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Finite Element Analysis of Performance of Asphalt Pavement Mixtures Modified using Nano Additives

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Abstract— In this study, a finite element analysis was performed to investigate and evaluate the pavement responses (Vertical Displacement and Total Stresses) for asphalt mixtures modified using different types of additives. The PLAXIS 2D Package software was used to simulate and model the proposed pavement structure. The proposed pavement structure consists of 10 cm asphalt wearing courses, 30 cm aggregate base course rested on subgrade material with CBR 15%. The infinity subgrade depth was represented in the model by depth 2.00 m. The asphalt layer was represented in the finite element model by five mixtures that modified by using five types of additives. The additives included Nano Silica, Silica Fume, Lime, Rubber, and Polymer. An experimental program was conducted to specify the Modulus of resilience and Poison's Ratio for each of the modified mixtures as well as the control mix. The finite elements analysis results of the tested mixtures indicated that the asphalt mixture modified using silica fume is the most resisting deformation and stresses under different traffic loads.

Index Terms — Finite Elements, Modified Asphalt Mixtures, Pavement Performance, Pavement Responses.

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1 INTRODUCTION

VARIOUS empirical methods have been developed for analyzing flexible pavement structures. Due to limitations of analytical techniques developed in the 1960's and 1970's, the design of flexible pavements is still largely based on the empirical method. Huang stated that the disadvantages of the empirical methods are the limitations of certain set of environmental and material properties. The study was stated also, that if the conditions are changed, the design is no longer be valid [1].

The recent technique is the mechanistic-empirical method which can simulate the wheel load and determine the stress and strain in the pavement. The mechanistic method is more effective for analyzing data than empirical method. However, the effectiveness of any mechanistic design method depends on the accuracy of the expected stresses and strains. Due to their flexibility and power, Finite Element (FE) methods are increasingly being used to analyze flexible pavements.

Flexible pavement can be simulated using FE by several methods; two-dimensional (2D) and three-dimensional (3D) FE. Turner et al. presented a concept method of finite elements [2]; Zienkiewicz, Taylor and Reddy devoted the theory and application of the method.

Two-Dimensional (2D) models were the first successful examples of the application of the FE method and since it was beginning, the literature on FE analysis has been grown exponentially [3, 4]. The FE method relies discretizing a domain into a number of smaller elements, each of which is responsible for capturing variations in displacements, strains, and stresses over its area or volume; Equation (1) gives the relationship between element nodal displacements and strains.

$E = S * U$ ……………............... (1).

Where, E is the strain vector; S is a suitable linear operator and U is the nodal displacement vector.

In order to overcome the limitations of layered elastic analysis and 2D FE methods, 3D FE methods are increasingly being developed to model the response of flexible pavements. 3D FE modeling is widely viewed as the best approach to understand pavement performance.

A pavement system is typically modeled as a multilayered structure with different materials properties. Interface elements or springs can be used to transfer the shear between layers, and well-controlled boundary conditions are critical to analyze the behavior of the entire pavement system [5]. Several researchers have shown that spatially varying contact pressures between the tire and pavement can significantly affect the pavement responses, Tielking et al., and Weissman [6, 7].

Metwally, et al., studied the effect of modifying the asphalt mixtures using Nano Silica. They studied the properties of the mixtures after adding the modifiers by different percentages. They used Nano Silica (NS) as Nano additives and the lime, rubber, and Low density Poly Ethylene (LDPE) as traditional modifiers. They found that the optimum percentages of the mentioned modifiers are 7%, 5%, 10% and 4% respectively [8].

Metwally, et al., studied the effect of modifying the asphalt mixtures using Silica Fume and Traditional additives. They studied the properties of the mixtures after adding the modifier by different percentages. They used Silica Fume (SF) as Nano additives and the lime, rubber, and Low density Poly Ethylene (LDPE) as traditional modifiers. They found that the optimum percentages of the mentioned modifiers are 6%, 5%, 10% and 4% respectively [9].

