Comparative Study of Performance of Modified Asphalt Mixtures Using Different Traditional and Nano Additives

M. G. Al-Taher[1]. Hassan D. Hassanin[2]. Mokhtar F. Ibrahim[3] and Ahmed M. Sawan[4]

Abstract-**This study investigates the performance of Hot Mix Asphalt concrete mixtures modified using different types of traditional and Nano additives. The traditional modifiers include rubber, polyethylene and lime while the Nano modifiers include Nano Silica and Silica Fume. The performance of the modified mixtures was comparatively evaluated in order to find the best modifier. The evaluation was done through conducting the comparison between results obtained on samples using Marshall, Indirect Tensile Strength, Direct Compression, and Wheel Tracking tests. The used samples were prepared and compacted at the optimum modifier percentage previously founded by other research studies. An economic study analysis for the direct cost of materials for production of 1 ton of the unmodified and modified mixtures was conducted. The results indicated that Nano Silica is considered the best modifier that achieved maximum stability, minimum flow, higher tensile strength; higher direct compression strength and lower rutting depth. On the second basis, Silica Fume is following NS in achieving relatively nearer results as Nano silica whereas the other modifiers achieved lower mixture performance rates. The economic analysis indicated that the cost of producing 1 ton of mixture shall be very high cost and not capable to be applicable solution since it shall cost 27192 L.E. excluding the NS from the economic analysis rating leaded to bring the Silica Fume to be 14% increase in cost compared with the unmodified mixture but with achieving most applicable improvement in mixture performance represented by mix stability, flow, direct compression resistance, indirect tensile strength and rutting resistance.**

Keywords: **Asphalt Mix, Comparative Study, Nano Silica, Performance, Polymer, Polyethylene, Rubber, Silica Fume.**

I. Introduction

Asphalt pavements suffered from different distresses due to deficiencies in its characteristics and the effect of weather on the properties of the asphalt binder. Many studies were conducting to improve the performance of asphalt mixtures to achieve more resistant to cracking and deficiencies. The most deficiencies types in asphalt pavements include fatigue, creep, cracks and rutting which resulted from the shortage in the mix characteristics and/or the excessive traffic loads.

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Kim et al studied the effect of using crumb rubber on asphalt mixture properties. The results indicated that the use of crumb rubber as a modifier seemed to improve the penetration resistance of the asphalt binder because of the increased viscosity at 60ºC. Also its advantage was more apparent at lower frequencies of loading, and the asphalt binder with higher crumb rubber contents was observed to have better resistance to permanent deformation at higher temperatures and elasticity at lower temperatures [1].

Crumb rubber is light in weight, durable and can last for a long period in a natural environment. The utilization of crumb rubber has proven to be economical, environmentally sound and effective in increasing the performance of the asphalt mixtures. Xiao et al (2010) concluded that increasing the rubber content improved the aging resistance of the binder and prolonged the fatigue life of the mixtures, while it caused decreasing in both the Indirect Tensile Strength (ITS) and the resilient modulus. Therefore rubber was used to enhance the flexibility of HMA to improve cracking resistance [2].

Yazan Issa, studied the effect of using rubber on the change of pavement properties. Waste tires rubber can be used in asphalt pavement with optimum replacement ratio of 10% by weight of total aggregates. The average stability for 10% rubber modified mixture was higher than the control mixture. Therefore, a significant improvement occurred in Marshall Properties of asphalt concrete mixtures modified using melted rubber [3].

Ahmed Mohamady et al studied the effect of using polymers on bituminous mixtures characteristics in Egypt. The study presented the effect of polymer on the stability and flow values for all HMA samples. They found that addition of polymer improved stability, flow and density of HMA up to 4% polymer percentage; and then the stability was decreased [4].

Ahmed A. L. studied the effect of using polyethylene on the pavement properties. The largest value of Marshall Stability occurred at polyethylene content equal to 10%. Adding polyethylene leads to increase mixture workability and efficiency of compaction for modified mixes [5].

Hinisloglu et al (2005**)** studied the effect of high density polyethylene (HDPE) in powder form as a binder modified on the permanent deformation (rutting) of the asphalt mixtures using Marshall Parameters (stability, flow, density, air voids, voids in mineral aggregates and voids filled with asphalt) and creep behavior. Also asphalt binder properties were evaluated such as penetration, softening point and ductility. Bitumen was mixed with four percentages 1%, 2%, 3% and 4% of HDPE at 185ºC for 60 minutes using high shear mixer. The results indicated that the maximum stability occurred at 3% of HDPE, while the better improvement in permanent deformation occurred at 2% HDPE, so it was difficult to investigate the optimum high density polyethylene. They concluded that the increase in stability ranged from 3 - 21% while flow decreased in the range of 17 – 25%. The creep resistance of the modified specimens was better than the values of the conventional specimens [6].

Sheelan A. Ahmed et al. found that using fiber in asphalt mixes improved the mix properties. The study indicated that the optimum fiber content was 1.5% by the total weight of the mixture in which the Marshall Stability increased by 14% [7].

