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Investigation of the Effect of Adding Silica Fume on Asphalt Concrete Properties

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ABSTRACT : Practical experience of highway networks showed that high percentage of road pavements are suffering from cracking and rutting. This problem had often occurred due to the shortage in asphalt mix properties as well as the increase in traffic loading. Fatigue, creep and rutting of asphalt mix in long term may be occurred due to the shortage in the mechanistic properties of either of the binder and/or the asphalt mix. This study investigates the effect of using silica fume (SF) as an additive to the binder on the behavior of asphalt mixes. The scope of the study includes the investigation of the properties of the asphalt mixes using different percentages of SF (2, 4, 6 and 8% by bitumen weight). Marshall, Direct Compression (DC), Indirect Tensile Strength (ITS) tests are used to examine the mixes properties whereas the wheel tracking (WT) test is carried out to investigate the rutting properties of the modified mixes. Results indicate that, the optimum SF percentage is 6% by weight of bitumen which achieve the best results in Marshall, DC, ITS and WT tests. Marshall Stability and flow are increased by about 23.61% and 4.67%, respectively. The unit weight increases, while the air voids percentage (AV %) is kept within the accepted limits. Adding SF reduces rutting depth by about 35.82%. The DC value increases by about 25% while the ITS value increases by about 3.83%. Finally, adding SF to the asphalt cement success in enhancing the properties of hot mix asphalt.

Keywords: Silica Fume (SF), Asphalt Mixes, Marshall Stability, Flow, Rutting Depth

1. INTRODUCTION

Hot Mix Asphalt (HMA) is a mixture of coarse aggregate, fine aggregate, mineral filler and a relatively small amount of asphalt binder. HMA is a solid mineral matrix with elements of various sizes connected to each other by an asphalt binder. It is interested that a small amount of binder (about 5% by mass) has a strong impact on the mechanical properties of the paving mix [1]. The previous researches showed that asphalt binder is quite often modified by various additives (polymers, fibres, rubber, nano materials, lime, combinations of fibres and polymers …. etc.) which may enhance the properties of bitumen and mix [1, 2, 3].

Recently, modern techniques used waste tire rubber and mineral fibre in modifying the HMA. They succeeded in improving the resistance of asphalt mixtures against cracks and rutting, respectively [4, 5].

The American Concrete Institute (ACI) defines SF as very fine non-crystalline silica produced in electric arc furnaces as a byproduct of production of elemental silicon or alloys containing silicon. It can exhibit both pozzolanic and cementitious properties and produced by reduction of high purity quartz with coal in the production of ferrosilicon alloys. SF has been used in improvement of the cement concrete compressive strength, bond strength, abrasion resistance and reducing permeability.

Yazan Issa (2016) studied the effect of using rubber on the pavement properties. Waste tires rubber can be used in asphalt pavement with optimum replacement ratio 10% by weight. Also**,** adding polyethylene leads to increase mixture workability and efficiency of compaction for modified mixes [4].

Ahmed A. L. (2007) studied the effect of using polyethylene on the change of asphalt mixes properties. It was found that adding polyethylene to asphalt mixes increased mixture workability and enhanced the compaction of the modified mixes [1].

Sheelan A. Ahmed et al. (2015) found that using fiber in asphalt mixes improved the mix properties. The study investigated that the optimum fiber content was 1.5% by the total weight of the mixture in which the Marshall stability increased by 14% [5].

Negi et al.(2013) studied the change of properties of clayey soil using SF. It was concluded that the addition of 20% SF to the soil decreased the potential swelling from 50% to 7% while the California bearing ratio (CBR) value increased by about 72% [6].

Priti Chauhan et al. (2016) studied the effect of using micro silica, lime and fly ash on the stabilization of black cotton soil. It was found that the optimum percentages of micro silica, lime and fly ash for stabilization black cotton soil were 5%, 3%, and 3% respectively. Black cotton soil stabilized with lime, fly ash, micro silica and their combination improved the soaked CBR to about 6.5 times and the un-soaked CBR to about 1.8 times of the un-stabilized soil [7].

Abd El-Aziz et al. (2004) studied the change in the properties of clayey soil after mixing with lime and SF. Laboratory experiments were carried out for several samples by lime contents of 1%, 3%, 5%, 7%, 9% and 11% and SF contents were 5%, 10% and 15%. The results of combination of L-SF soil indicated that the swelling potential was reduced from 19% to 0.016%, while the plasticity index (PI) decreased from 40.25% to 0.98% at

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percentages of L-SF mixture of 11-15% [8].

