International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 4 Issue 01,January-2015

Experimental Investigation on Rutting Performance of Micro Silica Modified Asphalt Mixtures

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***Abstract*— Many researches were down to investigated different ways such as changing the aggregate gradation and using of additive materials to modify bitumen and asphalt mixture. One of these ways is using of additive materials to improve of asphalt properties against dynamic loads. In the present study, the potential of micro silica powder in improvement of mechanical properties of hot mix asphalt (HMA) have been investigated. To achieve this goal, mixtures with different content of bitumen and micro silica were prepared and repeated load axial (RLA) test on asphalt concrete mixtures were performed to evaluate resistance against rutting and creep. Also, the empirical rheological test on bitumen (penetration, softening point, ductility and viscosity) and the fundamental rheological test by dynamic shear rheometer (DSR) are conducted on modified and unmodified bitumen. Finally by use of experimental results and the numerical analysis, two experimental models were performed for prediction of the creep behavior of conventional and modified asphalt mixtures by micro silica for different conditions depending on temperature and stress. The results of this investigation indicated that adding of micro silica to bitumen, had a great effect in improvement of permanent deformation of HMA. Also the results of tests on bitumen showed that adding of micro silica reduced the penetration, ductility, temperature susceptibility, and increased the softening point, stiffness and viscosity. Also the dynamic shear complex modulus (G*) value increases significantly across a loading frequencies.**

Keywords*— *Asphalt Mixture; Modified bitumen; Micro silica; Rheological properties; Creep compliancecomponent.

I. INTRODUCTION

During the last decade, increasing the axial loads, heavy traffic and severe climatic conditions and construction failures led to a need to enhance the properties of the original bitumen. Bitumen is a complex mixture of chemical components that include aliphatic, aromatic and naphthenic hydrocarbons. They are widely used to provide waterproofing and protective coating as binders in road construction because of its good viscoelastic properties [1]. Properties of bitumen depend on the nature of the crude oil and refinery processes employed. Fig. 1 shows the schematic representation of the chemical composition of bitumen.

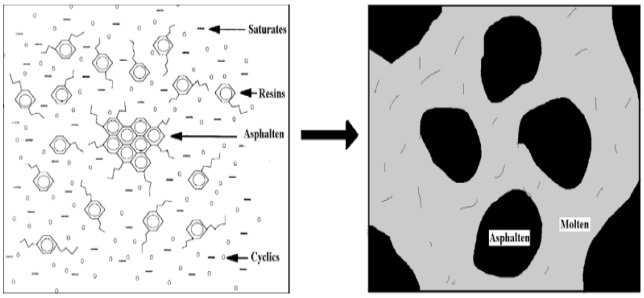

Fig1. Schematic of the chemical composition of bitumen [2]

Unfortunately, bitumen becomes brittle and liquid at lower and higher temperatures, respectively, which can result in low temperature cracking of pavement and high temperature rutting. Its application is limited by this temperature susceptibility. Therefore, to expand the performance of asphalt binder, it is essential to modify bitumen by adding modifiers like polymer, rubber and clay [3]. The ideal bitumen should be strong enough, at high temperatures, to withstand rutting or permanent deformation, and soft enough to avoid excessive thermal stresses, at low pavement temperatures, and fatigue at moderate temperatures. To choose the best additives to improve bitumen properties against traffic loads, must be recognize the pavement failure that are related to the infirmity of bitumen. These are mainly rutting, permanent deformation and fatigue cracking. Since the recovery and reconstruction of defects will be costly, therefore, the prevention of these would be more economical. To avoid these failures, one of the methods is to modify the properties of the bitumen and asphalt mixture. Researchers have used different methods including the use of various types of polymers and fibers [4]. For a polymer to be effective in road applications, it should blend with the bitumen and improve its resistance (to rutting, abrasion, cracking, fatigue, stripping, bleeding, aging, etc.) at medium and high temperatures without making the modified bitumen too viscous at mixing temperatures or too brittle at low temperatures [5]. The effect of polymer modification on the linear rheology depends on polymer nature and concentration, and testing temperature [6]. Temperature susceptibility characteristics and the physical properties of asphalt binder at high and low field operating temperatures can affect the final performance of the mixture.