Metwally, et al., conduct a comparative study of the effect of modifying asphalt mixtures using different types of Nano and Traditional additives. They studied the properties of the

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mixtures after adding the modifiers at the optimum percentages of each of them. They found that Nano silica and Silica Fume are the most effective modifiers in enhancement of mixture properties. The economic appraisal indicated that the Silica Fume modifier is considered the best additive [10].

2 OBJECTIVES AND METHODOLOGY

The main objective of this study is to use the finite element modeling and technique to investigate and evaluate the effect of using the nano and traditional additives in asphalt mixtures modification on the pavement responces, vertical displacement and stresses, of the modified mixture.

To achieve the above objective, the study included two basic steps; the first step included the laboratory work that included preparation of five modified asphalt mixtures using the five proposed additives; Nano Silica, Silica Fume, Lime, Low Desnsity Poly Ethylene and Rubber to define the basic parameters of the modified mixtures; Modulus of Resilience and Poison's Ratio.

The second step included defining the finite element program Plaxis 2D package that used for performing the analysis and evaluation of the pavement responses (Vertical Displacement and Total Stress) for the modified mixtures and compare the obtained results with those obtained for the unmodified control mix.

3 TRAFFIC LOAD SIMULATION

Previous researches indicated that the traffic load was presented as a pressure values applied on circular contact area. Faheem and Hassan simulated the traffic load by 50, 100, 200, 300, 400, 500 and 600 kpa on a circular area with radius of 0.20 m in Plaxis program [11]. These load values represent the variation and the expected traffic loads. Also, Lacey et al., simulated the traffic load by a high uniform pressure value of 800 kpa on a circular area with radius of 0.20 m in ANSYS program [12].

Therefore, in this research, the traffic load is simulated by load pressures of 100, 200, 300, 400, 500, 600 and 700 Kpa acting on a contact circular area with radius 0.20 m between the pavement surface and wheel load. Figure1) shows the load distribution of flexible pavement under wheel load.

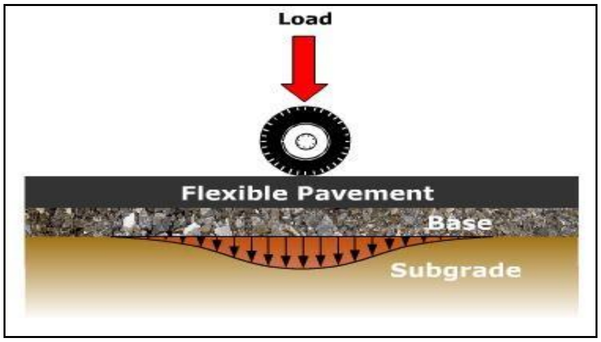

FIGURE 1. FLEXIBLE PAVEMENT LOAD DISTRIBUTION

4 PAVEMENT SECTION

Six pavement sections were selected to conduct the finite element analysis; they considered the change of the properties of the asphalt layer with constant base and subgrade layers. The asphalt layer parameters that used in the modeling process included Modulus of Elasticity and Poison's Ratio. The properties of the aggregate base course were taken from the modeling conducted by Faheem and Hassan [11], while the properties of the subgrade layer were taken from the modeling conducted by Mostafa et al. [13] as shown in Table 1.

TABLE (1)

BASE AND SUBGRADE LAYERS PROPERTIES [11, 13]

Layer / Property	Base Course	Subgrade
E, (Kpa)	100000	11900
N	0.35	0.25
γdry, (KN/m^3)	20.00	20.25
γ Saturated, (KN/m^3)	22.00	22.72
C, (Kpa)	30	30
φ, (deg.)	43.00	36.97
ψ, (deg.)	13.00	6.97

5 FINITE ELEMENT ANALYSIS

Recently, the use of finite element analysis has increased due to the enhancement of computer capabilities. The finite element (FE) technique is successfully used to simulate different pavement problems that could not be modeled using the simpler multi-layer elastic theory [14].

This research comprises the concept of FE to evaluate the effect of modifying the properties of asphalt layer using Nano and traditional modifiers on the pavement responses. The model is conducted to develop different relationships between the asphalt layer properties and the pavement responses; Total Stress (TS) and Vertical Displacement (VD) for the modified asphalt mixtures using LDPE, Rubber, Lime, Silica Fume (SF) and Nano Silica (NS).