Naresh Kumar (2014) studied the effect of using pozzolanic material (Metakaolin and SF) on the compressive and flexure strength of the cement concrete. Metakaolin and SF were used as cement replacement materials at 5%, 10% and 15% by weight, keeping water–cement ratio at 0.42. Compressive and flexural strengths were observed after 7 and 28 days of curing. It was observed that, the optimum dose of Metakaolin is 10% by weight of cement which achieved the maximum compressive strength in the cement concrete [9].

Farag Khodary (2016) studied the effect of adding SF on the soil properties for base course in highway construction. Results indicated that adding SF improved both the strength and stability of the modified soil. Adding SF to the base course material increased CBR from 54% to 94.5% [10].

The state of art showed that SF was used in the improvement of engineering properties of subgrade soils, highway base courses and cement concrete. Using SF in the improvement of hot mix asphalt concrete (HMA) is still a research issue. This study is focused on the investigation of the effect of using SF on the characteristics of the HMA for pavement wearing surfaces.

2. MATERIALS AND TESTING

2-1 Silica Fume (SF)

SF is obtained from Sika Company - 1st Industrial Zone (A) - El Obour City - Cairo – Egypt. The properties of the used SF minerals are shown in Tables (1) and (2). Figure (1) shows SF shape.

Table (1): Chemical Properties of SF, [6]

No.	Parameters	Test Value
1	Silica as SiO_2, % by mass	89.90
2	Total Sulphur Content as SO_3, % by mass	0.58
3	Lime as CaO, % by mass	7.85
4	Magnesia as MgO, % by mass	4.03
5	Alumina as AL_2O_3, % by mass	Nil
6	Iron Oxide as Fe_2O_3, % by mass	Nil

Table (2): Physical Properties of SF, [6]

No.	Parameters	Test Value
1	Density (gm/cm^3)	2.07
2	Physical state	Clear grey powder
3	Practical Size Distribution (%)	59

Figure (1): SF Shape

2-2 Asphalt Binder

The asphalt cement used in this research is obtained from Suez City. Asphalt cement grade is 60/70 with specific gravity 1.02 which is used in roads construction in Egypt. The consistency property tests of asphalt are carried out and the results are shown in Table (3).

Table (3): Asphalt Cement Properties

Property	AASHTO Designation No.	Result	Specification Limits
Penetration at 25 ^{o}c, 0.1mm	T-49	65	60-70
Rotation Viscosity at 135 ^{o}c, Cst.	T-201	378	≥ 320
Flash point, ^{o}c	T-48	268	≥ 250
Softening point, ^{o}c	T-53	52	45-55

2-3 Aggregates

Coarse and fine aggregates used in this study are dolomites crushed stones. The physical properties of the used aggregates are shown in Table (4). Table (5) shows the aggregate gradation used in asphalt mixtures. The gradation blending achieves the specs of HMA type (4C) according to Egyptian code for highways.

Table (4): Aggregates Properties

Property	AASHTO Designation No.	Coarse Aggregate Size (1)	Coarse Aggregate Size (2)	Fine Aggregate	AASHTO Limits
Los Angeles Abrasion	AASHTO T 96	35.20%	31.4%	---	40 Max
Bulk Secific Gravity	AASHTO (85-77)	2.495	2.505	2.640	---
Saturated and Dry Surface Specific Gravity	AASHTO (85-77)	2.555	2.562	---	---
Apparent Specific Gravity	AASHTO (85-77)	2.650	2.655	---	---
% Water Absorption	AASHTO (85-77)	2.00%	2.25%	---	5 Max

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Table (5): Aggregate gradation

Type		Coarse Aggregate				Fine aggregate (Natural sand+ crushed stone)		Mineral Filler		Design Mix gradation	Specification Limits
		Aggregate (1)		Aggregate (2)							
Sieve Size (inch)	Sieve Size (mm)	Passing %	25%	Passing %	26%	Passing%	45%	Passing %	4%		
1	26.5	100	25	100	26	100	44	100	4	100	100
3/4	19	95	23.75	100	26	100	44	100	4	98.75	80-100
1/2	13.2	38	9.5	100	26	100	44	100	4	84.5	---------
3/8	9.52	8	2	80	20.8	100	44	100	4	71.8	60-80
No 4	4.75	-----	----	8.4	2.184	95	42.75	100	4	48.93	48-65
No 8	2.36	-----	----	-----	----	71.8	32.31	100	4	36.31	35-50
No 30	0.6	-----	----	-----	----	44.3	19.49	100	4	23.94	19-30
No 50	0.3	-----	----	-----	----	26.2	11.79	100	4	15.79	13-23
No 100	0.15	-----	----	-----	----	8	3.6	90	3.6	7.2	7-15
No 200	0.075	-----	-----	-----	----	-----	----	75	3	3	3-8