Mahrez et al (2005) studied the effect of using glass fiber to improve the properties of hot mix asphalt (HMA). They found that the addition of fiber decreased the mix stability and increased the flow and the voids in the mix. The results indicated that the fiber has the potential to improve the fatigue life by increasing the resistance to cracking and permanent deformation of bituminous mixes. It concluded that fiber content of 0.3% by weight of the total mix resulted in the highest performance in terms of stiffness, resistance to permanent deformation and fatigue [8].

European lime association (2008) studied the effect of using lime in asphalt pavement mixtures. They noted that by adding hydrated lime to asphalt, it reacts with aggregates, strengthening the bond between the bitumen and the stone. In addition, hydrated lime reacts with highly polar molecules in the bitumen, blocking the formation of water-soluble soaps. These soaps result in weaker bond strength, and thus contribute to moisture damage [9].

Farag Khodary 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].

Metwally G. Al-Taher et al. studied the effect of adding silica fume on the asphalt concrete mixtures. They found that using SF in modifying the Hot Mix Asphalt 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%. They also found that the mix properties were improved such that Marshall Stability increased by about 23.61% and the Flow by 4.67%; and thus the Marshall stiffness increased by about 18.58%. The optimum silica fume content that achieves optimum mix properties is 6% by weight of bitumen content. Direct Compression (DC) value was increased by about 25%. Indirect Tensile Strength (ITS) value increased by about 3.83% and reduced rutting depth by about 36% (11).

Metwally G. Al-Taher et al. studied the effect of adding Nano Silica on the asphalt concrete mixtures. They found that adding NS to the asphalt binder improves the physical characteristics of the asphalt binder. It decreases the penetration and increases its viscosity. Modifying the asphalt mixture by 7% NS increases Marshall Stability by 25% and decreases the flow by 19%. Also, it increases the mixture stiffness by 54%, maintaining the unit weight and AV% within the accepted limits. It improves the DC test value by 32%, increases the ITS value by 2.7% and enhances the rutting resistance by 40% (12).

Mostafa (2016) studied the effect of Nano Silica and Nano Carbon on asphalt mixtures; he found that the optimal percentages for Nano-Silica and Nano-Carbon were 7% and 0.5% respectively. The optimal percentage of Nano-Carbon decreased the penetration by 9.4% in case of mechanical mixing and by 9.8% in case of high shears mixing. Whereas optimal percentage Nano-Silica decreased the penetration by 7.13% in case of mechanical mixing and by 8.1% in case of high shear mixing. The optimal percentage of Nano-Carbon increased viscosity by 10% in case of mechanical mixing and by 11.67% in case of high shear mixing; whereas 7% Nano-Silica increased viscosity by 8.33% in case of mechanical mixing and by 10% in case of high shear mixing [13].

The main aim of this paper is to conduct a comparative study to investigate the performance of asphalt concrete mixtures used in the construction processes of Egyptian road pavements using traditional additives compared to the Nano additives. as well as investigation of the best modifiers, most cost-effective improvements in pavement performance and identifying the binder additives that could improve the rutting, creep as well as crack resistance of asphalt mixes.

II. Materials

A. Aggregates

Crushed dolomitic aggregate was used to constitute the mixture in conjunction with the mineral filler and asphalt cement. The characteristics of the used aggregates are presented in Table (1) while the the gradation of aggregate mix is presented in Table (2).

Table (1): Aggregates Properties (11)

Property	AASHTO Designation No.	Coarse Aggregate Size (1)	Coarse Aggregate Size (2)	Fine Aggregate	AASHTO Limits
Abrasion	AASHTO T 96	35.20%	31.4%	-	40 Max
Bulk Specific Gravity	AASHTO (85-77)	2.495	2.505	2.640	-
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 (2): Aggregate Gradation (11)

Type		Coarse Aggregate				Fine Agg.		Mineral Filler		Agg. Mix	Limits
		Agg. 1		Agg. 2							
Sieve Size (inch)	Sieve Size (mm)	% Pass.	25%	% Pass.	26%	% Pass.	45%	% Pass.	4%		
1	26.5	100	25	100	26	100	45	100	4	100	100
3/4	19.0	95	23.75	100	26	100	45	100	4	98.75	80-100
1/2	13.2	38	9.5	100	26	100	45	100	4	84.50	-
3/8	9.52	8	2	80	20.8	100	45	100	4	71.80	60-80
#4	4.75	-	-	8.4	2.18	95	42.75	100	4	48.93	48-65
#8	2.36	-	-	-	-	71.8	32.31	100	4	36.31	35-50
#30	0.60	-	-	-	-	44.3	19.49	100	4	23.94	19-30
#50	0.30	-	-	-	-	26.2	11.79	100	4	15.79	13-23
#100	0.15	-	-	-	-	8	3.6	90	3.6	7.20	7-15
#200	0.075	-	-	-	-	-	-	75	3	3.00	3-8

B. Asphalt Binder

Suez asphalt 60-70 was used in the study. Its specific gravity is 1.021, while its physical properties including penetration and viscosity are presented in Table (3).

