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Numerical Simulation of the Effect of Repeated Load and Temperature on the Behavior of Asphalt Layers

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HIGHLIGHTS

- The composite effects for wheel loads and temperature were considered in the finite element analysis using Abaqus 6.14
- Increasing the asphalt layer thickness leads to a decreasing in the vertical displacement of about 0.59%
- Decreasing in the vertical displacement by 0.77% when the temperature increases to 50℃.

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ABSTRACT

Roads and highways are used by different vehicle types, and the heavy vehicles among them can be considered the most critical in loading, which causes failure in the pavement structure and increases rehabilitation and maintenance costs. In this study, the composite effects for wheel loads and temperature were considered in the finite element analysis using Abaqus 6.14. The asphalt layer was modeled as an elastic material, while the base and subbase layers were modeled as an elastoplastic material following the Mohr-Coulomb model. Also, the impact of wheel loads on flexible pavement settlement and the main output of analyzing pavement structure are almost represented by the vertical stresses and the surface deformation, which are considered the critical response point. A single unit truck was tried with two thicknesses of the asphalt layer, 14 cm, and 25 cm, with two different temperatures. Since base and subbase layer thicknesses remained constant, it does not affect the displacement variation. However, it was found that the increase of asphalt layer thickness from 0.14 m to 0.25 m leads to a decrease in the vertical displacement of about 0.59% and becomes 0.77% when the temperature increases to 50℃.

1. Introduction

Asphalt pavement fatigue life depends on mechanical and geometrical properties of layers and on conditions of applying load for the determination of asphalt pavement fatigue life in the laboratory is expensive and time consuming, so it is preferred for investigating this phenomenon by using numerical methods or the available theoretical approaches.

There are many complicated problems in structural, geotechnical, and pavement analysis. Therefore, for a limited class of load characteristics and simple geometric shapes, precise mathematical solutions can be solved for their differential equations, therefore a numerical technique was found to obtain the required solution. And the most used technique is the well-known method of the finite element that is used to achieve an approximate solution for a realistic type problem.

Ai et al. [1] intended to provide theory to select a suitable structure of asphalt pavement that can district with the large changes in temperature by using coupled thermal stress and transient thermal analysis and found that asphalt pavements with flexible bases like asphalt treated granular base (ATB) and crushed stone mixing with 2% cement and well-performed under big changes of temperature, therefore, flexible base considered suitable in a cold area, zones with high latitude and districts by large change of the temperature.

Chen et al. [2] built a model of asphalt pavement with a field of thermal stress continuous temperature changing by the analysis of finite element Abaqus software and studied the effect in changing the parameters of pavement material on thermal stresses. results showed that temperature-dependent elastic modulus, Poisson's ratio, and temperature contraction property can influence thermal stress and has a great influence when the three parameters change with the temperature at the same time.

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Beskou et al. [3] modeled pavement structure as a three-layer system with asphalt concrete as a top layer exhibiting viscoelastic or viscoplastic and other layers with Drucker Prager (elastic or elastoplastic) in the Ansys program and showed that elastic models with static loading estimate true pavements responding and should not use in the design meanwhile viscoelastic model give a close response to the true one under the condition of dynamic and static loading.

Jiang et al. [4] used a three-dimensional finite element model for investigating the effect of applying 6 nonuniform contact stresses distribution on the response of flexible pavement. It was shown that non uniformity has a significant effect on the shear strain of pavement structure that affects zone distributed mainly on the top and middle parts of the asphalt concrete surface layer .and the nonuniformity has a major effect on tensile strain at the bottom of the asphalt concrete layer.

Hernandez & Al-Qadi [5] studied interactions between the deformable tire with the road surface by using a validated model of finite element. Tire rubber and reinforcing materials are considered super-elastic and linearly elastic, respectively. The stiffness of the road surface increases the dissipation caused by friction by 9.3%, and the resistance of rolling is reduced by 5.2% of the hardest road to softest road, also though tires with road elasticity.

Albayati and Saadi [6] used “Kenlayer” software to estimate tensile strain at the bottom of asphalt layer and the compressive strain at the top of the subgrade layer and showed that the maximum allowable single axle load during the winter season is 15 tons and 9 tons during the summer season and permitted load of 13 tons for the single axle load and dual tire instead of 9 tons as per current local specification and that result in loss of one-quarter of pavement design life and the tensile and compressive strains increased with axle load increasing and decrease with asphalt layer resilient modulus increasing and that fatigue life decrease with axle load increasing.