2-4 Binder Modification

To prepare the modified binder, asphalt cement is heated in an oven at a temperature of 150^{o}c. The required amount of asphalt is weighted into a steel beaker. Then the amount of SF, from (2 to 8% by weight of asphalt) is added to Bitumen. The beaker is placed on a hot plate to maintain the mixing temperature at least 150^{o}c and the bitumen and SF are mixed carefully.

2-5 Consistency Tests

Consistency tests are carried out on both control and the modified binder to obtain penetration value, softening point, flash point and rotation viscosity values.

2-6 Marshall Tests

Marshall test method as per ASTM D 6927-06 is used in this study to determine the characteristics of asphalt mixes. The aggregates (coarse, fine and mineral filler) are prepared and the required asphalt cement (60/70) is estimated. Four sets of unmodified test specimens are prepared with various asphalt contents. Three specimens are prepared for each set. Each of the prepared specimens is tested to find/measure mix stability, flow, density, air voids percentage (AV%) and voids in mineral aggregates percentage (VMA%). The relations between the asphalt cement contents (AC %) and the five mentioned mix properties are plotted. The optimum asphalt content (OAC) that achieves maximum stability, maximum density, and 3% AV is obtained from the plotted graphs as per Marshall test procedure. Similar sets of modified test specimens are prepared by using the modified asphalt with the determined (OAC) and adding different percentages of SF (2, 4, 5, 6, 7, and 8% by weight of asphalt). The modified mix properties are obtained by conducting Marshall test on the modified mix specimens.

2-7 Direct Compression (DC) Test

DC as per ASTM (D-1074) is conducted on the modified asphalt concrete mix specimens to investigate the behavior of the mix under crushing loads. The specimen is placed under compression force with various values of loads. Marshall test specimens, 100mm diameter and 62 to 69mm height, are used for this test. The specimens are compacted as explained in Marshall test procedure. Six specimens are prepared for this test, three specimens for control mix with unmodified binder and the other three specimens are with the modified binder with SF.

The DC values (S_c) are calculated by using the following equation: $S_c = 4P/(\pi D^2)$, [kg/cm^2], where: P is the applied load in kg, D is the specimen diameter in cm.

2-8 Indirect Tensile Strength (ITS) Test

The ITS test as per AASHTO (T322-03) involves loading a cylindrical specimen with compressive load which acts parallel to and along the vertical diametrical plane. This loading configuration develops a relatively uniform tensile stress perpendicular to the direction of the applied load. This tensile strength causes the specimen to fail by splitting or rupturing along the vertical diameter. ITS values (S_t) are determined by using the following equation: $S_t = 2P/(\pi HD)$, (kg/cm^2), where: P is the applied load in kg, H is the specimen height in cm, and D is the specimen diameter in cm.

2-9 Wheel Tracking (WT) Test

This test method describes a procedure for determining the rutting depth of HMA pavement specimens in the WT device as per AASHTO (T324-04). The test is conducted at the laboratory of the General Authority of Roads and Bridges and Land Transport (GRBLT). The method describes the compaction procedure of HMA in a reciprocating rolling-wheel device. This test provides information about the rate of

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permanent deformation from a moving concentrated load. A laboratory compactor has been designed to prepare slab specimens. The test used to determine the premature failure susceptibility of HMA due to weakness in the aggregate structure, inadequate binder stiffness, or moisture damage. This test measures the rutting depth and number of passes or time to the final rutting depth. The test is conducted on both of the control and modified specimens with SF.

3. RESULTS AND DISCUSSIONS

3-1 Effect of Adding SF on Asphalt Cement Properties

By adding SF to the asphalt, the properties of asphalt change as shown in Figure (2). Adding SF to bitumen decreases penetration value from 6.50mm to 3.50mm which represents about 46.15%. This change is due to the presence of micro material (SF) which increases asphalt viscosity. This leads to enable the modified asphalt to resist the penetration of the needle into the specimen.