Table (3): Properties of Asphalt Binder [11]

Property	AASHTO Designation No.	Result	Specifications Limits
Penetration at 25°c, (0.1mm)	T-49	65	60-70
Rotation Viscosity at 13 °c, (Cst)	T-201	378	≥ 320
Flash Point, (°C)	T-48	268	≥ 250
Softening Point, (°C)	T-53	52	45-55

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C. LDPE

Waste Plastic bags are made from Low Density Polyethylene (LDPE). LDPE has a high degree of short and long chain branching, which means that the chains do not pack into the crystal structure as well. The Properties of LDPE are shown in Table (6) and its shape is shown in Figure (6).

D. Lime

Limestone dust filler with bulk specific gravity 2.75 gm/cm^3 was used in samples preparation, its gradation is shown in Table (4) and its shape is shown in Figure (1).

Table (4): Gradation of Lime [12]

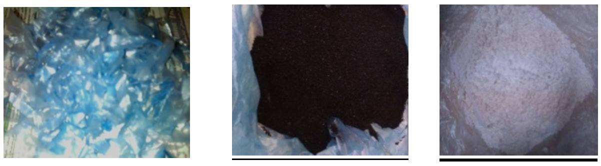
Sieve Size		% Passing	Specifications Limits
(inch)	(mm)		
No 30	0.6	100	≥ 100
No 50	0.3	100	-
No 100	0.15	90	≥ 85
No 200	0.075	75	≥ 65

E. Silica Fume (SF)

SF or micro-silica is a byproduct material. It can be produced by reduction of high-purity quartz with coal in electric furnaces in the production of silicon and ferrosilicon alloys. The physical composition of the used SF minerals is shown in Table (5) [14].

Table (5): Chemical Properties of Silica Fume [14]

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



Polymer (LDPE) Rubber Lime

Figure (1-a): Shape of Different Additives

Silica Fume Nano Silica

Figure (1-b): Shape of Different Additives

Table (6): Properties of Additives [12]

Type	Plastic Bags	Rubber	Lime	Silica Fume	Nano Silica
Molecular Formula	$(-CH_2-CH_2-)$ n	C_5H_8	$Ca(OH)_2$	Miro (SiO_2)	Nano (SiO_2)
Density (gm/cm^3)	0.910 - 0.940	1.07	2.75	2.07	-
Melting point (°C)	170 °C	125°C	-	-	-
Physical State	-	Clear Black Powder	Clear White Powder	Clear Grey Powder	Clear White Powder
Solubility	Insoluble	Insoluble	Soluble	Soluble	Soluble

F. Nano Silica (NS)

Nano Silica (NS) used in this research is produced in Faculty of science – Beni-Suef University. The chemical composition of NS is presented in Table (7) and Figure (2).

Table (7): Nano Silica Component [12]

Sample Name	SI	Calcite	0.28
Date	16-09-2015	Mulite	0
Time	23:28:32 PM	Magnetite	0
R_wp	6.64	Hematite	0
Alite_Sum	0	Thenardite	0
Lime	0.06	Rutile	0
Periclase	0.09	Si_amorph	99.15
Quartz	0.19		
Anhydrite	0.24		

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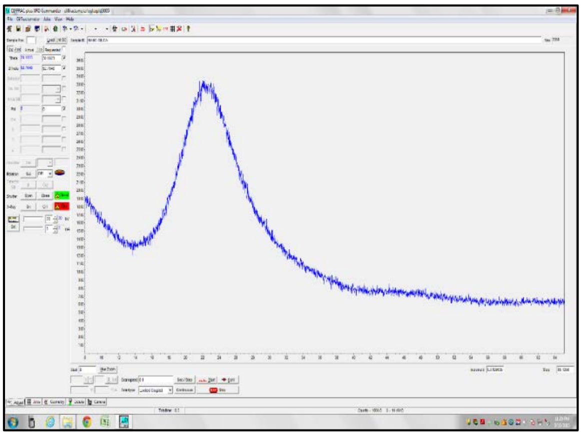

Figure (2-a): X-Rays Test of NS [12]

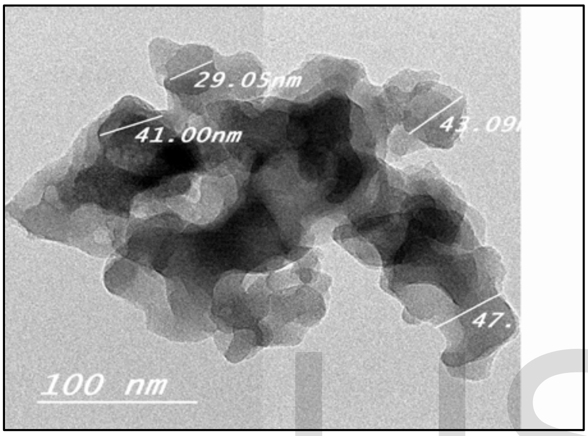

Figure (2-b): SEM of NS [12]

III. Testing Methods

Four test methods were used to evaluate and compare the obtained results of the asphalt concrete mixtures modified by using the different stated modifiers. The test methods include Marshall Test as per ASTM D 6927-06 to determine the properties of asphalt mixes. It was conducted on the control mix to get the optimum asphalt content and define the basic properties of such as stability, flow, unit weight, air voids, voids of mineral aggregate and voids of mineral aggregate. Then the test was conducted on the modified specimens by using Silica Fume, Nano silica, Rubber, Lime, and Polymer with optimum percentages 6, 7, 10, 5 and 4% respectively. The optimum percentages of the added modifiers were defined from the literature review. The second test is the Indirect Tensile Strength test (ITS) as per AASHTO T322-03 which used to evaluate the resistance of the asphalt concrete mixtures to the applied tensile stresses. This tensile stress causes the specimen to fail by splitting or rupturing along the vertical diameter.