The aim of this study is to evaluate the influence of micro silica powder on the engineering properties of bitumen and asphalt concrete mixtures. For this purpose, the rheological tests (penetration grade, softening point, viscosity, ductility and dynamic shear rheometer (DSR)) on modified bitumen by five different content of micro silica were conducted to evaluate the rheological properties of modified bitumen. Also repeated load axial (RLA) test on asphalt concrete mixtures by five different content of micro silica were performed to evaluate the rutting resistance and creep behavior. With the experimental results and the numerical analysis with Matlab Software, two experimental models were proposed for prediction of the creep behavior of both conventional and modified asphalt mixtures by optimum micro silica for different conditions depending on temperature and stress.

II. LITERATURE REVIEW

Although relatively little published information is available about micro silica modified asphalt mixtures, but many studies have been conducted on modified cement with micro silica in concrete structure. J.M.R. Dotto et al. carried out a study on Influence of silica fume addition on concretes physical properties and on corrosion behaviour of reinforcement bars. The addition of silica fume (SF) in concretes has been proposed as a form to improve their performance in resisting concrete reinforcement corrosion. In this study an experimental program on compressive strength, porosity, electrical resistivity and polarization curves was carried out with the purpose of evaluating the effect of different SF additions (0%, 6% and 12%). Concretes with different water–binder ratio 0.50, 0.65 and 0.80 were used. The results have allowed showing that there are significant improvements of the concrete properties with the SF addition, suggesting its use in aggressive environments. Also the obtained results showed that the addition of 6% of Silica fume increases the electrical resistivity of concrete by 2.5 times and 12% of SF increases it by 5 times. This suggests that the addition of SF can be effectively used in protecting steel reinforcement against corrosion [7]. Many researches were down on bitumen modification by polymer materials such as Styrene Butadiene Styrene Block Copolymer (SBS), Styrene Butadiene Rubber Latex (SBR) and Ethyl Vinyl Acetate (EVA). Studies on SBS show that, SBS improves the rheological properties of asphalt bitumen due to the polymer network formation in the bitumen. This network forms in two stages: at low concentrations, the SBS acts as a dispersed polymer and does not significantly affect the properties at higher concentrations, however, local SBS networks begin to form and are accompanied by a sharp increase in the complex modulus, softening point temperatures, and toughness [2]. Ghaffarpour et al. carried out comparative rheological tests on binders and mechanical tests on asphalt mixtures containing unmodified and nanoclay modified bitumen. Results showed that nanoclay can improve properties such as stability, resilient modulus, and indirect tensile strength, but it do not seem to have a beneficial effect on fatigue behavior in low temperature [8]. Yasmin et al found that the addition of Nanomer-I.28E and cloisite-30B into some pure epoxy polymers produce materials with higher elastic modulus than that of the pure epoxy [9]. Goh, S.W. et al found that, in most cases, addition of nanoclay and carbon microfiber improves the mixture's moisture susceptibility performance or decreases the moisture damage potential [10]. Sureshkumar, M.S. et al. found that the clay had a compatibilizing effect on asphalt and polymer and that the high compatibility between clay and polymer can lead to the better dispersion of the polymer in the asphalt; therefore, it influences the final rheological properties of the systems under study [11]. Khodadadi et al. investigated Nanoclay additive effect on long-term performance of asphalt pavement. Indirect tensile test were conducted on cylindrical specimens made of standard and modified bitumen at the stress levels of 200, 300, 400 and 500 kPa. The results showed that the addition of 2% nanoclay increases the fatigue life of the asphalt pavement [12].

In the current study, micro silica selected in case of its good characteristics in improvement of bitumen properties. The purpose of the present research were to characterize the rheological and mechanical properties of micro silica modified binders and hot mix asphalt (HMA). For this purpose five samples were prepared using various percentages of micro silica powder and properties of the modified bitumens and mixtures were evaluated using the rheological and repeated load axial (RLA) test.

III. MATERIALS AND METHODS

A. Bitumen

This study has used 60/70 penetration grade bitumen was obtained from Isfahan Mineral Oil Refinery, Isfahan, Iran, whose properties are shown in Table 1.

TABLE I. THE PHYSICAL PROPERTIES OF THE BITUMEN USED IN THIS STUDY

Property	Test method	Quantity
Penetration at 25 o C, 100g, 5 s (deci-mm)	ASTM D-5	61
Softening Point, ring and ball (o C)	ASTM D36	51
Flash Point, Cleveland open cup (o C)	ASTM D-92	262
Ductility at 25 o C at 5 cm/min (cm)	ASTM D-113	118
Solubility in trichloroethylene, (%)	ASTM D2042-76	99.5
Loss on heating, (%)	ASTM D-6	0.06

B. Aggregates

The aggregates used in this research were graded using the continuous type IV scale of the AASHTO standard, which is presented in Table 2 [13].

