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Investigating the Properties of Asphalt Concrete Containing Glass Fibers and Nanoclay

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ABSTRACT: The performance of asphaltic pavements during their service life is highly dependent on the mechanical properties of the asphaltic layers. Therefore, in order to extend their service life, scientists and engineers are constantly trying to improve the mechanical properties of the asphaltic mixtures. One common method of improving the performance of asphaltic mixtures is using different types of additives. This research investigated the effects of reinforcement by randomly distributed glass fibers and the simultaneous addition of nanoclayon some engineering properties of asphalt concrete have been investigated. The properties of a typical asphalt concrete reinforced by different percentages of glass fibers were compared with those containing both the fibers and nanoclay. Engineering properties, including Marshall stability, flow, Marshall quotient, volumetric properties and indirect tensile strength were studied. Glass fibers were used in different percentages of 0.2, 0.4 and 0.6% (by weight of total mixture), and nanoclay was used in 2, 4 and 6% (by the weight of bitumen). It was found that the addition of fibers proved to be more effective than the nanoclay in increasing the indirect tensile strength. However, nanoclay improved the resistance of the mixture against permanent deformation better than the glass fibers. The results also showed that the mixture reinforced by 0.2% of glass fiber and containing 6% nanoclay possessed the highest Marshall quotient, and the mixture containing 0.6% glass fibers and 2% nanoclay possessedthe highest indirect tensile strength.

Keywords: Asphalt Concrete, Glass Fiber, Nanoclay, Tensile Strength.

INTRODUCTION

Asphalt concrete in widely used in Iran for paving highways. Recently, the price of this material has been raised dramatically in Iran, due to an increase in the price of asphalt cement. A solution proposed by the government is the use of Portland cement concrete pavement, which is yet to be adopted in Iran. However, asphalt concrete is still the main material being used in pavement construction and accounts for approximately 100% of paved roadways in Iran. Preservation of the asphaltic layers for a longer time is environmentally and economically beneficial, and this can be achieved by improving their engineering properties. Like any type of paving material, asphalt concrete is subjected to distress mechanisms which lead to its disintegration

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over time. However, asphalt concrete is more sensitive than the other materials (Abtahi et al., 2009). With an attempt to minimize or reduce the distresses, scientists and engineers are constantly trying to improve the performance of asphalt pavements, by which the service life of the pavement can be extended, thereby saving cost. Over the last decades, the use of additives for improving the performance of asphalt concrete has been practiced by engineers and investigated on by researchers. The reinforcement of asphalt concrete by using different materials is a common method of improving its performance. It involves the incorporation of certain materials with some desired properties within another material which lack those properties (Maurer Dean and Gerald, 1989). One method of reinforcing a material is through the use of fiber, by random distribution within the material or by applying oriented fibrous materials, for example, geo-synthetics family. Different types of fibers, including nylon, polyester, polypropylene, carbon etc. have been used for reinforcing asphaltic mixtures. A comprehensive review of the studies on the properties of fiber reinforced asphalt mixtures can be found in Abtahi et al. (2013). The inclusion of fibers in paving material interconnects the aggregate particles, thereby increasing the tensile strength. This interconnection may allow the material to withstand additional strain energy before crack or fracture occurs. It is thought that the addition of fibers to asphalt enhances the material strength and fatigue characteristics while adding ductility. In addition, fibers have the potential to increase the dynamic modulus (Wu et al., 2007), moisture damage resistance (Putman and Amirkhanian, 2004), creep compliance, permanent deformation resistance (Chen et al., 2004), freeze-thaw resistance (Echols, 1989), ageing resistance and resistance against reflective cracking (Goel and Das, 2004) of asphalt concrete. It has been found that fibers have the ability to prevent the formation and propagation of cracks in asphalt concrete (Maurer Dean and Gerald, 1989). Another application for fibers in asphalt mixtures is in the prevention of asphalt binder drain down in gap graded mixtures (Hansen et al., 2000). Fibers have also been used in asphalt to increase the electrical conductivity of the asphalt mixtures, used for deicing, healing the cracks and as solar collector for heating adjacent buildings (Garcia et al., 2013; Wu et al., 2002, 2005, 2006).