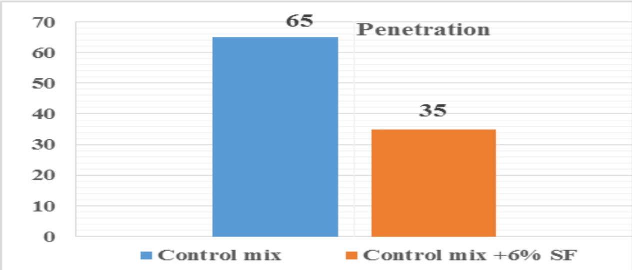

Figure (2): Effect of Adding SF on Penetration Value.

By adding SF to asphalt cement, the viscosity increases from 378 to 492 centistokes which represents about 30.16% as shown in Figure (3).

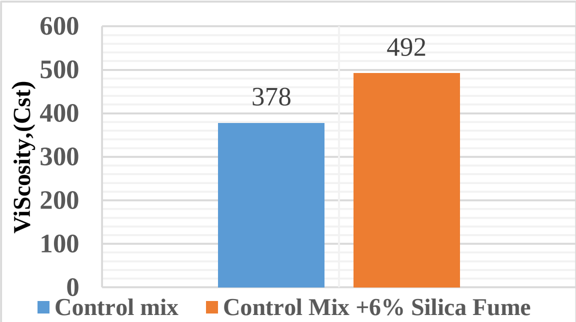

Figure (3): Effect of Adding SF on Bitumen Viscosity.

3-2 Effect of Adding SF on Marshall Stability

Figure (4) shows the relationships between the obtained Marshall stability and the AC% for different SF contents. While Figure (5) shows the relationship between the obtained stability and the SF contents at the OAC. Figure (4) shows that Marshall stability increases as the percentages of SF increase up to 6% and then it decreases. Figure (5) shows that the maximum stability occurs at 6% SF, the stability increases from 2880 to 3560 Ib which represents about 23.60%.

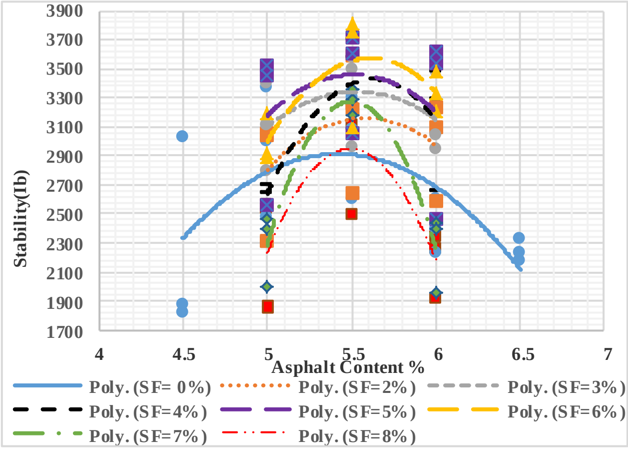

Figure (4): Effect of Adding SF on Marshall Stability

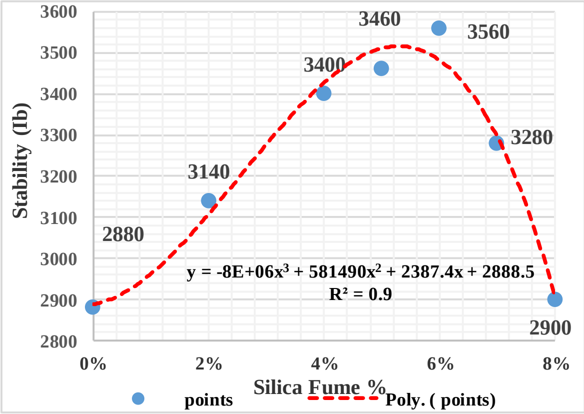

Figure (5): Effect of Adding SF on Marshall Stability at OAC

3-3 Effect of Adding SF on Marshall Flow

Figures (6) and (7) show the relationships between the flow and AC for different SF contents and also with SF content at OAC. Figure (6) shows that the mix flow is firstly decreases with an increase in SF contents up to 2% and then it increases with the increase in SF accordingly. The maximum flow value is obtained at 8% SF. The high flow values indicate high flexibility which increases the ability of HMA pavement to deform without cracking.

