loads, with an amplitude of 200 kPa were applied on the specimens at a frequency of 1 Hz, 200 ms of loading duration and 800ms of rest time. The test was set to be terminated at an accumulated vertical strain of 30000 micro strain or 40000 of load cycles. The vertical accumulated deformation of the specimens was measured during the test by two LVDTs and the vertical strain was determined by dividing the vertical accumulated deformation to the height of specimen.

Fatigue Tests

Fatigue of asphaltic materials under repeated traffic loading is the main cause of alligator cracking in asphaltic pavements. In order to capture the fatigue behavior of asphaltic mixtures, strain or stress controlled fatigue tests are conducted over a range of stress or strain values and the results are used for determination of fatigue model parameters. However, in this research, it was aimed to just compare different mixtures in terms of resistance against fatigue cracking. Therefore, one stress level, which is normally experienced by asphaltic mixtures in real pavements, has been used for fatigue testing. In order to evaluate the resistance of the mixtures against fatigue cracking, the tests were conducted according to BSI, 2nd draft DD ABF standard method on cylindrical specimens of different mixtures with 100mm in diameter and 40 mm in height using UTM 14. They were conducted at 25 ˚C by applying haversine cyclic loading with an amplitude of 350 kPa, frequency of 5 Hz and 150 ms of loading time and 50 ms of rest time. The constant cyclic loads were applied diametrically, which induce tensile strain along the thickness of specimen, and the number of cycles which leads to the fatigue failure of specimens were recorded as the fatigue life.

TEAST RESULTS

Volumetric Properties

Air voids content of compacted mixture (V_a), voids in mineral aggregates (VMA), and the voids filled with asphalt (VFA) are the volumetric properties, which are highly effective on the performance of the mixture. Hence, in the mix design process, they are considered to satisfy the requirements of specification. Table 6 shows, the V_a, VMA and VFA of the mixtures at their optimum binder content. As can be seen, the air voids content of the mixtures increases with increasing the nanoclay and nylon fibers content in the mixture, which is consistent with the results of previous studies (Huang and White, 1996; Ghaffarpour Jahromi et al., 2010). In addition, the mixtures containing both the nanoclay and nylon fibers have a higher air voids content than those with only nanoclay or nylon fibers. The increase of fibers content increases the resistance against densification and the displacement of aggregate particles, resulting in the increase of air voids content. The increase of the air voids content with the increase of the nanoclay is thought to be due to the high specific area of nanoclay particles, which requires additional bitumen to coat the nano-particles leaving more air voids content in the mixture. Iranian code (Iran Asphalt Pavement Roads, 2012), requires a minimum and maximum air voids content of 3 and 6%, respectively, for binder coarse, which is satisfied by all the mixtures.

Table 6. Volumetric properties of the mixtures

Mixture	V_a	VMA	VFA
Control	4.08	16.1	74.65
2% NC	4.3	15.9	72.95
4% NC	4.65	15.7	70.38
7% NC	5.18	15.5	66.58
0.1% NF	4.15	16	74.06
0.2% NF	4.5	15.65	71.24
0.3% NF	5.2	15.4	66.23
0.4% NF	5.5	15.32	64.1
0.3% NF - 4% NC	5.42	15.38	64.76
0.3% NF - 7% NC	5.62	15.33	63.33
0.4% NF - 4% NC	5.67	15.25	62.81
0.4% NF - 7% NC	5.73	15.05	61.92

The results also show that the voids in mineral aggregate (VMA) decreases with increasing the nanoclay and nylon fibers content in the mixture. The VMA includes the volume of air voids and the effective bitumen in the mixture. Although the air voids content of the mixtures increases with increasing the nanoclay and nylon fibers content; however, the inclusion of nanoclay and nylon fibers in the mixture results in a lower amount of effective bitumen, as shown in Table 7 for VFA. A minimum VMA value of 13% is required by the specification in code 234 (Iran Asphalt Pavement Roads, 2012) for the asphalt concrete with the maximum aggregate size of 25 mm, which is satisfied by all of the mixtures. The minimum and maximum values of the VFA of asphalt concrete for heavy traffic are defined by specification to be 60 and 75%, respectively. As can be seen, all the mixtures meet the requirement of the specification (Iran Asphalt Pavement Roads, 2012).