The Plaxis 2D software package was used to develop the the pavement structure model that represents the actual field pavement section that is famous to be used in many situations.

5.1 Development of the FE Model

The developed pavement section structure of the Model consists of asphalt concrete (AC) layer, base course layer and subgrade layer. The geometry of the developed models is shown in Figures 2.

The thickness of asphalt surface layer is 10 cm and base layer thickness is 30 cm. The dimensions of the subgrade layer are assumed to be 5.00 m wide and 2.00 m depth which considered infinite in both the horizontal and vertical directions.

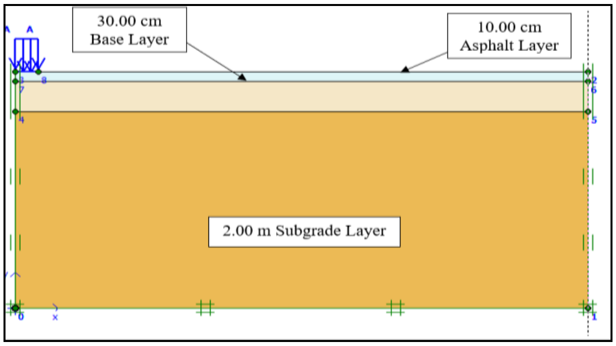

FIGURE 2. PROPOSED PAVEMENT STRUCTURE MODEL

6 EXPERIMENTAL WORK PROGRAM

A laboratory testing program was conducting to define the modified asphalt mixtures properties that include the Modulus of Resilience (Mr) and the Poison's Ratio (ν). Table 2 presents the properties of the used aggregates that include coarse and fine aggregates.

Different specimens were prepared for the different modifiers with the optimum modifier's contents that specified from the previous research of the Authors. The FE Model requires the basic properties of the pavement layers that include the Modulus of Resilience and the Poison's Ratio.

To define the required parameters of the modified mixtures, compression tests were conducted on the modified mixtures as well as the Control Mix. The Modulus of elasticity was measured from static load. The stress was measured from dividing the compression load on the specimen affected area, the vertical strain is the ratio between the difference changes in height related to the specimen height. Modulus of Elasticity is expressed by vertical stress per vertical strain. Poison's ratio is calculated as the ratio between horizontal and vertical strains. The height, diameter, horizontal displacement and vertical displacement are measured by Vernier caliper tool.

Table 3 presents the results of the testing program. It shows the obtained Modulus of elasticity and the Poison's Ratio for the modified asphalt mixtures and the control mix.

TABLE 2
AGGREGATE PROPERTIES USED IN MODELING

Property	AASHTO No.	Coarse Agg. Size (1)	Coarse Agg. Size (2)	Fine Agg.	AASHTO Limits
Los Angeles Abrasion	ASHTO T 96	35.20%	31.4%	---	40 Max
Bulk Specific Gravity	AASHTO (85-77)	2.495	2.505	2.64	---
Saturated 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

TABLE 3
ASPHALT MIXTURES PROPERTIES USED IN MODELING

Type	Modulus of Resilience (KN/m^2)	Poison's Ratio	Unit Weight (KN/m3)
Control Mix	38178.395	0.336	22.595
10% Rubber	43360.650	0.320	22.555
4% LDPE	40502.168	0.329	22.545
5% Lime	81390.243	0.357	22.585
6% SF	112376.266	0.374	22.604
7% NS	83044.721	0.364	22.545

7 RESULTS AND DISCUSSION

Plaxis 2D program was used for modeling the pavement structure considering the mentioned thickness of different layers and seven pressure loads (100, 200, 300, 400, 500, 600 and 700 kpa), and six types of asphalt mixtures; control mix and five modified mixtures. The basic pavement section consists of the control mix asphalt surface over the aggregate base course lying on the assumed subgrade; whereas the modified pavement section consists of the modified asphalt layer using either of the NS, SF, LDPE, Rubber, or Lime lying on the same base course and subgrade layers.

Different runs were processed by Plaxis 2D Program to specify and investigate the Vertical Displacement (VD) and the Total Stress (TS) for the considered pavement sections. The obtained results are presented and analyzed in the following paragraphs.