The Direct Compression Test (DCT) as per ASTM D-1074 was conducted on the modified asphalt concrete mix specimens to investigate the behavior of the mix under crushing loads. DCT was used to evaluate compression strength of asphalt mix and comparison with another additive. The specimen is placed under compression force with various values of loads. Three specimens were prepared for this test for the control mix and similar three specimens were prepared and tested for each of the five types of modifiers. 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.

The fourth test is the Wheel Tracking Test (WTT) which used to measure the rutting depth of hot mix asphalt mixtures in the wheel-tracking device as per AASHTO (T324-04). The method describes the compaction procedure of asphalt mixtures in a reciprocating rolling-wheel device. This test provides information about the rate of permanent deformation from a moving concentrated load.

IV. Results and Discussion

A. *Asphalt* Cement Properties Evaluation

Characteristics of asphalt cement were examined for the modified specimens with different traditional and Nano additives. The comparison was made through conducting the penetration and viscosity tests on the modified specimens. Figure (3) shows the effect of adding different percentages of waste plastic bags, rubber, lime, Silica Fume and Nano Silica to the asphalt cement on the penetration test values. Results of penetration test indicated that the penetration value decreased for all modified samples. Waste plastic bags and lime record the lowest penetration, they decreased the penetration by 68% and 55.4% respectively. Adding Silica Fume, Rubber, and Nano Silica decreased the penetration by 46.2%, 21.5%, and 17% respectively.

Figure (4) shows the effect of adding different additives to asphalt cement on the viscosity values. Viscosity test results indicated that the viscosity increased for the all modified specimens using the different additives. Adding waste plastic bags and lime achieved the highest viscosity values; they increased the viscosity by 44.18% and 35.0% respectively. Silica Fume, Rubber, and Nano Silica increased the viscosity value by 30.16%, 15.1%, and 9.8% respectively.

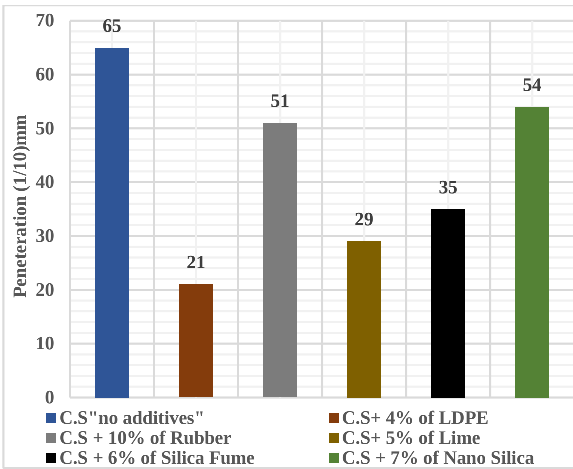

Figure 3: Effect of Different Additives on Penetration

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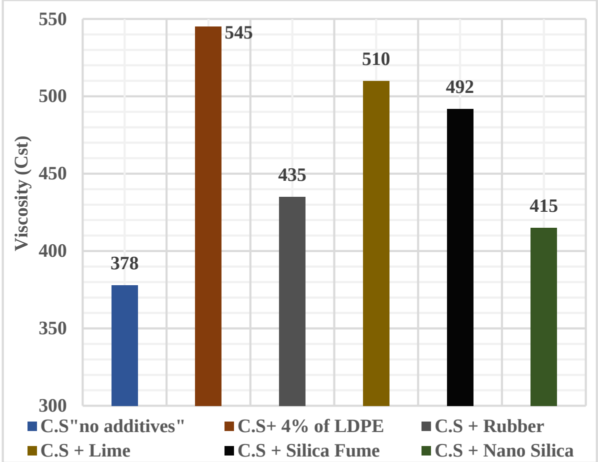

Figure 4: Effect of Different Additives on Rotational Viscosity

B. *Asphalt Mixtures Properties* Evaluation

1. Stability/Flow Evaluation

Figure (5) shows the effect of using different additives including traditional and Nano on the stability of asphalt mixtures. The additives were added to the mix at its optimum percentage as founded previously and the percentage of asphalt content was chosen as the optimum from Marshall Control mix. Results indicated that the maximum stability of modified asphalt using Nano Silica and Silica Fume was improved by 25% and 23.61% respectively. Waste Plastic Bags, Lime, and Rubber increase the stability by 21.32%, 19.69% and 12.84% respectively. Accordingly, Nano Silica and Silica Fume are the best additives in improving the stability of asphalt mixtures.