Marshall Tests Results

Figure 3 shows the Marshall stability of the mixtures. As can be seen, the Marshall stability increases with increasing the nylon fibers and nanoclay content of the mixtures. It can also be seen that, the mixtures containing both the nanoclay and nylon fibers have higher Marshall stability than the mixtures containing only one of the additives at the same amount. The highest Marshall stability is obtained by reinforcing the mixture with 0.4% of nylon fibers and addition of 7% of nanoclay, for which the Marshall stability is 34% higher than that of the control mixture. The increase of the Marshall stability of the mixtures containing nanoclay is attributed to the microscopic morphology and surface properties of the nanoclay, which has not been investigated in detail in this research. The microscopic morphology is related to the geometry of nano-particles, which is effective on the interaction with bitumen and other constituents of the mixture. The increase of the Marshall stability with increasing fiber content is consistent with the findings of Jahromi and Khodaii (2008) and Tapkin (2008).

Figure 4 shows the flow of the mixtures. As can be seen, the flow decreases with increasing the nanoclay and nylon fibers content of the mixtures. In addition, the mixtures containing both the nanoclay and nylon fibers have a lower flow than those containing one of them, with the lowest flow for the mixture containing 0.4% of fiber content and 7% of nanoclay. These results indicate that the additives used in this research cause stiffening of the mixtures. The minimum value of flow required by specification (Iran Asphalt Pavement Roads, 2012), for the asphalt concrete to be used in binder course of heavy traffic highways is 3mm, indicating that most of the mixtures don't meet the requirement. Marshall Quotient is defined as the ratio of the Marshall stability to the flow, which is an indication of resistance against permanent deformation (Hinislioglu and Agar, 2004). Figure 5 shows the Marshall Quotient of the mixtures. As can be seen, the Marshall Quotient of the mixtures increases with increasing the nanoclay and nylon fibers content, and the addition of both the nanoclay and nylon fibers has a better effect on the resistance against permanent deformation. The mixture containing 0.4% of nylon fibers and 7% of nanoclay has the highest Marshall Quotient, which is almost 2.5 times of that of the control mixture.

Table 7. Cost analysis of the mixtures

Mixture Denotation	Price of the Mixture (IR/ton)	Percentage of Increase in Price (%)
Control	1200000	0
2% NC	4500000	275
4% NC	8800000	550
7% NC	12750000	962
0.1% NF	1360000	13.3
0.2% NF	1520000	26.7
0.3% NF	1680000	48
0.4% NF	1840000	53.3
0.3% NF - 4% NC	10480000	773
0.3% NF - 7% NC	14430000	1192
0.4% NF - 4% NC	10640000	786
0.4% NF - 7% NC	14590000	1115