TABLE II. GRADATION OF AGGREGATES USED IN THE PRESENT STUDY

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

C. Micro silica

Micro silica is an amorphous (non-crystalline) polymorph of silicon dioxide, silica. It is an ultrafine powder collected as a by-product of the silicon and ferrosilicon alloy production and consists of spherical particles with an average particle diameter of 150 nm. Micro silica is an ultrafine material with spherical particles less than 1 µm in diameter, the average being about 0.15 µm. This makes it approximately 100 times smaller than the average cement particle [14]. The bulk density of micro silica depends on the degree of densification in the silo and varies from 130 (undensified) to 600 kg/m3. The specific gravity of micro silica is generally in the range of 2.2 to 2.3. The specific surface area of micro silica can be measured with the BET method or nitrogen adsorption method. It typically ranges from 15,000 to 30,000 m2/kg [15]. Separation of silica discs from each other results in a micro silica with a large active surface area (it can be as high as 30000 m2/kg). This helps to have an intensive interaction between the micro silica and its environment (bitumen in our case). In process, realizing the separation (surface treatment) depends upon the type of material mixed [2]. The chemical compositions and the physical properties of micro silica summarized in Table 3. Figure 2 show that the Micro silica particles in a transmission electron microscope view.

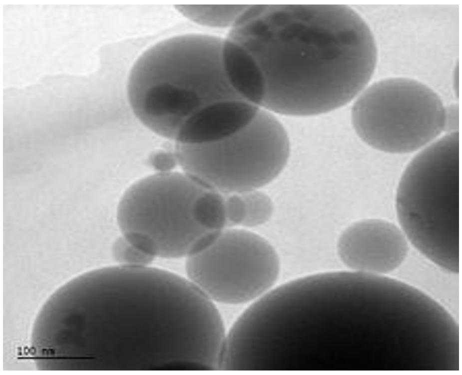

Fig2. Micro silica particles viewed in a transmission electron microscope

TABLE III. CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF MICRO SILICA[15]

Item	SiO2 (%)	Al2O3 (%)	SO3 (%)	Loss of ignition (%)	Specific gravity	Specific surface area (m2/kg)
Micro silica	90.36	0.71	0.41	3.11	2.2	21080

Micro silica powder with the average diameter of 150 nm was used in the present research. Table 4 demonstrates the properties of the utilized micro particles.

TABLE IV. THE PROPERTIES OF MICRO SILICA

Diameter (nm)	Surface volume ratio (m2/g)	Density (kg/m 3)	Loss of ignition (%)
150±30	20±10	300	3.11

D. Experimental Setup and Procedure

The tests more used to evaluation the resistance of asphalt mixtures against permanent deformation are the Marshall test, the static creep test, the dynamic creep test, repeated load axial (RLA) test, and the wheel-tracking test [16]. In this research, the modified asphalt mixtures resistance against permanent deformation by different micro silica content was evaluated by using RLA test. The program for the prepared samples and the experimental tests is presented in Table 5.

TABLE V. PROGRAM FOR SPECIMEN PREPARATION AND TESTING

Parameter	Levels
Percentage of Micro Silica	(0, 3 , 5, 7, 10)%
Test temperatures	(40, 50, 60) o C
Type of gradations	Topeka
Stress	100, 200, 300, 400 and 500 (KPa)

For this research, cylindrical samples were prepare with a height of 70 mm and the diameter is 101 mm. Specimen preparation and compaction were conducted in accordance with ASTM D1559 [ASTM, 2002]. The RLA test was used to evaluate the effects of micro silica on the creep behavior of asphalt mixtures. The micro silica content selected were 3%, 5%, 7%, and 10% by weight of bitumen.