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 (Issacson and Lu, 1999; Airey, 2002; Hinislioglu and Agar, 2004; Lu and Issacson, 1997; Yousefi, 2003; Yildrim, 2007). Different types of polymers including plastics and elastomers are among the widely used polymers. They have been 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 possess some limitations including the high cost, compatibility with bitumen and stability during storage. Due to these limitations, alternative materials have been sought to be used for the modification of asphaltic mixtures. In recent decade, the use of nano scale non organic materials for improving the mechanical properties of bitumen and asphaltic mixtures have attracted the attention of engineers and researchers (Lan et al., 1994; Lan et al., 1995; Zedra and Lesser, 2001; Becker et al., 2002 and Liu et al., 2003). Nano materials are defined as materials having at least one dimension which falls within the length scale of 1 to 100 nm. Due to their small size and high surface area, their properties are much different from normal size materials. Some studies have shown that the rutting and fatigue cracking resistance of asphaltic binders and mixtures can be improved by the addition of nano materials such as nanoclay and carbon nano fibers (Chow et al., 2003; Goh et al., 2011; Ghile, 2006; Ghafarpour Jahromi and Khodaii, 2009; You et al., 2011; Khattak et al., 2011; Xiao et al, 2011). Cheng et al. (2004) investigated the moisture susceptibility of warm mix asphalt containing nanosized hydrated lime. The combination of Nano-SiO2 and SBS were mixed with stone matrix asphalt, and the physical and mechanical properties of asphalt binders and mixtures were improved (Ghasemi et al., 2012).

Nanotechnology is the creation of new materials, devices, and systems at a molecular level as the phenomena associated with atomic and molecular interactions strongly influence the properties of macroscopic materials (Chong, 2004). Even though engineers are interested in material properties at the macro and meso-scales, the nano and micro scales provide fundamental insight for the development of science and technology.

Many types of clays are alumina-silicates having a layered structure. Clays consist of silica SiO_4 tetrahedron bonded to alumina AlO_6 octahedron in a variety of forms. A 2:1 ratio of the tetrahedron to the octahedron results in mineral clays, the most common of which is montmorillonite. The thickness of the montmorillonite layers is 1 nm with high aspect ratios, typically 100 to1500 (Grim, 1959). The expansion of montmorillonite is determined by their ion (for example, cation) exchange capacities, which can vary widely. One of the characteristics of these types of clay is the cation exchange capacity (CEC), which represents the amount of cations between the surfaces. The CEC of montmorillonite ranges from 80 to 120 meq/100g (milliequivalents per 100 grams) whereas, kaolinite have CEC values ranging between 3 and 5. The expansion pressure of montmorillonite is very high with sodium ions constituting the majority of the adsorbed cations (called Na-montmorillonite), leading to exfoliation and dispersion of the crystal in the form of fine particles or even single layers. When Ca^{2+}, Mg^{2+} and ammonium are the dominant exchangeable cations, dispersion is low and the size of the particle is relatively large. Separation of clay discs from each other results in a nanoclay having a huge active surface area (it can be as high as 700 to 800 m^2 per gram). This helps in the intensive interaction between the nanoclay and its environment (bitumen in our case). The process of realizing the separation (surface treatment) depends upon the type of material to be mixed (Lan et al., 1995).Layered silicates (nanoclay) are widely used in the modification of polymer matrices to realize significant improvement in mechanical, thermal, and barrier properties. Roy et al. (2007) enhanced the compressive and shear strength of thermoplastic polymers by using only a small weight percent of nanoclay reinforcement.

Sufficient documents can be found in literature, which investigated the properties of fiber reinforced asphalt mixtures. However, there is limited research on the asphalt concrete reinforced by glass fibers. Yoo and Kim (2015) investigated the indirect tensile strength and the resistance against rutting of thermoplastic polymer coated glass fiber reinforced asphalt concrete and found that the glass fiber reinforced mixture possessed higher tensile strength and resistance against permanent deformation. Shukla et al. (2013) investigated the mechanical properties of glass fiber reinforced asphalt concrete, and found that the glass fiber reinforced asphaltic mixtures possessed higher stiffness and better resistance against fatigue cracking and rutting. It has been hypothesized that the use of both glass fiber and nonoclay in asphalt concrete is more effective than the individual compounds on the mechanical properties of asphalt concrete. Therefore, in this research, the effects of using glass fiber and nonoclay modified bitumen on some engineering properties of asphalt concrete was investigated.