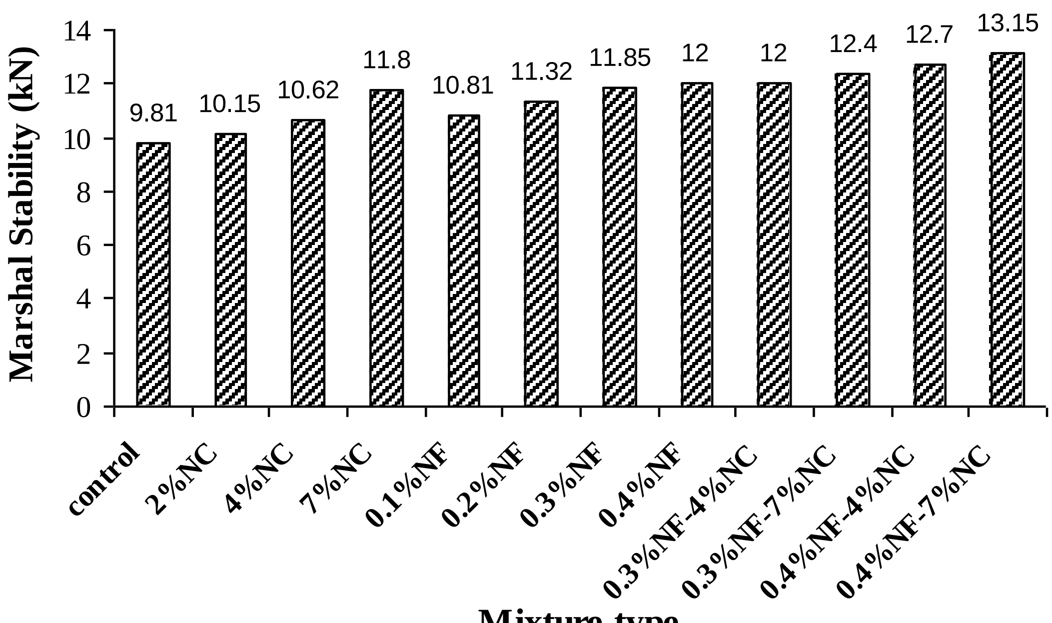

Fig. 3. Marshall Stability of mixtures

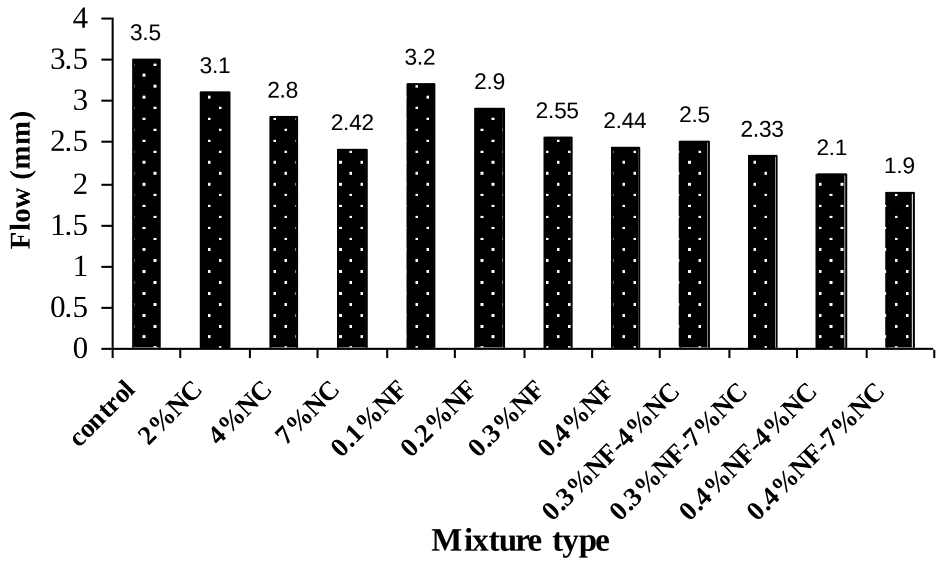

Fig. 4. Flow of the mixtures

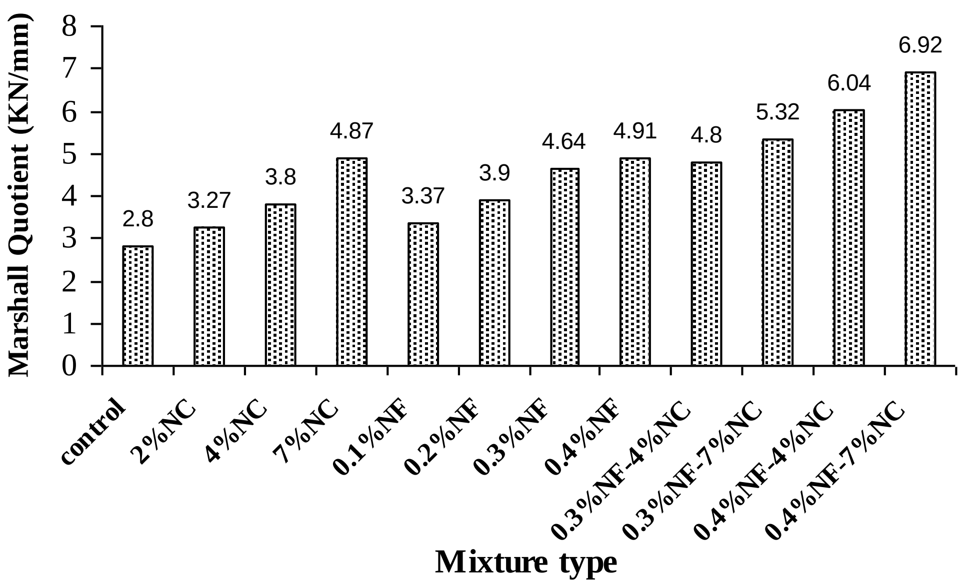

Fig. 5. Marshall Quotient of the mixtures

Resilient Modulus Tests Results

Figure 6 shows the resilient modulus of the mixtures. Resilient modulus is an indication of the stiffness of asphaltic mixtures under traffic loading and its ability to distribute the applied load on the underlying layers. Resilient modulus is also related to the resistance against permanent deformation and cracking. As can be seen, consistent with the results of the Marshall Quotient, the resilient modulus increases with increasing the nanoclay and nylon fiber content, indicating that these additives have a stiffening effect on the mixture. It can also be seen that the mixtures containing both the nanoclay and nylon fibers have a higher resilient modulus than those containing only one of the additives. Over the range of the utilized additives, it can be seen that, the nylon fiber is more effective than the nanoclay in increasing the resilient modulus of asphalt concrete.

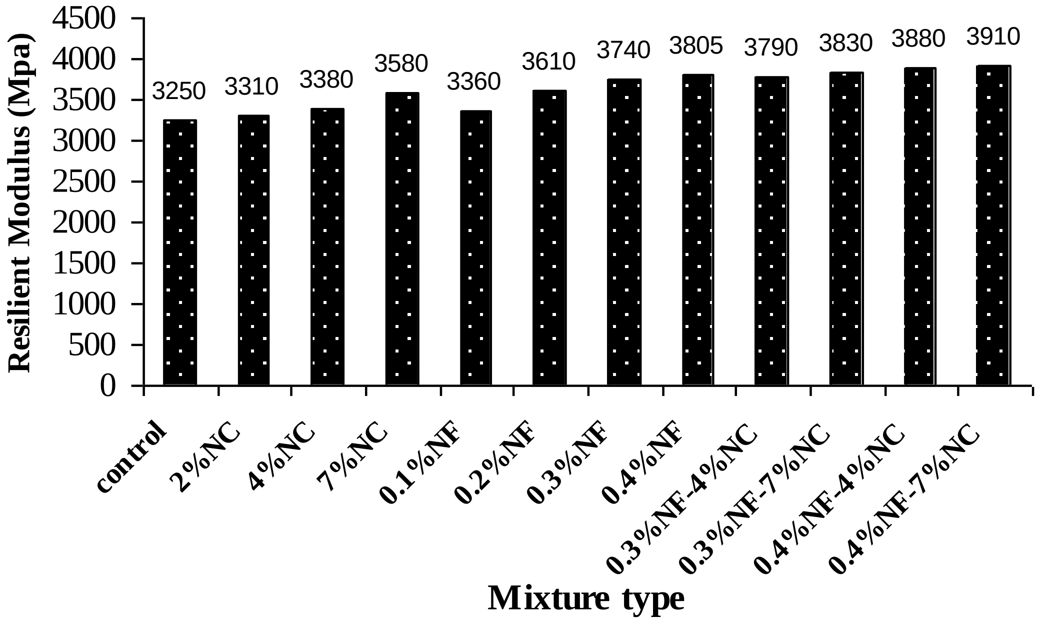

Fig. 6. Resilient modulus tests results

Dynamic Creep Tests

Figure 7 shows the dynamic creep tests results, where the accumulated strain after 40000 of load cycles is shown for different mixtures. The lower accumulated strain is an indication of a higher resistance against permanent deformation. As can be seen, all of the mixtures containing additives are more resistant against permanent deformation than the control mixture. It can also be seen that, the resistance against permanent deformation of the mixtures increases with increasing the nylon fibers and nanoclay content. However, over the range of the additives contents used in this research, the effect of nanoclay on the resistance against permanent deformation is higher than that of the nylon fibers. This is attributed to the microscopic interaction of nano-particles and bitumen, in part, and also the higher air voids content of the mixtures containing nylon fibers than those containing nanoclay, as seen in Table 6. The accumulated strains of the mixture containing 7% of nanoclay and 0.4% of nylon fibers are 32% and 21.6%, respectively, less than that of the control mixture. The results also show that the resistance against permanent deformation of the mixtures containing both the nylon fibers and nanoclay is higher than that of the mixture containing only the same amount of nylon fiber and lower than that of the mixture containing only the same amount of nanoclay. This may be due to the effect of fibers in increasing the air voids content. It can be concluded that, the highest resistance against permanent deformation is achieved by the addition of 7% of nanoclay.