7.1 Investigation of the Vertical Displacement (VD)

The typical deformed shape of Vertical Displacement (VD) and VD distribution of the tested model are shown in Figures (3) and (4) respectively. Table 4 and Figure 5 present the obtained vertical displacements of the investigated modified and unmodified pavement sections under different load pressures.

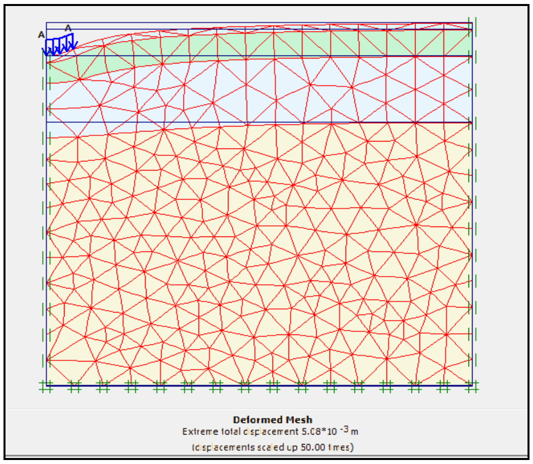

FIGURE 3. TYPICAL VD IN PLAXIS

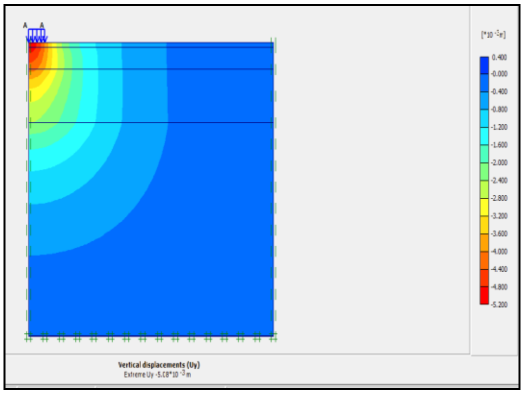

FIGURE 4. TYPICAL VD DISTRIBUTION IN PLAXIS

TABLE 4

THE OBTAINED VD IN PAVEMENT SECTIONS UNDER DIFFERENT TRAFFIC LOADS

Wearing Surface Type	Vertical Displacement VD (mm)						
	Load Pressure, (KPa)						
	100	200	300	400	500	600	700
Control Mix	0.975	1.97	2.99	4.04	5.16	6.35	7.59
10% Rubber	0.959	1.94	2.94	3.98	5.07	6.23	7.46
4% LDPE	0.967	1.96	2.96	4.01	5.12	6.29	7.52
5% Lime	0.837	1.70	2.58	3.51	4.48	5.52	6.60
6% SF	0.793	1.61	2.46	3.34	4.26	5.24	6.26
7% NS	0.831	1.69	2.57	3.49	4.45	5.48	6.54