MATERIALS

The materials used in this research include aggregate, asphalt cement, nanoclay and glass fibers. Siliceous aggregates used in this study were collected from Sirood asphalt plant in Gilan province in four different sizes of 12 to 19, 6 to12, 0 to 6mm and filler. They were first graded, and based on the gradation of each fraction and by selecting No. 4 gradation in Iranian National code for asphalt concrete, the percentages of each fraction was calculated by setting the average of upper and lower limits as the target gradation. Table 1 shows the upper and lower limits of the code gradation, and the gradation of the mixture used in this research. The specific density and the water absorption of the aggregates were also measured and the results are shown in Table 2 together with some other properties of aggregates. The asphalt cement used in this research was a 60/70 penetration grade bitumen supplied by Pasargad refinery. Table 3 shows the specifications of the bitumen from which the specimens were made. The glass fibers of type A-Glass, supplied by Bloorin Tar company in Alborz province, was used for reinforcing the mixtures(Figure 1-a). Table 4 shows the physical and mechanical properties of the fibers. Nanoclays are nanoparticles of layered mineral silicates. Nanoclay type montmorilonite NA^+ (Figure 1-b) supplied by Pishgaman Co. was used in this research, of which its properties have been presented in Table 5.

Table 1. Gradation of the mixture aggregates

Sieve Size (mm)	Passing Percentages (%)	
	Specification Limits	**Gradation of Mixtures**
19	100	100
12.5	90-100	95
4.75	44-74	60
2	28-58	44
0.3	5-21	11
0.075	2-10	6.2

Table 2. 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	-	17	-	98	1.6	2.658	18	0.4
Fine Aggregate	65	-	N.P	-	2.3	2.62	-	-
Filler	-	-	N.P	-	-	2.734	-	-

Table 3. Specifications 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	68
Softening Point (˚C)	ASTM-D36	49
Ductility in 25˚C (cm)	ASTM-D113	150
Solubility in Trichloroethylene (%)	ASTM-D2042	99.2
Flash Point (˚C)	ASTM-D92	311
Loss in weight after thin film oven test (%)	ASTM-D1754	0.02
Retained penetration after thin film oven test (%)	-	68
Ductility after thin film oven test (cm)	-	113

Table 4. The properties of the fibers used in this research

Length (mm)	Diameter (μm)	Density (gr/cm^3)	Tensile Strength (GPa)	Melting Point (˚C)	Elastic Modulus (GPa)	Strain at Failure (%)
12	20	2.6	3	550	70	4.8

Table 5. Properties of nanoclay

Property	Value
Base	Moontmorilonite
Concentration of modifier	48 meq in 100gr of clay
Moisture content	1-2%
PH	7.3-7.6
Free space between particles (A˚)	60
Specific surface (m^2/gr)	500-750
Density (gr/cm^3)	5-7
Particles size (nm)	1-2

Fig. 1. (A) Glass fiber, (B) nanoclay

EXPERIMENTAL PROGRAM

In addition to the control mixture, which is the mixture without reinforcing fiber and nanoclay, two types of mixtures were also used in this experimental investigation, with all having the same aggregate and bitumen type as those of the control mixture. One with different percentages of glass fibers, and one in which both the fibers and nanoclay have been used simultaneously at different percentages. Table 6 shows the denotations used for these mixtures and the amount of additives. In Table 6, the percentage of the fibers is by the weight of total mixture, and that of the nanoclay is by the weight of bitumen. The percentages of the nanoclay and glass fibers were selected based on the values used in previous studies (Ghaffarpour Jahromi et al., 2010; Mahrez et al., 2005).

MIX DESIGN AND FABRICATION OF SPECIMENS

The optimum binder content of the control mixture was determined using the Marshall design method, which was 5.5%. The mixtures containing glass fibers and nanoclay were made by the same optimum binder content of the control mixture.

The specimens required for testing were made using Marshall method according to ASTM D1559. For making the specimens reinforced by fiber, an attempt was made to determine the different methods for addition of fibers, with the aim of choosing the best. It was found that the addition of fibers to the hot aggregates and mixing, before the addition of hot asphalt resulted in the uniform distribution of fibers in the mixture. Therefore, the required amount of fibers were first mixed with hot aggregate, and then mixed with hot bitumen in a laboratory mixer. The uniform distribution of the fibers in the mixture was controlled visually. For making the mixtures containing both the fibers and nanoclay; first the nanoclay was mixed with hot bitumen at 155˚C, using higher shear mixer at 5000 rpm for 2 h, followed by mixing with a mixture of hot aggregate and fibers. The mixture was placed in the Marshall compactor mold and compacted by the automatic compacter at 75 blows on each side. After 24 h the specimens were removed from the mold and used for the desired testing program.