Figure (6) shows the effect of using different types of additives on the flow values of asphalt mixtures compacted at OAC and optimum additive content for each type. Results indicated that all types of additives decreased the flow value compared to the control mix flow value except that for adding Silica Fume which increased the flow value by 3.29%. Waste plastic bags decrease flow by 10.5%, Rubber decreases flow by 12.5%, Lime decreases flow by 14.47% and Nan0 Silica decreases flow by 19.08%. Accordingly, Nano Silica is considered the best additive in improving the flow of asphalt mixtures.

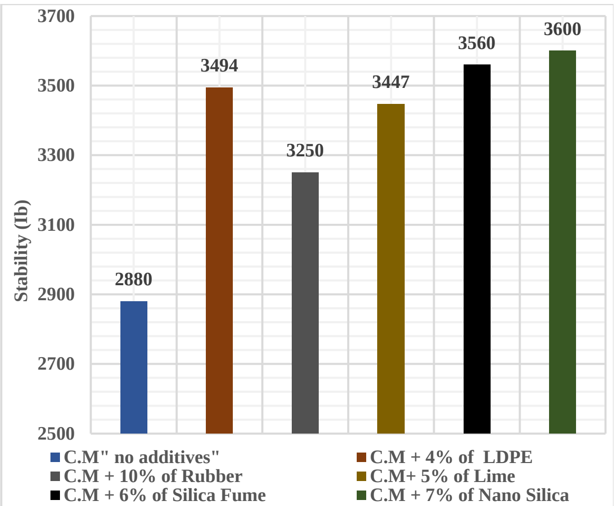

Figure 5: Effect of Different Additives on Stability

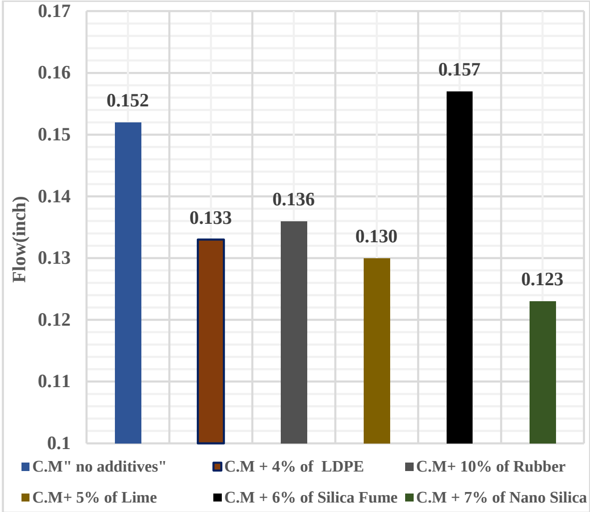

Figure 6: Effect of Different Additives on Flow

2. Unit Weight and Air Voids

Figure (7) shows the effect of using different types of additives on the AV% of asphalt mixtures at OAC. The Figure shows that at OAC, the air voids % for all types of additives increases compared to the control mix air void % although all obtained air voids percentages for all types of additives are still within the accepted specification limits. Waste plastic bags increases air voids by 8.75%, rubber increases air voids by 7.5%, lime increase air voids by 1.88%, Silica Fume increases air voids by 3.13% and Nano Silica increases air voids by 14%.

Figure (8) shows the effect of using different types of additives on the unit weight values of asphalt mixtures at OAC. Results indicated that the obtained unit weight for all types of additives ranges from 2.299 to 2.305 gm/cm^3. The higher unit weight is occurred when adding Silica fume and the lower unit weight is occurred when adding Rubber and Nano Silica.