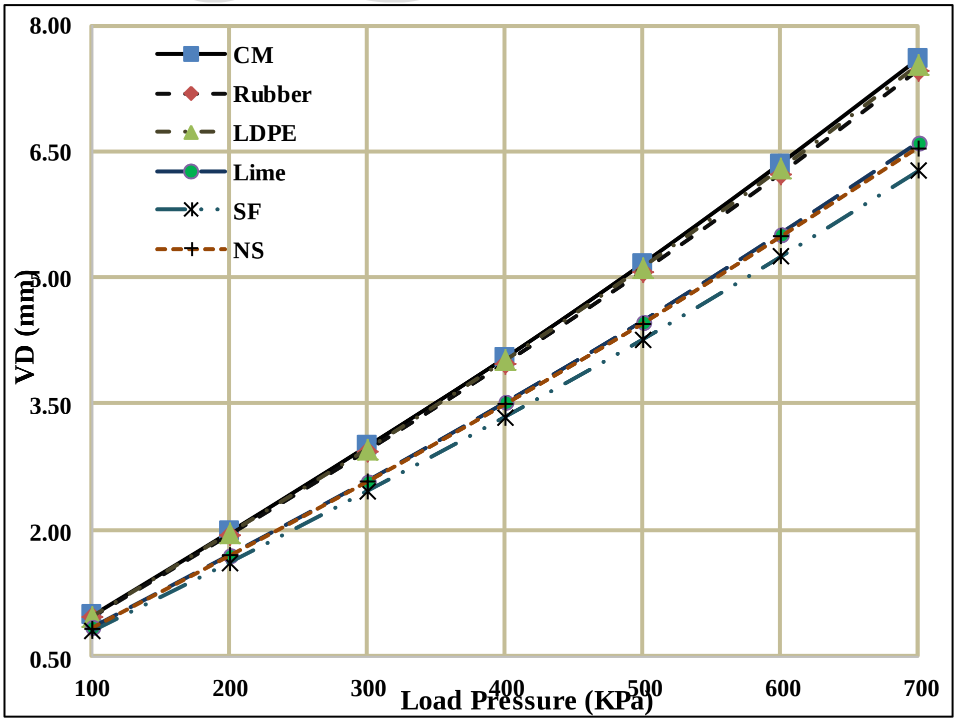

FIGURE 5. MAXIMUM VD VERSUS APPLIED PRESSURE

Figure 6 shows the obtained VD values at the maximum load pressure 700 kpa for both cases of unmodified and modified asphalt layer. The developed Models investigated the effect of applying the maximum pressure load of 700 kpa on the proposed pavement structures because this value is considered the maximum pressure load that nearly equivalent to the 18000 lb single axle load according to AASHTO guide for pavement design.

The figure also shows that the VD value is 7.59 mm at 700 kpa pressure load for the unmodified layer. Whereas, for the modified layers using Rubber, LDPE, Lime, SF and NS the VD was reduced to 7.46, 7.52, 6.60, 6.26 and 6.54 mm respectively. This means that the VD reduction percentages are 1.71%, 0.92%, 13.04%, 17.52 % and 13.83%, respectively.

The above results indicate that no significant change is occurred using both LDPE and Rubber; in contrast using Lime, SF and NS introduce a major enhancement in the pavement section performance. This enhancement is due to the increase in stiffness (rigidity) of the pavement section by increasing the modulus of resilient of the asphalt layer keeping the sub-layers properties constant. The chemical composition of SF as well as its fine particles penetration into the mixture voids that result in obtaining a dense mixture that has a capability to resist the vertical deformations.

Results indicates that modifying the asphalt mixture using Silica Fume is considered the best modifiers that achieve the lowest vertical displacement under the effect of the maximum traffic load.

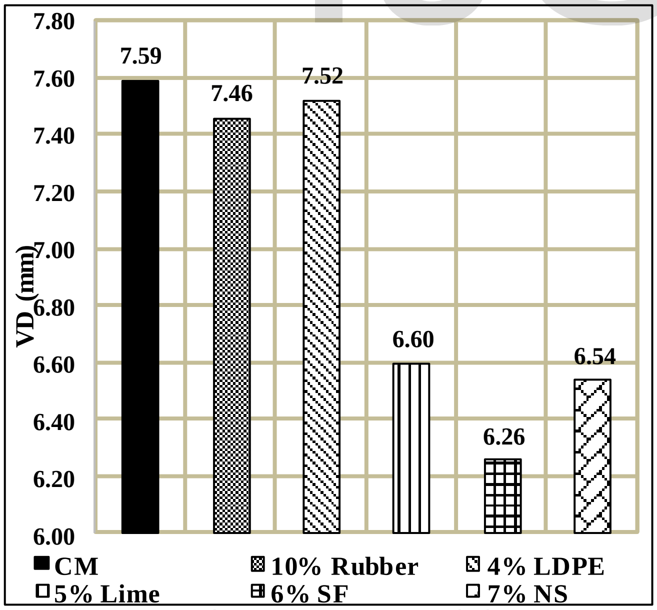

Figure 6. Maximum VD Versus Applied Pressure at Load = 700 kpa

7.1 Investigation of the Total Stress (TS)

This section investigates the effect of using the modified additives to the asphalt layer on the TS developed under the applied pressure. Figure 7 illustrates the typical stress distribution under the applied pressure in Plaxis Model. Table 5 presents the typical TS distribution in all section's types.