Table 6. Mixtures used in this research

Mixture Denotation	Percentage of Fiber (%)	Percentage of Nanoclay (%)
Control	0	0
0.2%GF	0.2	0
0.4%GF	0.4	0
0.6%GF	0.6	0
0.2%GF-2%NC	0.2	2
0.2%GF-4%NC	0.2	4
0.2%GF-6%NC	0.2	6
0.4%GF-2%NC	0.4	2
0.4%GF-4%NF	0.4	4
0.4%GF-6%NC	0.4	6
0.6%GF-2%NC	0.6	2
0.6%GF-4%NC	0.6	4
0.6%GF-6%NC	0.6	6

EXPERIMENTS

Marshall Tests

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

Before carrying out the Marshall tests, measurements of the bulk density of the compacted mixtures according to ASTM D2726 standard method was made. The maximum theoretical density of the mixtures was also measured according to ASTM D2041 standard method. Using the bulk and the maximum theoretical density of the mixtures, and other required data, 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).

Indirect Tensile Strength Tests

The indirect tensile strength tests were conducted at 60˚C according to the ASTM D6931 standard method. The specimens were immersed in water tank set at the desired temperature for 30 min, after which they were placed in ITS frame and loaded diametrically by 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. (1).

$$S_t = \frac{2000P}{\pi t D} \quad (1)$$

where S_t: 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 specimen in mm.

TEST RESULTS

Marshall Tests Results

Figure 2 shows the Marshall stability of the mixtures. As can be seen, at the nanoclay content of 0, 2 and 4%, the Marshall stability increased with increasing fiber content. However, at 6% of nanoclay, Marshall stability decreased with increasing fiber content. It can also be seen that, the highest Marshall stability was achieved at 6% of nanoclay and 0.2% of glass fiber content. The increase in Marshall stability with increasing fiber content can be attributed to the reinforcing effect of the fibers. The fundamental equations of composite materials are used to explain the results. According to the "law of mixtures" (Vasiliev and Mozorov, 2007) the ultimate strength, σ_c of fiber reinforced mixture can be expressed as:

$$\sigma_c = \sigma_f V_f + \sigma_m V_m \quad (2)$$

where σ and *V*: are the strength and volumetric fraction, respectively, and the indices *f*, *c* and *m*: represents the fiber, composite and matrix. Eq. (2) states that the strength of the composite increases with increasing the fiber content. Marshall stability is fundamentally, the compressive strength of asphalt concrete. Therefore, the increase of the Marshall stability with fiber content can be described by the aforementioned equation. It can also be seen that, the Marshall stability increased with increasing nanoclay content of the mixtures, which can be attributed to the stiffening effect of the nanoclay on the asphalt binder (Ghaffarpour Jahromi et al., 2010). The minimum Marshall stability required by specifications for asphalt concrete to be used as surfacing layer was 850 Kg, indicating that all mixtures possessed a higher stability than the required value.

Figure 3 shows the flow of the mixtures. As can be seen, at the same nanoclay content, flow of the mixtures increased with increasing fiber content, indicating that the fibers increased the ductility of the asphalt concrete. However, the values of flow of all the mixtures were lower than the maximum allowable flow of 3.5 mm, as defined by Asphalt Institute (Asphalt Institute, 1997). The results also showed that the addition of nanoclay resulted in the reduction of flow, indicating that the resistance against permanent deformation can be increased by using nanoclay. Marshall quotient is used as an indication of mixture stiffness and is related to the resistance against permanent deformation. There is not requirement on the Marshall quotient of asphalt concrete in Iranian specifications. However, some countries require a minimum value for the Marshall quotient to ensure proper resistance against permanent deformation, and some specifications may further require a maximum value for sufficient flexibility in order to resist cracking. For example, a minimum Marshall quotient of 175 kg/mm is required by Australian specifications for the mixtures compacted by 50 blows. Minimum and maximum values of 200 and 500 kg/mm is required by UK specifications for mixtures compacted by 75 blows. Figure 4 shows the Marshall quotient of the mixtures. It can be seen that the Marshall quotient decreased with increasing the fibers content, and increased with increasing nanoclay content. It can also be seen that the highest Marshall quotient and stiffness was achieved by the addition of 0.2% of glass fiber and 6% of nanoclay. The results show that, while all the mixtures passed the requirement for the minimum value of Marshall quotient, some of the mixtures exceeded the maximum limit of 500 kg/mm, set by the UK specifications. The mixtures need to be evaluated in terms of other mechanical properties, such as resistance against thermal and fatigue cracking. However, due to the higher price of nanoclay, an economical analysis needs to be conducted to find the most economical mixture.