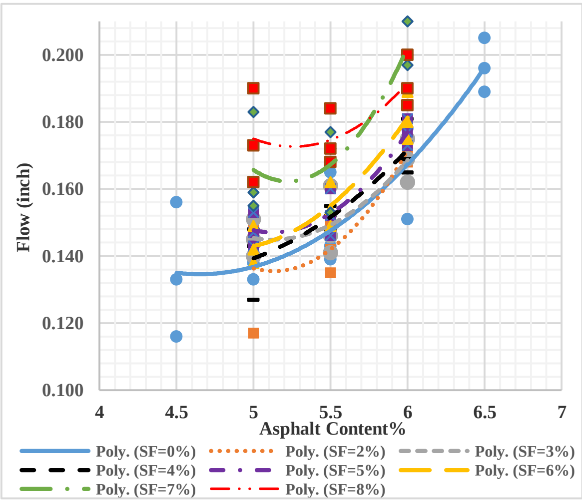

Figure (6): Effect of Adding SF on Marshall Flow Values

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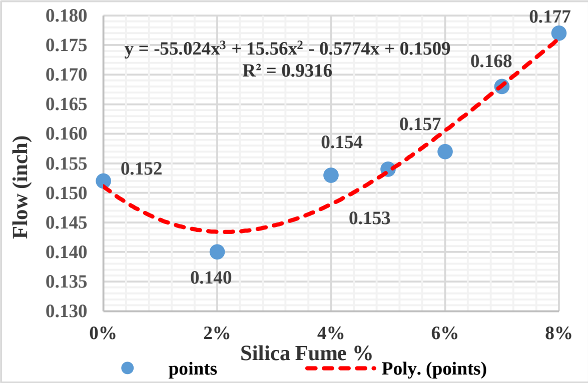

Figure (7): Effect of Adding SF on Flow Values (at OAC)

3-4 Effect of Adding SF on Marshall Unit Weight (γ)

The relationships of unit weight versus asphalt content at various percentages of SF are shown in Figures (8) and (9). Figure (9) shows that, the unit weight values increase as the SF increases up to 2% and then it decreases. It should be mentioned that, all values of unit weight of the modified mixtures are greater than the value of control mix except of SF 7 and 8%. This increase in unit weight is due to the presence of micro fine particles (SF) in the HMA that makes the mix denser than the control mix.

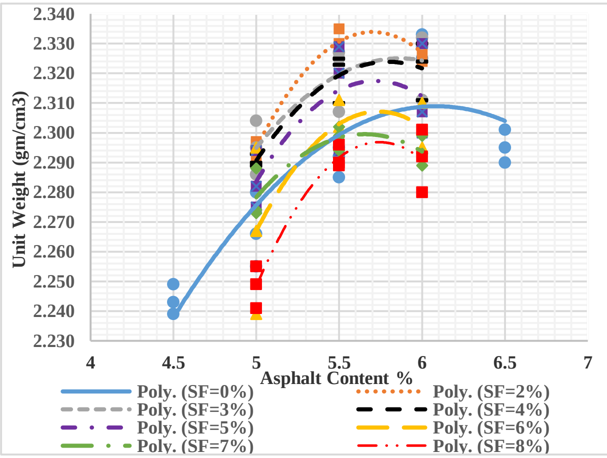

Figure (8): Effect of Adding SF on Marshall Unit Weight

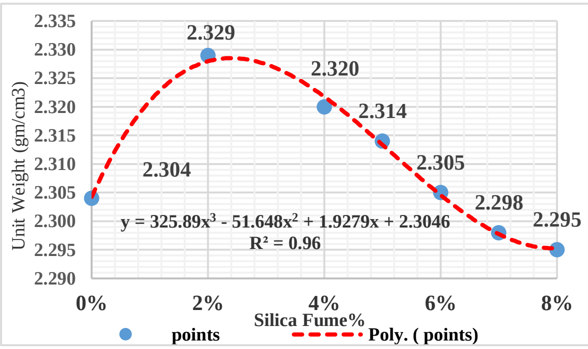

Figure (9): Effect of Adding SF on Marshall Unit Weight at (OAC)

3-5 Effect of Adding SF on AV %

Figures (10) and (11) show that the AV% decreases as the SF content increases up to 2% and then it increases accordingly. Figure (11) shows that AV % of 3% can be obtained at either 0.5% or 5% SF contents. Also, it is found that the recorded value of AV% at 6% SF is 3.30%.