Fatigue Tests Results

Figure 8 shows the fatigue tests results, where the fatigue life is plotted against type of mixture. As can be seen, the mixtures containing additives have a higher fatigue life than the control mixture. However, over the range of the additives content used in this research, reinforcing the mixture by nylon fibers is more effective than the addition of nanoclay on the increase of fatigue life. This is attributed to the increase of tensile strength of the mixture through the interconnection of aggregate particles by fiber reinforcement. This interconnection may allow the material to withstand additional strain energy before occurring crack or fracture. The fatigue life of the mixture reinforced by 0.4% of nylon fibers and that of the mixture containing 7% of nanoclay are 26.6% and 16.67%, respectively, higher than that of the control mixture. However, the mixtures containing both the nylon fibers and nanoclay are more resistant against fatigue failure than the mixtures containing only the fibers or nanoclay. The highest resistance against fatigue is achieved by reinforcing the mixture by 0.4% of nylon fibers and addition of 7% of nanoclay, which the fatigue life of the resulting mixture is 33% higher than that of the control mixture.

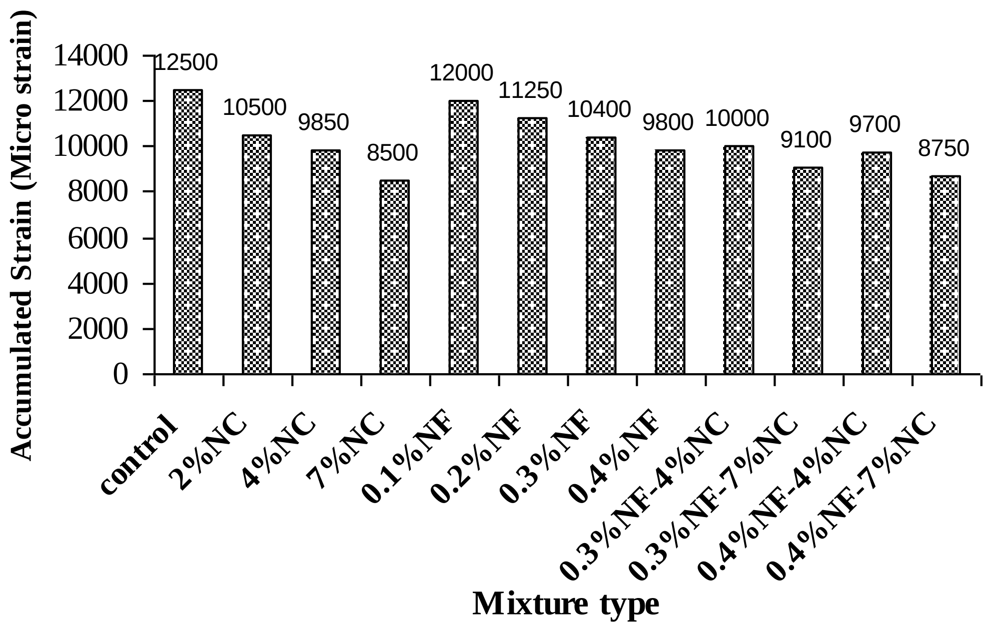

Fig. 7. Dynamic creep test results

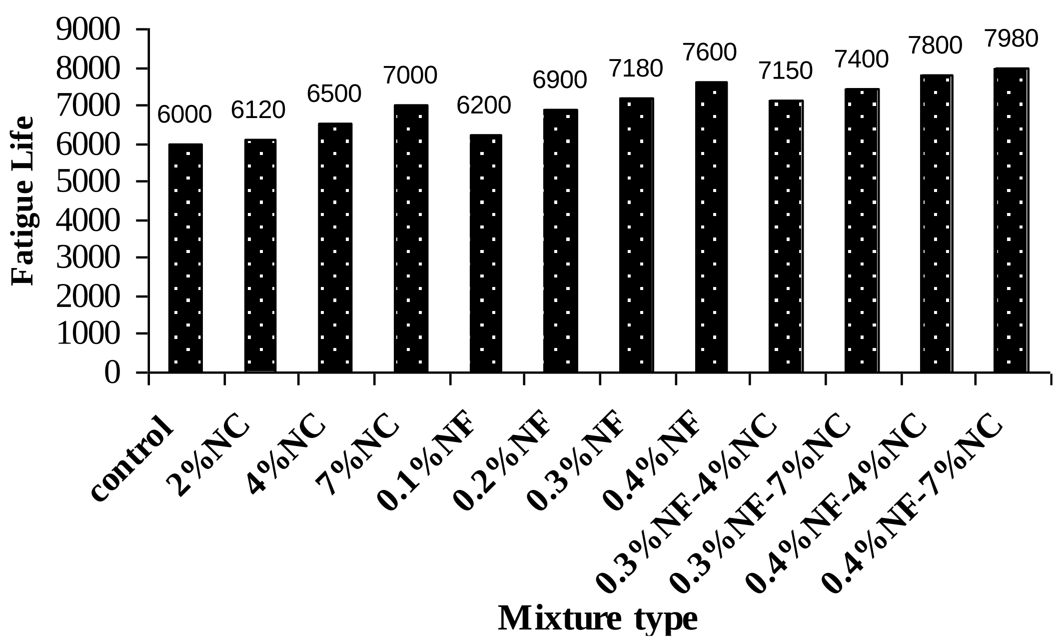

Fig. 8. Fatigue tests results

Economical Analysis

In order to evaluate the feasibility of using the additives in asphalt concrete, in terms of costs, the unit cost of each mixture was calculated in Iranian Rial (IR) for each ton, and compared with the control mixture. The evaluation was performed by calculation of the percentage of the increase in price with that of the performance compared with the control mixture. The cost analysis was performed using the unit cost of 1200, 160000 and 3000000 IR for each kg of the asphalt concrete without additives, nylon fibers and nanoclay, respectively. The price for each metric ton of the mixtures was calculated, which are presented in Table 7. As can be seen, due to the higher unit price of nanoclay, the mixtures containing nanoclay are much more expensive than the control mixture and the mixtures containing nylon fibers. However, as seen in previous sections, the increase in price is considerably higher than the increase in performance indices, such as fatigue life. For example, the mixture containing 0.4% of nylon fibers and 7% of nanoclay is 1115% more expensive than the control mixture, while the fatigue life is only improved by 33%. However, the cost of nanoclay production may decrease in future, which could make it