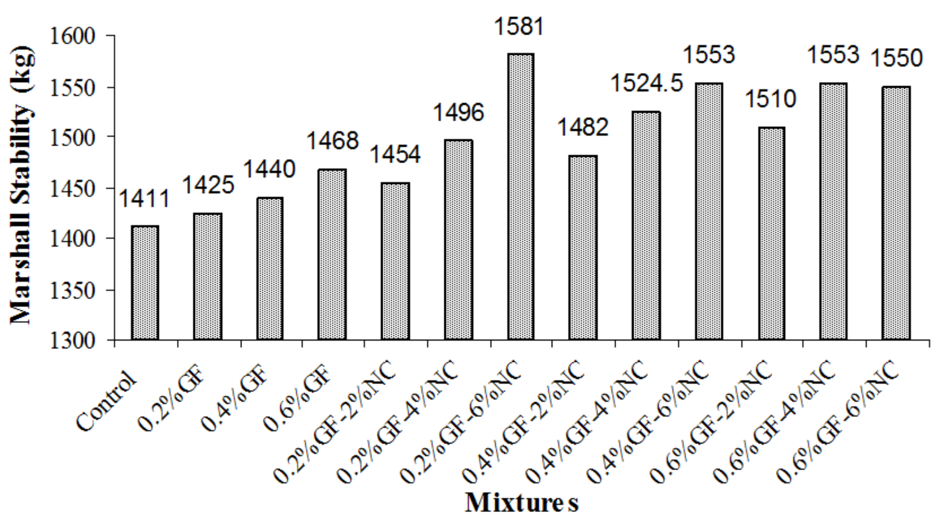

Fig. 2. Marshall stability of mixtures

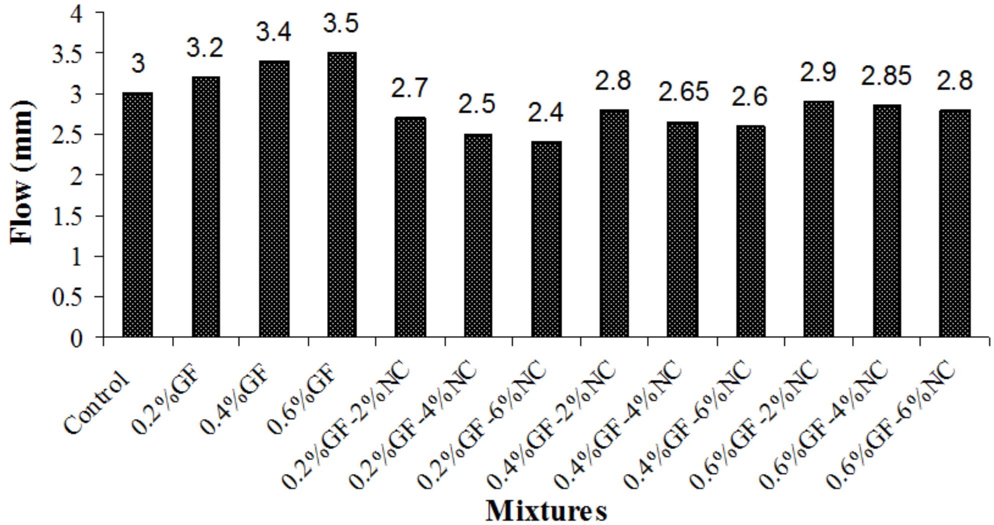

Fig. 3. Flow of mixtures

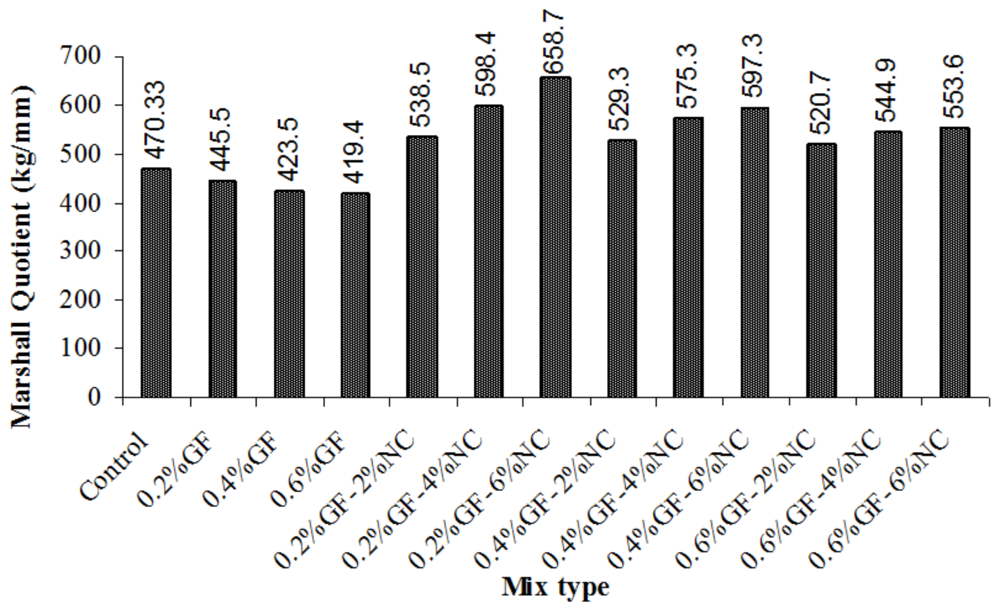

Fig. 4. Marshall quotient of the mixtures

Volumetric Properties

Air voids content of compacted mixture, voids in mineral aggregates (VMA), and the voids filled with asphalt (VFA) are the three important volumetric properties of asphalt concrete which considerably affect the performance of the mixture, and are considered in the mix design process to satisfy the limitations specified by the codes. Figures 5-7 show, respectively, the air voids content, VMA and VFA of the mixtures. As can be seen in Figure 5, the air voids content of the mixtures decreased with increasing fiber content, and increased with increasing nanoclay content. The decrease of air voids content with increasing fibers content can be related to the use of the same binder content for the fiber reinforced mixtures and the control mixture. The addition fibers, with a lower density than the aggregates, occupied more spaces between particles resulting in the reduction of air voids content, which can also be used in describing the reduction of VMA with increasing fiber content, as shown in Figure 6. However, in the addition of nanoclay with a high specific surface, more binder was used to coat the particles, resulting in the increase of air voids content. As the specifications set the minimum and maximum allowable air voids content at 3 and 5%, respectively, some of the mixtures did not meet these requirements, and this can be solved by redesigning the mixtures containing the additives and determining a new optimum binder content. As can be seen in Figure 6, VMA of the mixtures decreased with increasing glass fiber content and increased with increasing the nanoclay content. However, all the mixtures met the required minimum VMA of 14% defined by specification. Figure 7 shows that the voids filled with asphalt (VFA) increased with increasing glass fibers content and decreased with increasing nanoclay content, which can be described as similar to the results of air voids content. The VFA of all the mixtures was higher than the allowable minimum values, which was 60. However, the VFA of some mixtures can exceed the allowable maximum value of 75, for heavy traffic, which is because of the use of the optimum binder content of control mixture for those with the additives.