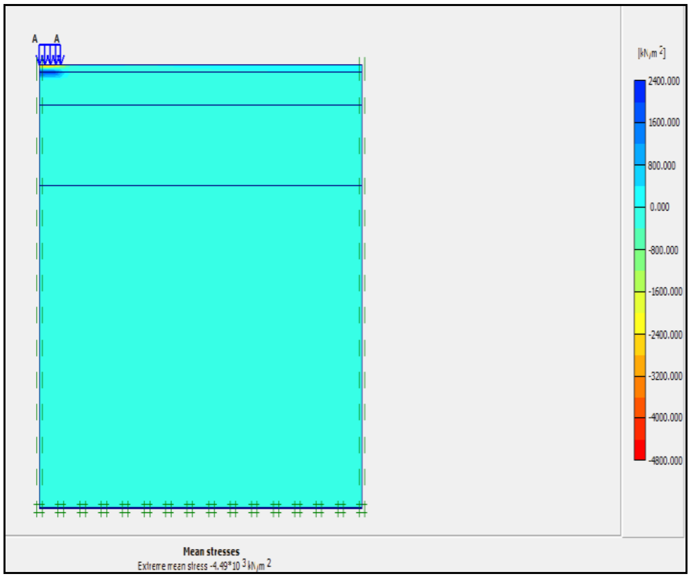

Figure 7. Typical Total Stress (TS) Distribution in Plaxis Model

Figure 8 shows the TS versus load pressure for the control mix and the modified asphalt layer mixtures. The figure shows that the TS value is 744.22 Kpa at load 700 kpa for the control mixture, while its values were decreased to 743.06, 743.75 when modifying the asphalt layer by Rubber and LDPE respectively.

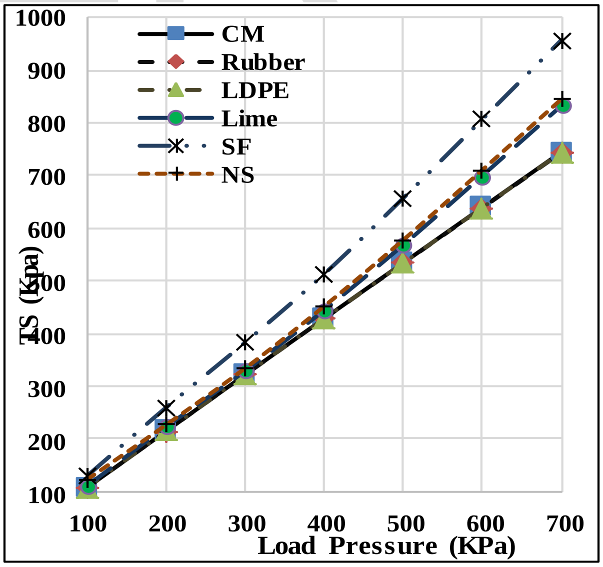

Figure 8. The TS versus load pressure for different Mixes

Table 6 presents the percentages change in TS for the tested sections. The relationships between the percentage changes in the TS for the tested sections at various applied load pressures are shown in Figure 9.

TABLE 6

PERCENTAGE REDUCTION IN TOTAL STRESS FOR DIFFERENT PAVEMENT SECTIONS

Wearing Surface Type	TS % Change						
	Load Pressure, (Kpa)						
	100	200	300	400	500	600	700
Control Mix	0	0	0	0	0	0	0
10% Rubber	-0.07	-0.07	-0.07	-0.07	-0.12	-0.15	-0.16
4% LDPE	-0.04	-0.03	-0.03	-0.03	-0.04	-0.06	-0.06
5% Lime	2.91	3.81	2.22	3.71	6.38	9.41	11.81
6% SF	20.38	20.94	19.06	19.75	23.05	26.14	28.56
7% NS	13.95	5.53	3.78	5.44	8.17	11.1	13.47