IV. Laboratory Tests

A. Empirical Rheological Tests on Bitumen

To determine the optimum content of micro silica, empirical rheological tests (penetration grade, softening point, viscosity and ductility) carried out on conventional and modified bitumen with different micro silica content. The modification of bitumen with micro silica was performed by thermodynamic driving force. Bitumen was first heated up until becoming a fluid at 163 °C and subsequently micro silica powder was added to the bitumen and the mixture was blended at speed of maximum 4700 rpm for 15 min. The empirical tests were performed according to the standard test procedures. For determination the softening point of bitumen in the range from 30 to 157°C, the ASTM-D36 and viscosity the ASTM D88 is used. The penetration test is an empirical test which measures the hardness of asphalt at a specified test condition according to ASTM-D5 standard. Also ductility of bitumen is determined according ASTM-D113 standard.

B. Fundamental Rheological Test by Dynamic Shear Rheometer (DSR)

The dynamic shear rheometer (DSR) was used to provide the viscoelastic behavior of the bitumen according to ASTM D7175 standard. The DSR measures the viscous and elastic behavior of the binder as represented by the complex shear modulus (G*) and phase angle (δ), both used to evaluate performance parameters of rutting resistance and fatigue cracking [17]. The (G*) is used to evaluate the rutting potential of asphalt binder and the phase angle represents the time lag between the applied shear stress and the resulting shear strain. When the phase angle is zero, the subject asphalt binder is a purely elastic material, and when the phase angle is 90o, it is a purely viscous material. High (G*) means stiffer in the asphalt binder at high temperature.

C. Repeated Load Axial Test (RLA)

To determine the creep behavior of the modified asphalt, Repeated Load Axial (RLA) test has been used for a long time, which is because of its simplicity and logic relation with permanent deformation of asphalt mixture. The significant result of RLA test is accumulative strain curve facing number of loading cycles which depends on compound rutting strength. Fig. 3 shows a form of this curve. As shown in Fig.3, the curve was made of three major parts: primary stage with relatively large deformation during a short number of cycles; secondary stage which the rate of accumulation of permanent deformation remains constant; and tertiary stage, the final stage that the rate of deformation accelerates until complete failure takes place. This stage is usually associated with the formation of cracks [8].

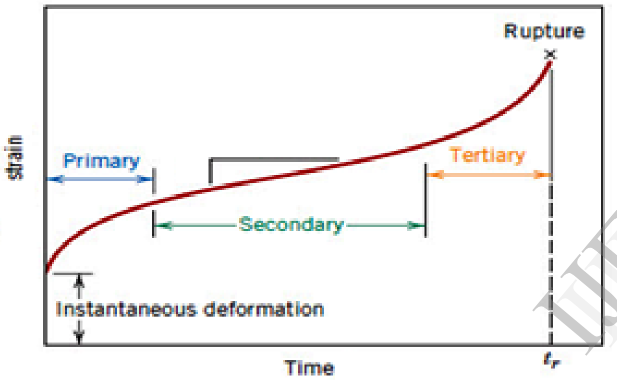

Fig3. A typical creep curve

V. RESULTS AND DISCUSSION

A. Empirical Rheological Tests on Asphalt Binder

Classic rheological tests on unmodified and modified bitumen with different micro silica content were penetration, softening point ductility and viscosity tests. The classical tests were performed following the standard test procedures. The micro silica contents selected during the above test were 3%, 5%, 7% and 10% by weight of bitumen. The results are shown in Figs 4–8. It can be seen in these figures, adding various percentages of micro silica have positive effect on the rheological properties of bitumen. Table 6 demonstrates the effect of the micro silica content on the properties of the modified bitumen.

TABLE VI. BASIC PROPERTIES OF MICRO SILICA MODIFIED BITUMEN BINDERS

Property	Bitumen+0% micro silica	Bitumen+3% micro silica	Bitumen+5% micro silica	Bitumen+7% micro silica	Bitumen+10% micro silica
Penetration at 25 oC (d-mm)	66	63.4	60.2	58.7	61
Softening Point (oC)	51	53.1	56	59.2	54.6
Viscosity (135oC) (s)	6	6.5	7.1	8	7
Ductility at 25 oC at 5 cm/min (cm)	118	92.5	83.7	77	85

B. Penetration and Softening Point

Penetration and softening point tests are the most important tests that are used to determine the physical properties of bitumen. These tests conducted for modified and unmodified bitumen. Figure 4 and 5 showed the penetration grade and softening point test results on conventional and modified asphalt binder. According to these figures and table 6, it can be seen that the penetration grade of modified bitumen is decreased and softening point of bitumen is improved by adding the micro silica powder. Also absorption of maltene phase by micro silica increases the asphaltene part of bitumen. Furthermore, the stiffness of micro silica particles is more than bitumen. Hence, increasing the micro silica content leads to increased stiffness modulus at 25oC. Based on obtained results, it could be concluded that, micro silica had considerable effect on stiffness properties of studied bitumen. Increase the softening point is desirable, because, bitumen with high softening point has less temperature susceptibility and asphalt mixtures made with this bitumen are more resistance against the permanent deformation and rutting at high temperatures. As can be seen in figures addition of micro silica improves the properties of bitumen until 7% additives because high percentage of silica powders in bitumen doesn't have significant effect on bitumen properties.