Indirect Tensile Strength Results

Figure 8 shows the indirect tensile strength of the mixtures at 60˚C. As can be seen, the indirect tensile strength of the mixtures increased with increasing glass fibers content, which is consistent with the results of previous studies (Yoo and Kim, 2015; Shukla et al., 2013). This can be described by Eq. (2) and is related to the high tensile strength of the glass fibers. In addition to the increase of indirect tensile strength, addition of fibers into the asphalt concrete prevented the opening of cracks and postponed the degradation of asphalt concrete. It can also be seen that, after an increase of the tensile strength by adding 2% of nanoclay, it decreased with increasing the nanoclay content. The higher indirect tensile strength of the mixture containing 2% of nanoclay is consistent with the results of the research conducted by Esfahani et al. (2013). Using the direct tensile tests on the bitumen, they found that the addition of 2% of nanoclay into the bitumen increased the toughness of the bitumen, resulting in a higher tensile strength. This was attributed to the stiffening effect of the nanoclay provided by the formation of bond chains within the binder. On the other hand, the decreases of the indirect tensile strength of the mixtures with increasing nanoclay content in the mixture, was due to the stiffening and brittleness effect of the nanoclay. The highest tensile strength was achieved by the addition of 0.6% of glass fiber and 2% of nanoclay. The indirect tensile strength of asphalt concrete was related to the resistance against fatigue and thermal cracking, with the mixture having a higher tensile strength has a higher fatigue life (Ghaffarpour Jahromi et al., 2010).

ECONOMIC CONSIDERATIONS

The practical use of additives requires an economical evaluation of the application of the mixtures in pavement. This includes the initial and maintenance costs. The cost of one ton of asphalt is tripled by the use of 2% of nanoclay, while this level of improvement in the properties is not achieved. Therefore, the use of nanoclay is not economical. However, glass fibers are not expensive and their use results in some improvement on the properties of asphalt concrete. The fiber reinforced mixtures consumes slightly higher bitumen than the plain mixtures which must be considered in economical evaluation.