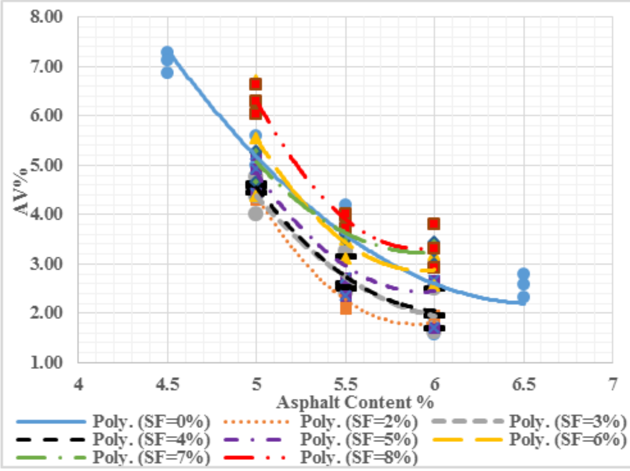

Figure (10): Effect of Adding SF on %AV

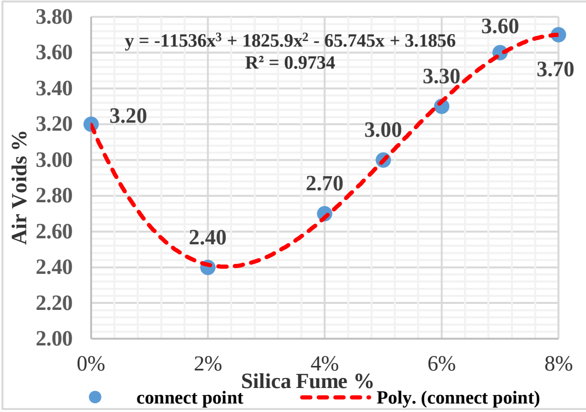

Figure (11): Effect of Adding SF on AV% at (OAC)

3-6 Effect of Adding SF on VMA %

Figures (12) and (13) show that the VMA% decreases as the SF increases up to 2% and then it increases accordingly. The maximum value of VMA% is obtained at 8% SF, while the minimum value occurs at 2%. Also, it is observed that the values of VMA% of the modified mixes are lower than the value of the control mix except of at SF 7 and 8%.

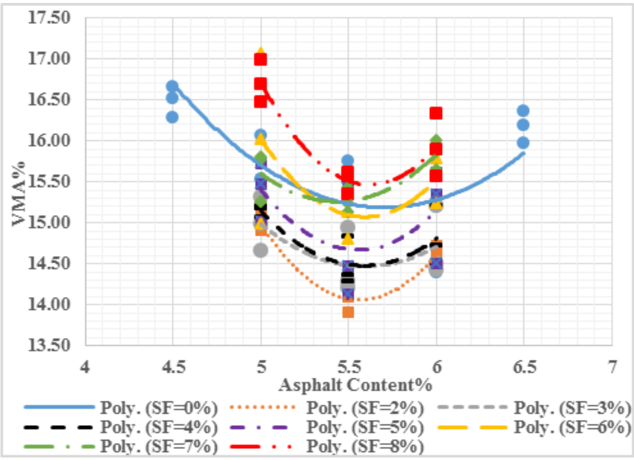

Figure (12): Effect of Adding SF on VMA%

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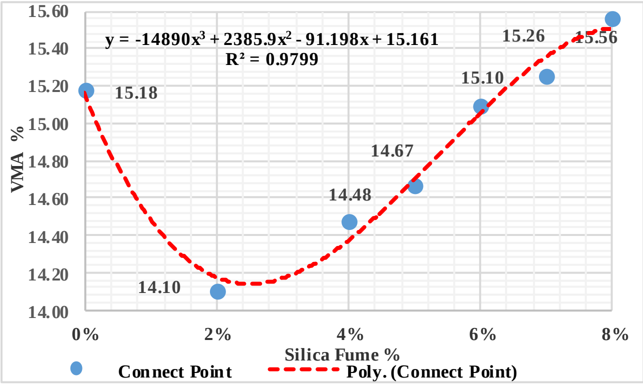

Figure (13): Effect of Adding SF on VMA% at OAC

3-7 Effect of Adding SF on VFB %

Figures (14) and (15) show the variation in VFB% after adding SF to asphalt mixes. As shown in Figure (15), the maximum value of VFB% is obtained at 2% SF. On the other hand, the minimum value of VFB occurs at 8% SF. The Figure shows also that the values of VFB% are greater than those of the unmodified mix for the range of silica fume content from greater than 0.0% to less than 6%.