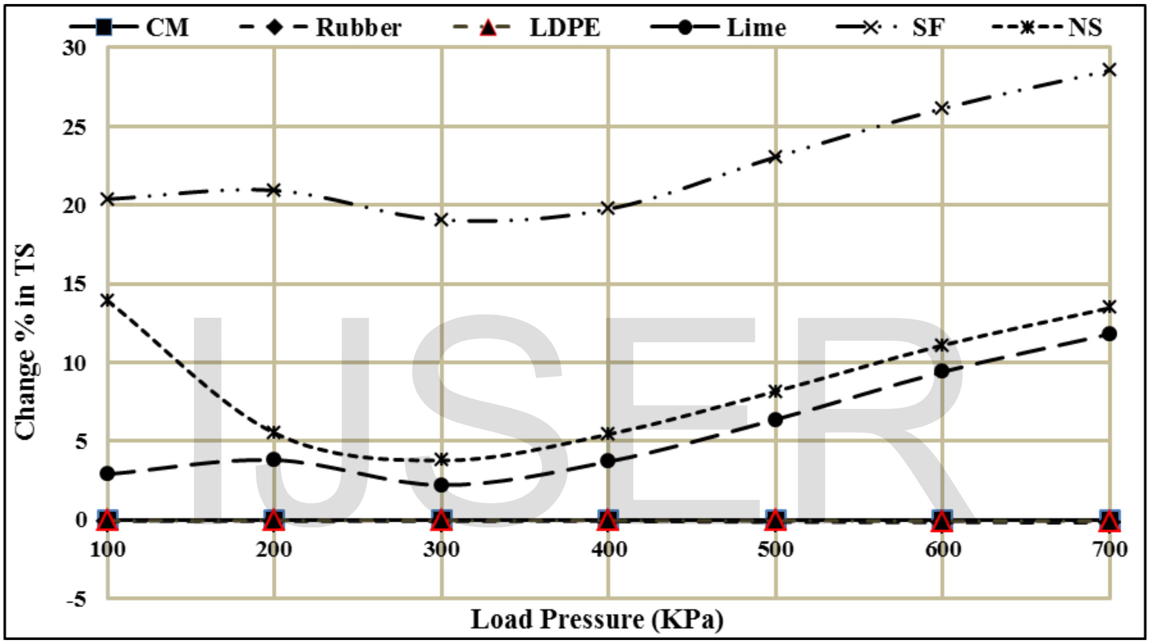

FIGURE 9. PERCENTAGE CHANGE IN TS VERSUS LOAD PRESSURES FOR DIFFERENT PAVEMENT SECTIONS

Figure 9 shows that no significant changes in the TS were occurred for asphalt layer modified with LDPE and Rubber but significant changes in TS were occurred for asphalt layer modified with Lime, SF and NS. The Figure shows that the SF is considered the most additive that achieve greater TS in the pavement sections; about 28% increase. Results indicates that modifying the asphalt mixture using Silica Fume is considered the best modifiers that achieve the greater Total stress under the effect of the maximum traffic load.

8 CONCLUSION

In this study, a finite element analysis was conducted to investigate and evaluate the responses (Vertical Displacement and Total Stress) of asphalt mixtures wearing course modified using different types of Nano and Traditional additives. The used additives included Silica Fume and Nano silica while the traditional additives included Lime, Rubber and Low Density Poly Ethylene. A laboratory testing program was conducted to define the modulus of Elasticity and Poison's Ratio of the used asphalt mixtures that are considered the basic input parameters in modeling pavement section in Plaxis 2D software program. The following conclusions were obtained from the analysis of the modeled modified pavement sections:

- No significant changes in Vertical Displacement and Total Stress were obtained when modifying the asphalt mixtures using Rubber or Low-Density Polyethylene.
- Significant changes in Vertical Displacement and Total Stress were obtained when modifying the asphalt mixtures using Lime, Silica Fume and Nano Silica.
- Modifying the asphalt mixture using Silica Fume is considered the best modifier that achieves the lowest vertical displacement under the effect of the maximum traffic load. It achieves about 17% reduction in VD compared with the unmodified mixture.
- Modifying the asphalt mixture using Silica Fume is considered the best modifier that achieves the greater Total Stress

under the effect of the maximum traffic load. It achieves 28% increase in TS compared with the unmodified mix.

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