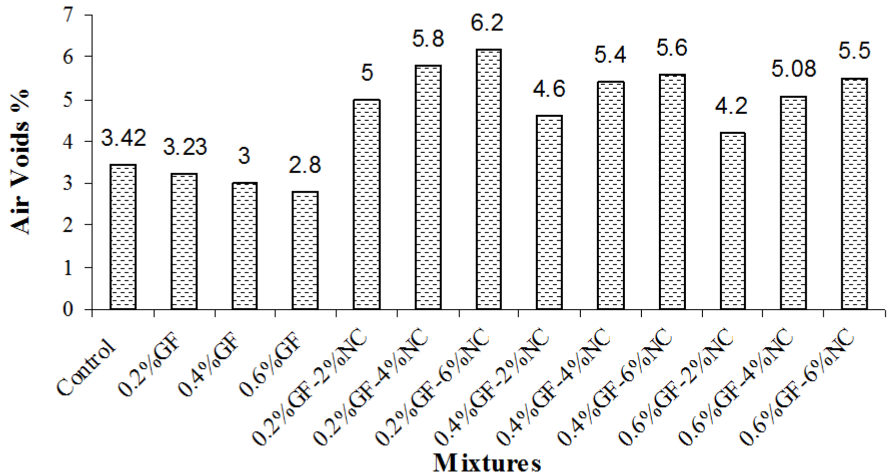

Fig. 5. Air voids content of the mixtures

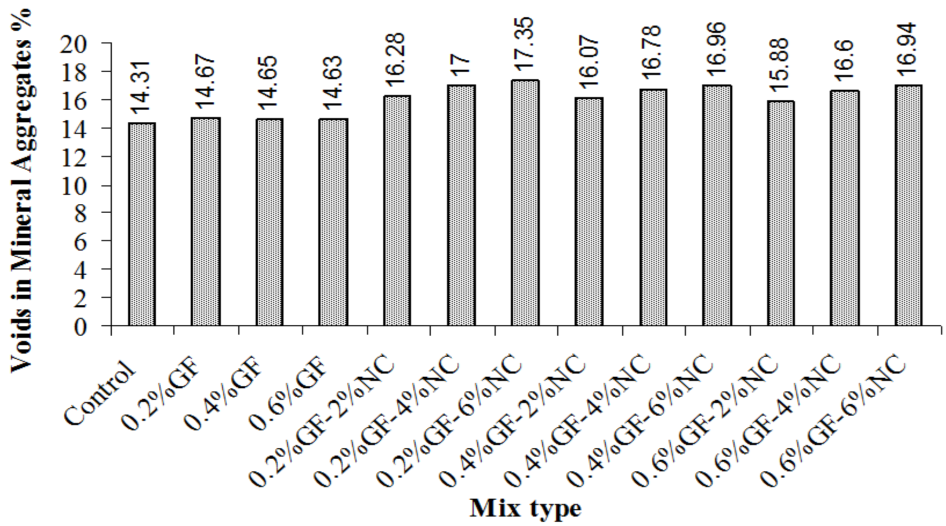

Fig. 6. Voids in mineral aggregates of the mixtures

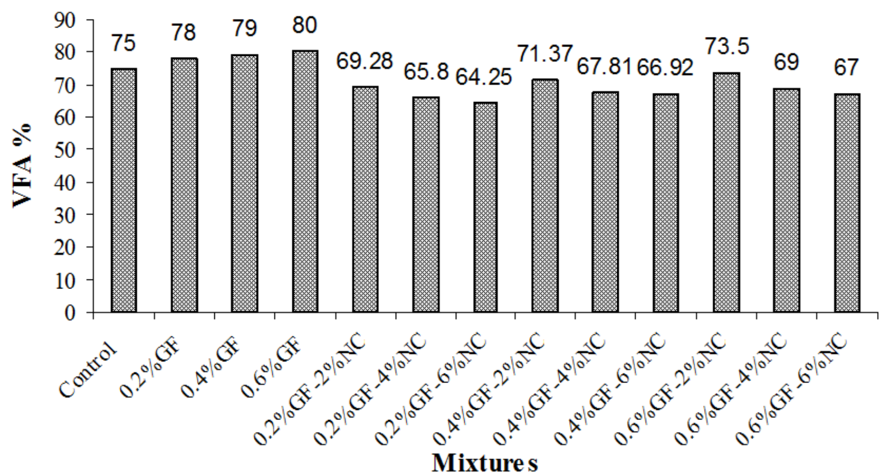

Fig. 7. Voids filled with asphalt of the mixtures

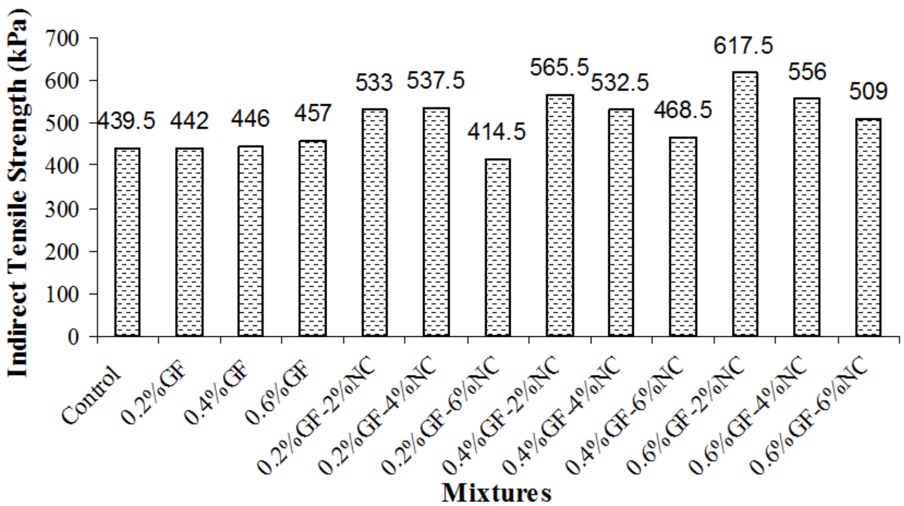

Fig. 8. Indirect tensile strength of the mixtures

CONCLUSIONS

Glass fibers and nanoclay have been added to asphalt concrete at different proportions and some engineering properties have been evaluated. A brief result is as follows.

- Marshall stability of asphalt concrete increased with increasing glass fiber and nanoclay content, with the highest Marshall stability achieved at 0.2% of fiber content and 6% of nanoclay.
- Flow of asphalt concrete increased with increasing glass fibers content and decreases with increasing nanoclay content.
- Marshall quotient of asphalt concrete decreased with increasing glass fibers content and increased with increasing nanoclay content.
- Air voids content and the voids in mineral aggregates decreased with increasing glass fibers content, and increased with increasing nanoclay content.
- Voids filled with asphalt binder increased with increasing fibers content and decreased with increasing nanoclay content.
- Indirect tensile strength of asphalt concrete increased with increasing glass fibers content. The addition of nanoclay may cause the reduction of indirect tensile strength of asphalt concrete.
- A combination of 2% of nanoclay and 0.6% of glass fibers resulted in the highest indirect tensile strength of asphalt concrete.

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