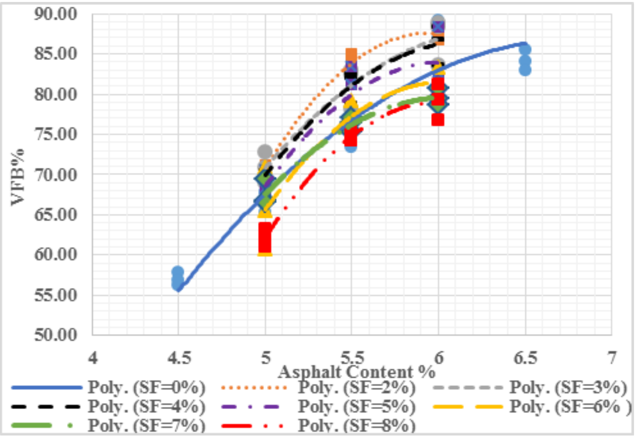

Figure (14): Effect of Adding SF on VFB%

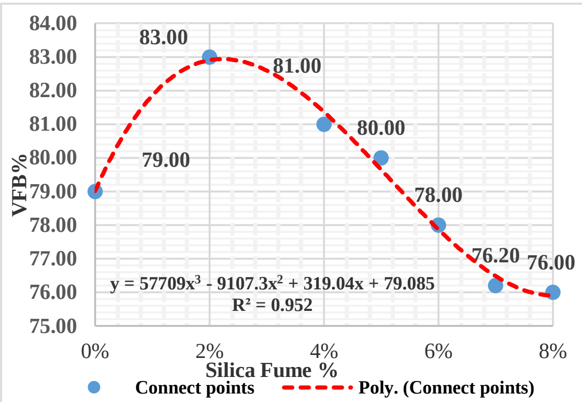

Figure (15): Effect of Adding SF on VFB% at OAC

3-8 Effect of Adding SF on Marshall Stiffness

Mix stiffness is defined as the Marshall Stability divided by the flow in lb/in. The relationships between the stiffness and asphalt contents for different SF contents are shown in Figure (16), while Figure (17) shows the stiffness-SF relationship at OAC. It shows that the mix stiffness increases as the SF content increases up to 6% and after that it decreases. The firstly increase in stiffness is due to the gained stability while the flow is still low; after that the increase in SF increases the flow gradually making the overall stiffness to be decrease. The figure also shows that the stiffness values for the modified mixes are greater than those of the unmodified mix for the range of SF contents from greater than 0.0% and less than 7.20%.

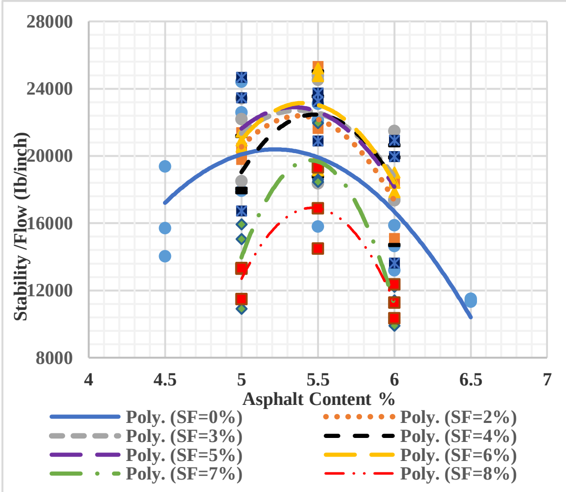

Figure (16): Effect of Adding SF on Marshall Stiffness

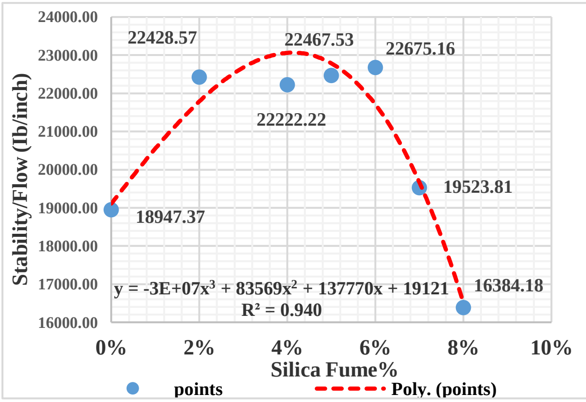

Figure (17): Effect of Adding SF on Marshall Stiffness

3-9 Effect of Adding SF on DC Value

The DC test value defines as the maximum vertical compression load affecting on a specimen until its damage. Two sets of specimens, three samples in each set, are examined in this test. The first set is for control mix without SF, while the second set is for the modified mix with 6% SF (the obtained optimum SF% from Marshall test). Results indicate that adding 6% SF changes the DC value from 30.134 to 37.773 kg/cm^2 as shown in Figure (18). This value of SF enhances DC value by about 25.35% which means increasing in load carrying capacity by about 25%.