Aarabi and Tabatabaei [7] conducted a study on many realistic models that developed to represent the effect of thickness variation of the asphalt mixtures with concerning time and the rate dependent of asphalt concrete behavior by employing viscoelasticity theory and results show that base course influenced by the variation of asphalt thickness and the thinner the lesser ability to reduce loading pressure, and showed that the compressive stress at the top of the subgrade that affected by the asphalt thickness and stress-induced history.

Jasim et al. [8] focused on two main goals. First, check the influence of the geogrid (Tensar SS) on the traditional flexible pavement on the subgrade. The second one determines the best location to integrate the pavement system with the geogrid. To quantify the effectiveness of the geogrid in the flexible pavement structure, a simulation by 3D finite element was carried out by using a thick base pavement structure. To determine a better location to install geogrid on the road, two different geogrid positions were implemented. When the geogrid position changes in the proposed pavement structure, constant load conditions are applied. The study determined two different conclusions. First, the performance of the pavement can be improved by implementing a single geogrid layer in the upper third of the layer. Second, to achieve structural stability, the subgrade-base layer interface may require a geosynthetic stabilizer layer.

The objectives of this research are studying the deformation behavior of pavement layers using finite element (FE) simulations under given conditions and investigating the effect of axle load and pavement layer thicknesses increase on the overall pavement life.

From data collected from the critical national highway to compute the impact of vehicles on the vertical displacement of pavement structure to investigate the impact of temperature change during the day and its long term influence on the pavement fatigue life, two different temperatures were studied by the finite element analysis with building a model of asphalt pavement by a field of thermal stresses and studied the effect of changing parameters: elasticity and thickness of asphalt layer and the effect of increasing wheel load with various temperatures is also considered.

2. Problem Definition

The system of asphalt pavement used in (Abaqus 6.14) software consisted of asphalt concrete layer and local base layer, granular subgrade layer and natural subgrade layer. The dimensions of the pavement model are: the length is (x) direction and (y) direction is the width of the model, and the total thickness of the pavement structure is (0.5 m) above natural subgrade depth of (2 m). Asphalt concrete layer thickness is (0.25 m) while the base layer thickness is (0.3 m) as shown in Figure 1.

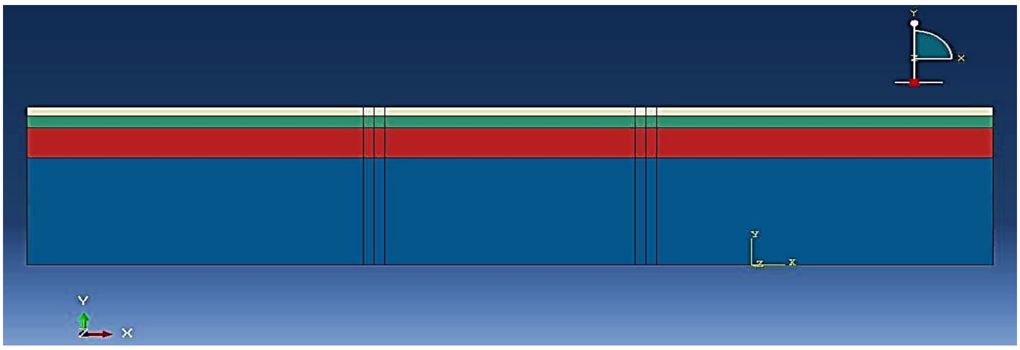


Figure 1: Schematic of asphalt pavement structure layers using Abaqus program

In mesh generation, at the model of pavement structure mesh was created for the use of small step time, the mesh consists of (930) elements (2945 nodes) and a CPE8R (8 nodes biquadratic plane strain quadrilateral, reduced integration) element and three degrees of freedom (2D space) as shown in Figure 2.

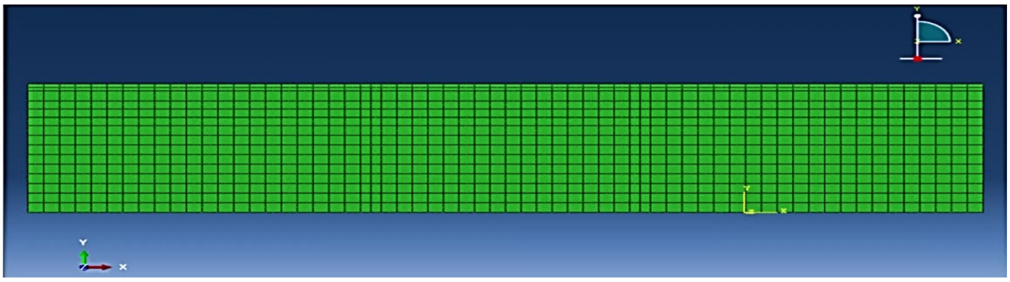


Figure 2: Mesh geometry by using ABACUS software for the model of asphalt pavement layers

For applying boundary conditions, degrees of freedom on the bottom of the model and for both front and rear lateral surfaces were fixed perpendicular to the shear surface, as shown in Figure 3.