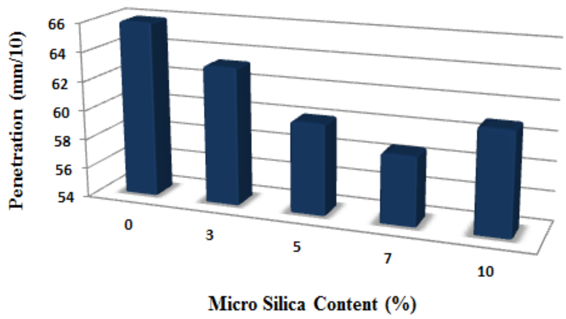

Fig4. Penetration grade test results on Conventional and modified asphalt binder.

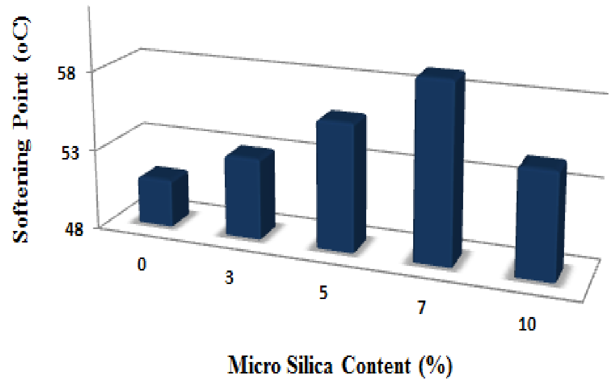

Fig5. Softening point test results on Conventional and modified asphalt binder.

C. Ductility

Ductility of studied specimens was reduced by increasing micro silica content. Reducing the oily materials in maltene phase, increase viscosity and stiffness led to a decrement in ductility. Ductility is an indication of the viscosity of bitumen. It is illustrated in figure 6 that ductility is reduced by improvement of modified bitumen stiffness in comparison with conventional bitumen.

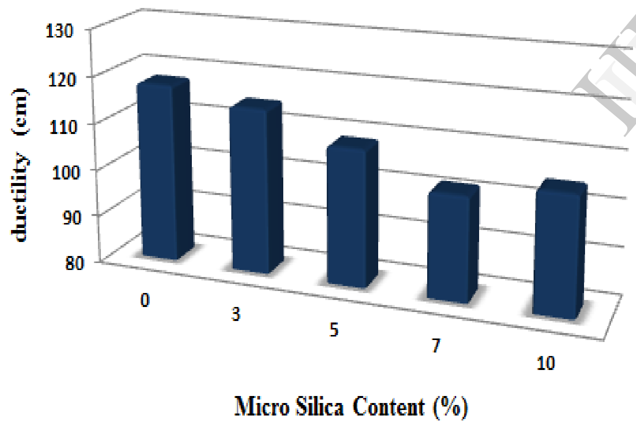

Fig6. Ductility test results on conventional and modified asphalt binder

D. Viscosity

Viscosity quantity that determines the properties of bitumen at high temperatures. The values of viscosity versus micro silica content in bitumen samples are shown in figure 8. According to Table 6 and figure 8, viscosity has been increased by increasing the micro silica content Because the micro silica absorb maltene phase and increases the asphaltene part of bitumen. Asphalt mixture that made with bitumen with high viscosity is appropriate for road construction in summer and areas with heavy traffic.