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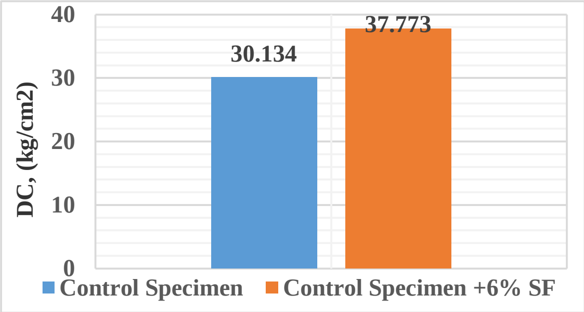

Figure (18): Effect of Adding SF on DC value

3-10 Effect of Adding SF on ITS Value

Figure (19) shows the results of ITS test for control and modified specimens. The presence of SF in the modified mix makes it to be denser and resists load. The cementation effect of the modified specimen increases the ITS value. It is found that the value of ITS increases from 9.91 kg/cm2 to 10.29 kg/cm2 which represents about 3.83% improvement by adding 6% SF to the asphalt mix.

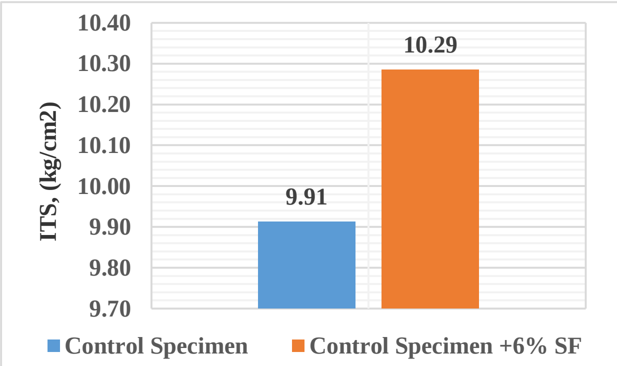

Figure (19): Effect of Adding SF on ITS Value

3-11 Effect of Adding SF on Rutting Depth

Figure (20) shows the results of WT test for both control and 6% SF modified specimens. The results of rutting test are taken every 5 minutes along 60 minutes as a total measuring period. The observed results indicate that the rutting depth of the modified specimen reduces by about 35.82%. This indicates that adding 6% SF to the asphalt mix improves the rutting resistance and reduces rutting depth by 35.82%.

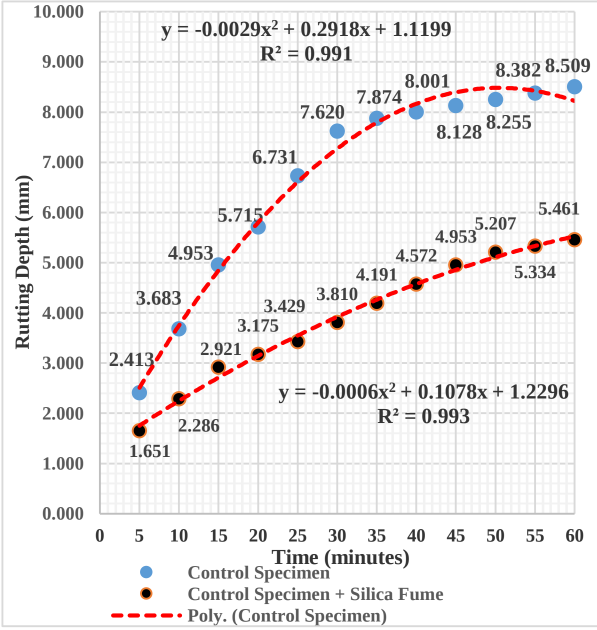

Figure (20): Effect of Adding SF on Rutting Depth

4- CONCLUSIONS

The conclusions of this study can be summarized as follows:

1. Using SF in modifying the HMA has a major effect in improving the bitumen properties. It decreases the penetration value by 46.15%, and increases the viscosity by about 30.16%,
2. Adding SF to the HMA increases Marshall stability by about 23.61% and the Flow by 4.67%; and thus the Marshall stiffness increases by about 18.58%.
3. Adding SF to the control mix increases the unit weight of modified mix and keeps the AV% within the acceptable limits.
4. The optimum SF content that achieves optimum mix properties is 6% by weight of bitumen.
5. The DC value increases by about 25% by adding 6% SF to the control mix which enhances the load carrying capacity by about 25%.
6. Adding 6% SF to the control mix increases the ITS value from 9.91 to 10.29 kg/cm^2, with an improvement of 3.83%.
7. Modifying the asphalt mix by 6% SF improves the rutting resistance and reduces rutting depth by about 36%.

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