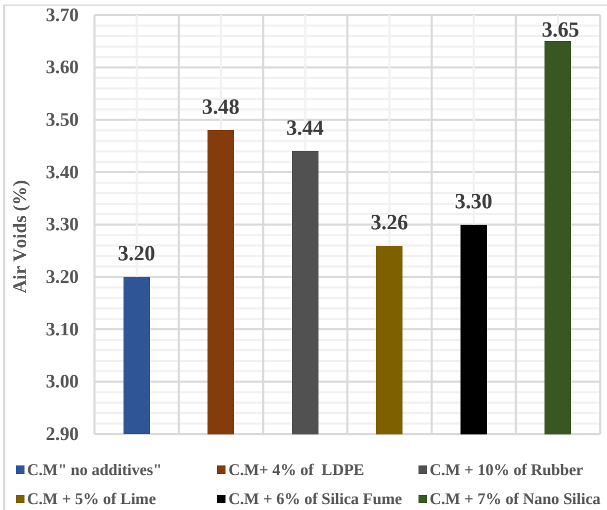

Figure 7: Effect of Different Additives on AV%

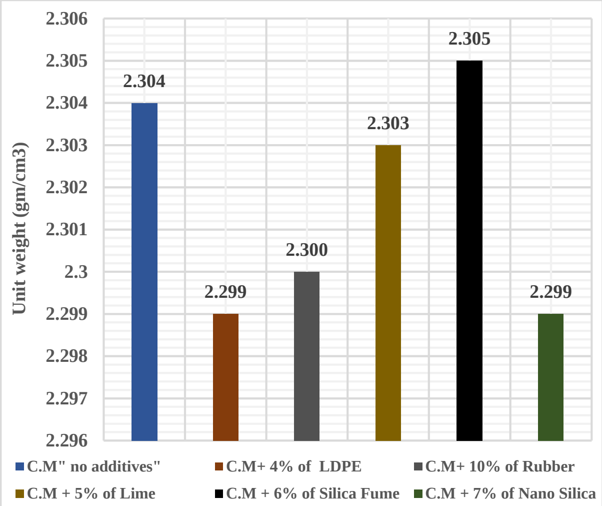

Figure 8: Effect of Different Additives on Unit Weight

Figures (9) and (10) show the effect of adding different types of additives on both of the Voids in Mineral Aggregates percentage (VMA) and the percentage Voids Filled with Bitumen (VFB). Results indicated that the % VMA is increases for all types of additives except the Silica Fume which decreases the % VMA. Results indicated also that the % VFB is decreased for all types of additives.

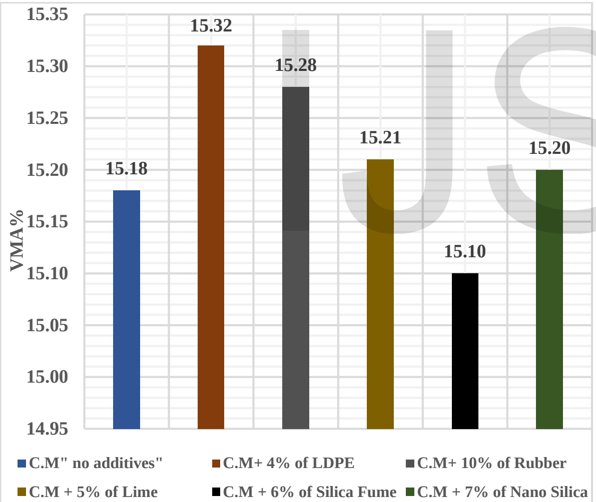

Figure 9: Effect of Different Additives on VMA%

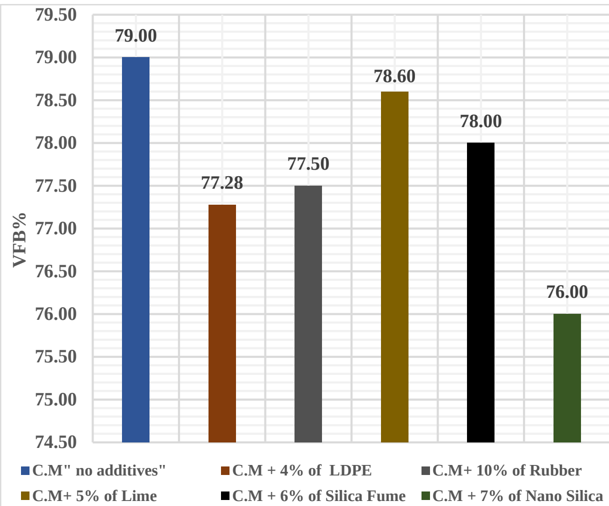

Figure 10: Effect of Different Additives on VFB%

Figure (12) shows the effect of using different types of additives on the stiffness value of the modified asphalt mixtures. Results indicated that the values of stiffness increases with all types of additives. Nano Silica seems to be the best additive that improves stiffness of asphalt mixtures by about 54.5%.

3. DC & ITS Evaluation

Figures 12 and 13 present the comparison between the Direct Compression test value and the Indirect Tensile strength values for the different used additives. Figures show that Silica fume achieved compressive strength with about 26.80% increase compared with the control mix. Figures show also that Silica Fume, LDPE and Nano Silica achieved approximately nearer Indirect tensile strength about 7% increase compared with the control mix.

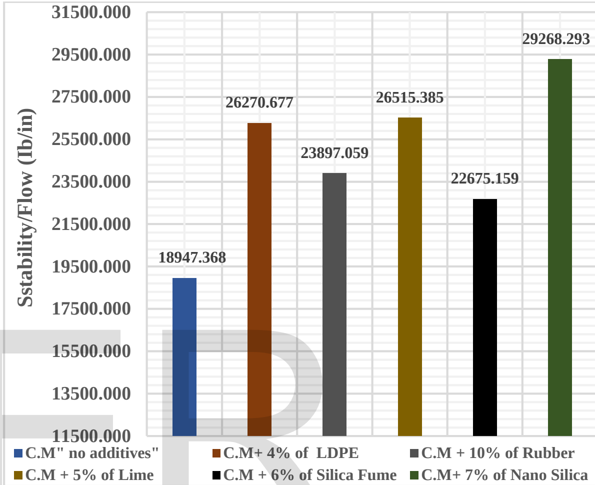

Figure 11: Effect of Different Additives on Stiffness

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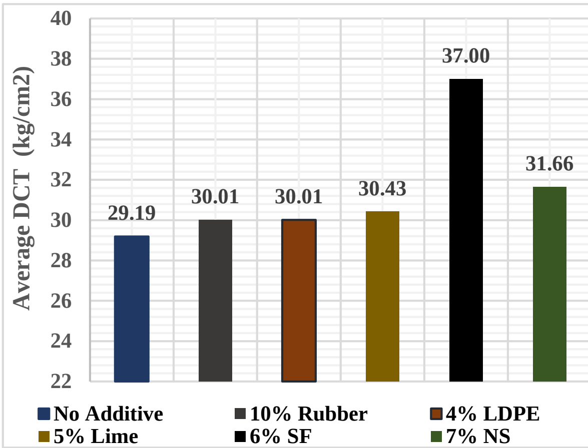