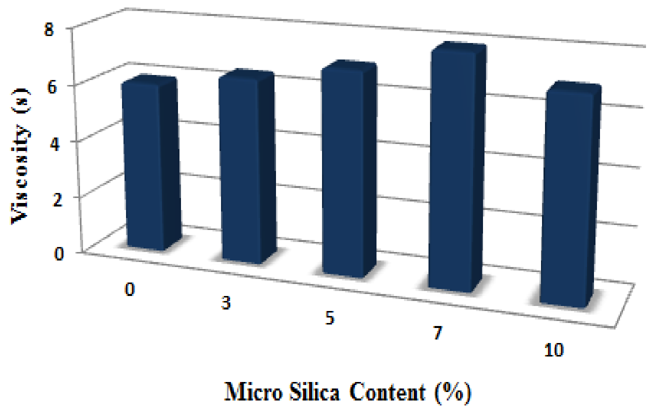

Fig8. Viscosity test result results on conventional and modified asphalt binder at 135 ^{o}C

The results obtained by the penetration grade, softening point, viscosity and ductility tests for bitumen showed that 7% micro silica as modifier of bitumen is an optimal content. As a result, to evaluate the effect of micro silica on the creep compliance of asphalt mixtures, the samples were made with modified bitumen by percentages of 3%, 5%, 7% and 10% micro silica.

E. Dynamic Shear Rheometer (DSR)

From figure 9, the complex shear modulus master curves of micro silica modified asphalt binder and control asphalt binder are displayed. It can be described that the complex modulus (G*) values of 7% micro silica modified asphalt binder are more than the control asphalt binder. According to figure 9, the complex shear modulus has been increased by increasing the frequency. An interesting feature in the shear complex moduli results of the DSR test is their convergence as the frequency increases. It is approve that as the frequency increases to 100 Hz (or traffic loading time decreases); the micro silica molecules play less role in bearing the shearing load. Therefore, it could be stated that at low frequency, both the action of the asphalt binder and micro silica are significant, and at high frequency, the asphalt binder tends to become more significant than the micro silica. In other words, the modified asphalt binders demonstrate a higher ability to maintain elastic/viscous capability than the unmodified asphalt binder.

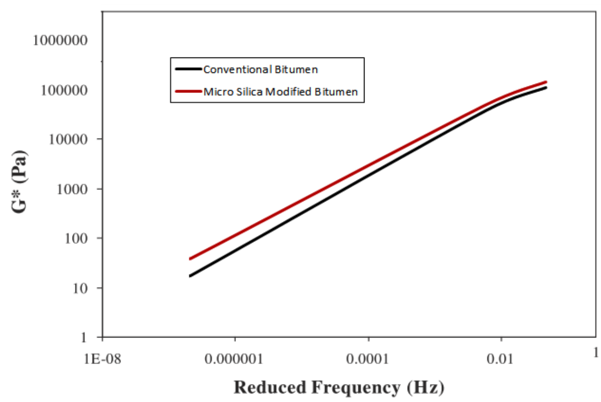

Fig9. DSR shear complex moduli (G*) plot on original and 7% micro silica modified asphalt

F. Repeated Load Axial Test (RLA)

The values of final strain versus micro silica content in asphalt specimens at different stresses and temperatures are shown in figures 10-12. The results of the RLA tests show that the samples without micro silica had more permanent deformation than the samples containing micro silica as modifier of asphalt binder. The value of final strain at a specific temperature for micro silica modified specimens was less than conventional specimens. As can be seen in the figures, it could be concluded that, the main reason of decreasing mixture final strain is better adhesion between micro silica modified bitumen and aggregates in comparison with conventional asphalt mixtures. Also it can be seen in figures, the amount of final strain significantly increased by increase of temperature.

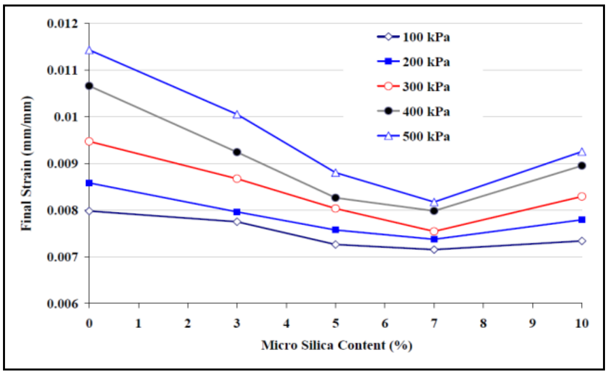

Fig10. Variation of final strain versus Micro Silica content in Asphalt Specimens at 40ºC