feasible to be used for asphalt concrete modification. Furthermore, this research enhances the knowledge about the behavior of asphaltic mixtures containing nano materials. Therefore, alternative cheaper nano materials may be evaluated to be used in practice. Due to the lower cost of the nylon fibers, the mixtures containing nylon fibers are considerably less expensive than the mixtures containing nanoclay, and slightly more expensive than the control mixture. For example, the mixture containing 0.1% of nylon fiber is only 13.3% more expensive than the control mixture, while, for example, its fatigue life is only 3.33% higher than the control mixture. The same can be resulted for the rest of the mixtures containing nylon fibers, indicating that the increase of initial cost is higher than the increase of performance life. However, this research shows that fiber reinforcement can improve the mechanical properties, and, finding cheaper fibers, such as waste fibers, for using asphalt concrete reinforcement is economical and environmentally friendly.

CONCLUSIONS

Different percentages of nanoclay and nylon fibers have been added to asphalt concrete and some engineering properties have been evaluated. Over the range of nanoclay and nylon fibers contents used in this research, the following results can be drawn:

- Air voids content of asphalt concrete increases with increasing nanoclay or nylon fibers content.
- Marshall stability of asphalt concrete increases with increasing nanoclay and nylon fibers content, with higher stability for the mixtures containing both the nanoclay and nylon fibers.
- Resistance against permanent deformation of asphalt concrete increases with increasing the nanoclay and nylon fibers content in the mixture. Higher resistance can be achieved by using only nanoclay than by using nylon fibers, or using both the nanoclay and nylon fibers.
- Fatigue life of asphalt concrete increases with increasing nanoclay and nylon fibers content, with a higher effect of fibers on improving the resistance against fatigue cracking than the nanoclay. A higher fatigue life is achieved by using both nanoclay and nylon fibers in the mixture.
- Stiffness of asphalt concrete increases with increasing nanoclay and nylon fibers content. The effect of using both

additives results in a higher stiffness than using either nanoclay or nylon fibers.

- The cost analysis shows that the use of the additives used in this research is not economical in practice. However, this research enhances the knowledge about asphaltic composites and cheaper additives with the same effects may be found to be used.

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