Figure 12: Effect of Adding Different Additives on DCT

4. Evaluation of Rutting Depth

Wheel Tracking Test (WTT) was performed on asphalt mix samples prepared at the optimum asphalt content obtained from Marshall Test. WTT test value is considered an important measure for the ability of the asphalt mixture to resist rutting. The WTT test was performed on asphalt mix samples containing optimum percentage of different types of additives. The results of WTT test are shown in figure (14). Results indicated that

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rutting depth increases with the increasing of time (direct relationship). The rutting depth values, at the end of the test, of modified asphalt mixes decrease the depth of rutting. All the used additives decreased the rutting depth but waste plastic bags are the best additive because it decreased the rutting to 4.572 mm. Rubber and SF decreased the rutting as the same result.

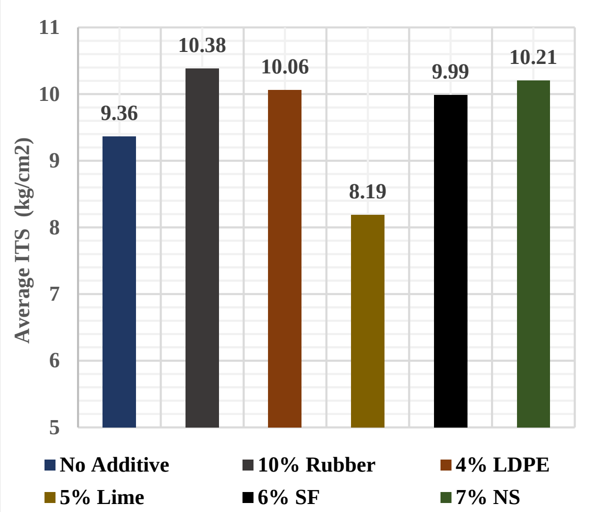

Figure 13: Effect of Adding Different Additives on ITS

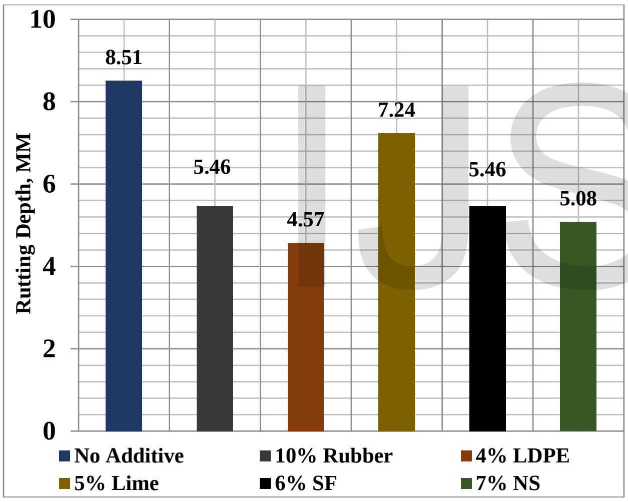

Figure 14: Effect of Different Additives on Rutting Depth

C. Economic *Evaluation of Modified Mixtures*

An economic study was conducting to differentiate between the direct costs of producing a constant quantity of asphalt mixture (1 M^3) using the different evaluated types of investigated additives. The cost analysis was based only on the direct cost of the materials constitutes the mixtures which includes Coarse Aggregate (CA), Fine Aggregate (FA), Mineral Filler (MF), Asphalt Cement (AC), and the used modifiers. The indirect production cost and profits were not included in this analysis since it shall be approximately constant for all mixtures.

Table 8 presents the properties of different modified mixtures using different modifiers. It shows the type of modifier and its related OAC, optimum modifier percentage, and the obtained mixture unit weight.

Table 9 presents the calculation of the materials direct cost of both of 1 M^3 and 1 Ton of each of the modified mixtures as well as the unmodified mix. The calculations were conducted based on the mix gradation shown on Table 2 as well as the obtained mixture properties shown on Table 8.