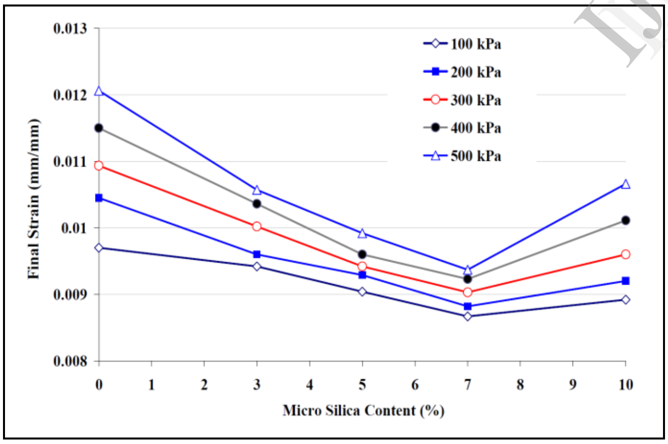

Fig11. Variation of final strain versus Micro Silica content in Asphalt Specimens at 50ºC

For a specific modified sample, the amount of final strain at 60 °C was about 1.22 times of final strain at 40 °C. Also, because of high thermal sensitivity of the asphalt binder, the final strain and permanent deformation of the conventional and modified mixtures increased by increasing the temperatures tests. This subject could be explained by the stiffness modulus and viscosity of the bitumen, which decreased at higher temperatures.

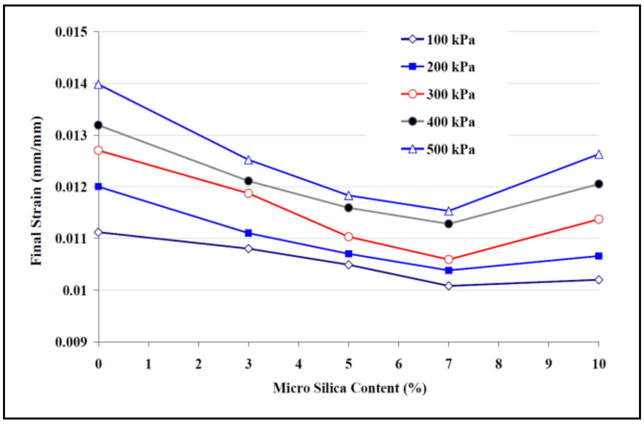

Fig12. Variation of final strain versus Micro Silica content in Asphalt Specimens at 60ºC

The results of this investigation indicated that adding 7% micro silica powder to the bitumen is the best replacement for reducing final strain and permanent deformation of specimens. Also this additive can improve creep behaviour of asphalt concrete mixtures.

G. Experimental Creep compliance Models

By use of experimental results and the numerical analysis with Matlab Software two experimental models were performed for prediction of the creep behavior of micro silica modified and conventional asphalt mixtures just for optimum content of micro silica (7%) for different conditions depending on temperature and stress. The suggested creep compliance model for the prediction of the strain of conventional asphalt mixtures in terms of the variation in stress and temperature can be seen below:

$$\varepsilon(\sigma,\mathrm{T}) = 0.00431 + 1.249\times10^{5}(\sigma) - 2.15\times10^{-6}(\mathrm{T}) - 1.313\times10^{-10}(\sigma^{2}) - 1.038\times10^{-7}(\sigma\times\mathrm{T}) + 1.82\times10^{-6}(\mathrm{T}^{2})$$

$R2 = 98.2\ \%$ (2)

In this equation:

T: Temperature (°C)

σ Stress (KPa)

ε Final strain of the specimens (mm/mm)

The three dimensional interpretation of the proposed creep compliance models for conventional mixture are demonstrated in Figure 13. It show that although the strain trend of all of the specimens is highly dependent upon the changes in the temperature and stress, the addition of micro silica as modifier of asphalt binder can improve the creep behaviour of asphalt mixtures even at high temperatures and stress.

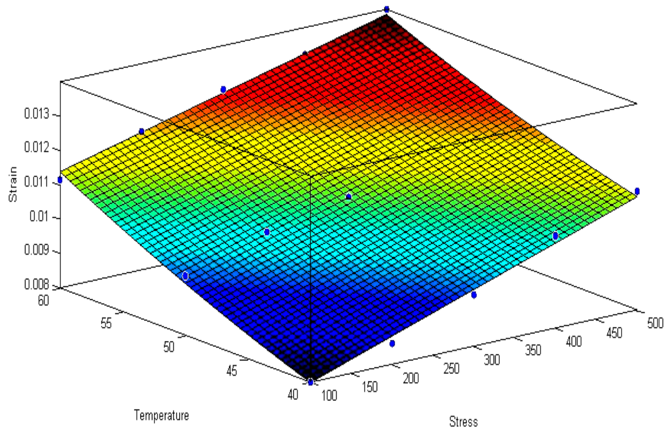

Fig 13. 3D interpretation of the proposed model for final strain vs. temperature and stress in conventional asphalt mix

Also the suggested creep compliance model for the prediction of Strain of modified asphalt mixtures by 7% Micro Silica in terms of the variation in stress and temperature can be seen below: The parameters that used in this equation as same as equation2.

$$\varepsilon(\sigma,\mathrm{T}) = 0.005909 - 9.174\times10^{-7}(\sigma) - 4.399\times10^{-5}(\mathrm{T}) + 1.328\times10^{-9}(\sigma^{2}) + 5.75\times10^{-8}(\sigma\times\mathrm{T}) + 1.832\times10^{-6}(\mathrm{T}^{2})$$

R2 = 98.9 % (3)

Also three dimensional interpretation of the proposed creep compliance models for modified mixture are demonstrated in Figure 14.

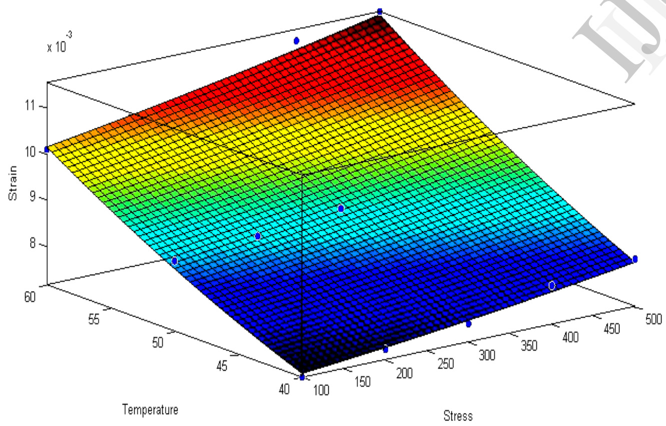

Fig 14. 3D interpretation of the proposed model for final strain vs. temperature and stress in Modified asphalt mix by 7% Micro Silica

A complex interaction between the effects of different parameters can be observed that might be a result of better heat transferring ability of modified asphalt binder by micro silica in comparison with the conventional asphalt binder.

VI. CONCLUSION

The main goal of the present research was to characterize the viscoelastic behaviour and rheological properties of micro silica modified asphalt binders. Adding modifiers to the pure bitumen improved the viscoelastic behaviour of the bitumen by increase the (G*) values and changed its rheological properties. The micro silica as a modifier had positive influence on the rheological properties of bitumen binder. The results obtained by the repeated load axial (RLA) tests for samples show that 7% micro silica as modifier of bitumen is an optimal content in asphalt mixtures that can improves the creep compliance behaviour of the asphalt mixtures. Based on laboratory tests were conducted on the bitumen binder with different modifier content and the data were analysed and the results were compared, the following conclusions can be drawn:

1. The stiffness modulus of the bitumen increased with the increase of the micro silica content for the conventional bitumen. Therefore micro silica had considerable effect on stiffness properties of studied bitumen.

2. DSR test performed on bitumen samples proved that the micro silica modifications help to increase the (G*) values, stiffness and rutting resistances. In the proposed approach, when bitumen was modified with small amount of micro silica, its physical properties were successfully enhanced on the condition that the silica disperses at microscopic level.

3. Penetration decreased by increasing the micro silica content and the softening point, ductility and viscosity increased by this trend in the modified binders.

4. Temperature susceptibility of micro silica modified bitumen has been reduced by increasing the micro silica content. Binders with less temperature susceptibility have more resistance against rutting and low temperature cracking.

5. By increasing the temperature, final strain of all specimens increased. This behaviour is due to high thermal sensitivity of bitumen in asphalt mixtures.

6. Three dimensional interpretation of the proposed creep compliance models showed that although the strain trend of all of the specimens was highly dependent upon the changes in the temperature and stress, the addition of micro silica as modifier of asphalt binder can improve the creep behaviour of asphalt mixtures even at high temperatures and stresses.

7. By increasing the stress, tolerance of modified samples against stress with higher rate enhanced. Also Sensitivity of modified samples against stress has been reduced by increasing the micro silica content.

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