Table 8: Properties of Modified Mixtures

Additive Type	OAC	Additive, %	Unit Weight, Kg/M^3	Cost of Modifier, LE/Ton
No Additive	5.65	0	2304	0
LDPE	5.65	4	2299	15000
Rubber	5.65	10	2300	30000
Lime	5.65	5	2303	500
Silica Fume	5.55	6	2305	25000
Nano Silica	5.45	7	2299	7000000

Table 9: Cost Analysis Calculation of Direct Cost of Modified Mixtures Materials

Modifier Type	None	LDPE	Rubber	Lime	SF	NS
Modifier, %	0	4	10	5	6	7
Mix Unit Weight, Kg/M^3	2304	2299	2300	2303	2305	2299
OAC, %	5.65	5.65	5.65	5.65	5.55	5.45
Weight of M^3 Mix, KG	2304	2299	2300	2303	2305	2299
Weight of AC, Kg	130	130	130.0	130	128	125
Weight of CA, Kg	1109	1106	1107	1108	1110	1109
Weight of FA, Kg	978	976	977	978	980	978
Weight of Filler, Kg	87	87	87	87	87	87
Weight of Modifier, Kg	0.00	5.20	13.00	6.51	7.68	8.77
Cost of Modifier, L.E./Kg	0	15	30	0.5	25	7000
Cost of AC L.E./Kg	8	8	8	8	8	8
Cost of CA L.E./Kg	0.04	0.04	0.04	0.04	0.04	0.04
Cost of FA L.E./Kg	0.03	0.03	0.03	0.03	0.03	0.03
Cost of Filler L.E./Kg	0.5	0.5	0.5	0.5	0.5	0.5
Cost of 1 M^3, L.E.	1159	1234	1546	1161	1333	62514
Cost of 1 Ton, L.E.	**503**	**537**	**672**	**504**	**578**	**27192**

As shown on Table 9, the cost of production of 1 ton of the unmodified mix is 503 L.E., the same cost as using lime. While that for using LDPE is 537 L.E. and that for using Silica Fume is 578 L.E. and 672 L.E. using Rubber. The cost of using Nano Silica in production 1 ton is very high, it is about 27192 L.E. which represent about 5000 time the cost of unmodified mix.

Table 10 presents the percentage increase in the materials direct cost while Figures 15 and 16 presents the relative direct cost of them.

Table 10: % increase in Cost of 1 Ton of Modified Mixtures

Additives Type	Total Cost (LE/Ton)	% increase
None	503	0.00
Lime	504	0.20
LDPE	537	6.76
Silica Fume	578	14.91
Rubber	672	33.60
Nano Silica	27192	5305.96

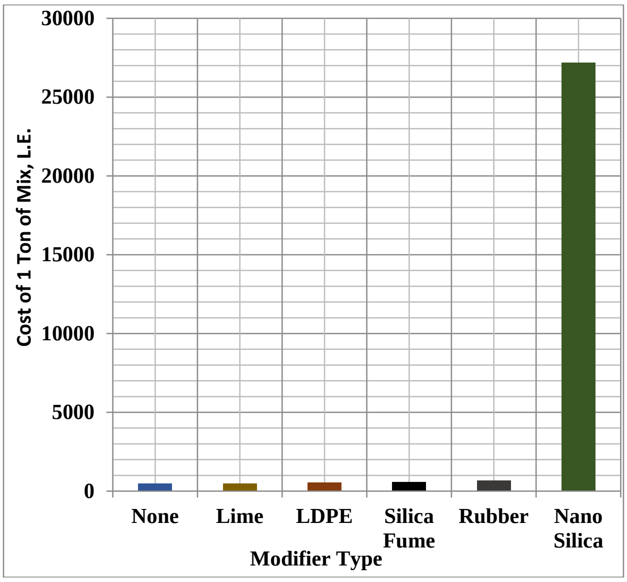

Figure 15: Cost of Production of 1 Ton of Mixtures

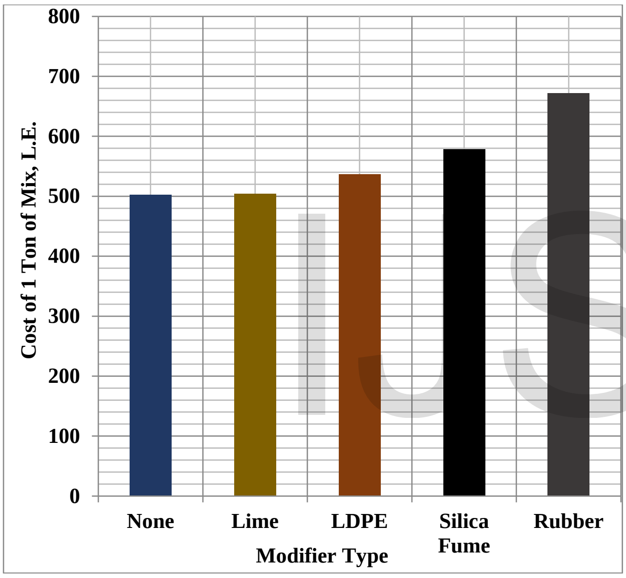

Figure 16: Cost of Production of 1 Ton of Mixtures Excluding Nano Silica

V. Conclusions

In this study, the performance of asphalt concrete mixtures modified by using different types of traditional and Nano materials was evaluated. Nano Silica is considered the best modifiers since they achieve the best performance.

Economic analysis of the materials direct cost of the used Additive indicated that Nano Silica is not applicable for use since it is very costly. It costs about 5000 times the unmodified mixture.

Silica Fume is considered the most appraisable additive in obtaining the good performance with moderate cost increase (about 14%).

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