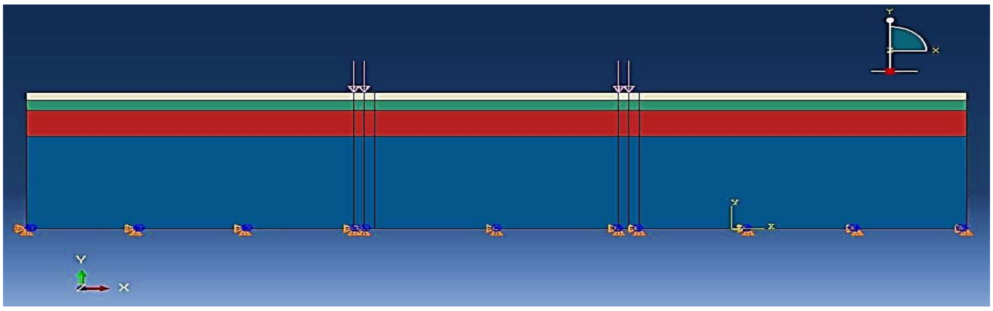


Figure 3: Boundary conditions by using ABACUS software for the model of asphalt pavement layers

3. Numerical Simulation

Since the crack of the road surface is usually subjected to many variables and complex states of traffic loading, Abaqus (finite element method) could be used as a powerful tool to estimate and investigate their deformation. The Asphalt layer was modeled as a viscoelastic model to simulate the real hot mix asphalt combines as elastic viscous and plastic properties that are significant at the high temperature especially. The use of a viscoelastic model could be sufficient for describing the real response of the asphalt layer at high temperature. The bottom layers of the pavement were modeled by the Mohr Coloumb material model that was used for analyzing the granular material at the low stress level [9]. Table (1) lists the material properties of pavement while Table (2) presents the thermal properties of asphalt materials.

Table 1: The input of flexible pavement layers properties

Layer	Thickness (cm) *	E (MPa) *	Density (kg/m^3) *	Poisson's ratio*	Friction angle ϕ (°)**	Dilation angle (°)**
Asphalt	14	508	2305	0.35	-	-
Local base	20	275.79	2334	0.35	38	8
Local subgrade	42	211.53	2288	0.4	40	10
Subgrade	200	34.47	1789	0.45	-	-

* Ministry of Construction, Housing Municipalities, and Public Works.
** From Hassan et al. [7].

Table 2: Thermal properties of flexible pavement layers

Layer	Thermal Conductivity k (W/(m.K)) *	Density (kg/m^3)*	Specific heat c (kJ/Kg/°C)*	Radiation**	Emissivity **	Stefan constant (W/m^2.k^4)**	Film coefficient (W/m^2.°C) ***
Asphalt	1.3	2210	800	0.9	0.81	$5.67*10^{-8}$	15.6
Local Base	1	2000	800	-	-	-	-
Local Subgrade	1.85	1900	750	-	-	-	-
Subgrade	-	-	-	-	-	-	-

* From Qin et al., [13].
** From Wang et al., [14].
*** From Yang and Liu, [17].

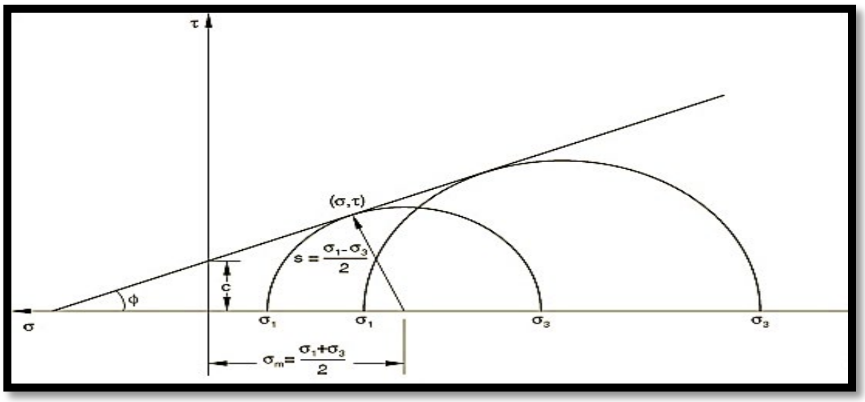


Figure 4: Mohr-Coulomb failure criterion

Mohr Coulomb failure criterion of strength is used widely in geotechnical applications and this theory assumed that failure is controlled by the maximum shear stresses which depend on the normal stress and it is represented by plotting the circle of Mohr to state stress at failure in terms of maximum and minimum principal stresses. The line of Mohr which is a straight line touches circles as shown in Figure (4) and the criterion of Mohr Coulomb is as follows:

$$\tau = \mathrm{c} - \sigma \tan\varphi \tag{1}$$

where **τ** is the shear stress, **σ** is the normal stress (negative in compression), ***c*** is the material cohesion value, and ***φ*** is the friction angle of the material.

From Mohr's circle.

$$\tau = \mathrm{s}\cos\varphi \tag{2}$$

$$\sigma = \sigma_m + s\ \sin\varphi \tag{3}$$

Substituting for **τ** and **σ**, the criterion of Mohr-Coulomb can be rewritten as:

$$s + \sigma_m\ \sin\varphi - c\ \cos\varphi = 0 \tag{4}$$

where:

$$s = \frac{1}{2}\,(\sigma_1 - \sigma_3) \tag{5}$$

Is half of the difference between the maximum and minimum principal stresses (and is, therefore, the maximum shear stress) and

$$\sigma_m = \frac{1}{2}\,(\sigma_1 - \sigma_3) \tag{6}$$

is the average of maximum and minimum principal stresses (normal stresses).

3.1 Thermal Stress Analysis Method

The transient of heat transferring is a process of cooling or heating where the temperature rate of heat transfer, boundary condition, and the dramatic change in internal energy that cause a large difference in the temperature of the system. According to the conservation energy law of transient heat transfer equilibrium equation is [1]:

$$[\acute{C}]\{\dot{T}\} + [\acute{K}][T] = \{Q\} \tag{7}$$

where:

$[\acute{C}]$ specific heats matrix, $[\acute{K}]$ The conductivity matrix, [T] Vector of The nodal temperature, and $\{\dot{T}\}$ Temperature to time derivatives. And $\{Q\}$ the nodal vector of heat flow rate.

In respect of hot mix asphalt temperature sensitivity, thermal parameters of the pavements materials like the coefficient of convection, conductivity, and emissivity, are the temperature field functions, written as follow:

$$\int_V \left([C^t(T)]\{\dot{T}\} + [K^t(T)]\{T\}\right)dV = \int_V \{Q(T)\}dV + \int_S \left(h(T)(T_B - T) + \varepsilon(T)\eta F_B(T_B^4 - T^4)\right)dS \quad (8)$$

It can be noticed that the temperature field is nonlinear, and the heat transfer could be affected by the wind speeds, radiations, reflectivity, and maximum and minimum temperature of the day and many other factors.

Eq. (8) shows that thermal parameters of the material are considered as the main influence factors in the thermal analysis of pavement.

3.2 Analysis of Coupled Thermal Stresses

In the modeling of finite elements, the temperature field exerted on the element acts as an external force to generate thermal stress on the road surface, according to the virtual work law, the equation of stress equilibrium is:

$$[K_e]\{u\} + [C_e]\{\dot{u}\} = \{F_e^{th}\} \quad (9)$$

where [ke] matrix of stiffness,
$[C_e]$ is the damping matrix that considers materials nonlinear property,
{u} is the displacement matrix, and
$\{\dot{u}\}$ is the displacement to time derivative matrix.
Thermal load is written as shown below:

$$\{F_e^{th}\} = \int_V [B]^T [K_e]\{\varepsilon^{th}\}dV \quad (10)$$

where the $\{\varepsilon^{th}\}$ thermal strain matrix is:

$$\varepsilon^{th} = \int_{T_{ref}}^{T} \alpha(T)dT \quad (11)$$

T coefficient of expansion and temperature function.
T, T_{ref} are calculating and reference temperature.
Flexible pavement thermal stress analysis equilibrium equation, derived from Eqs. (8) and (9):

$$\begin{bmatrix} C & 0 \\ 0 & C^t \end{bmatrix} \begin{Bmatrix} \{\dot{u}\} \\ \{\dot{T}\} \end{Bmatrix} + \begin{bmatrix} K & 0 \\ 0 & K^t \end{bmatrix} \begin{Bmatrix} u \\ T \end{Bmatrix} = \begin{Bmatrix} \{F^{th}\} \\ \{Q\} \quad \{Q^{surf}\} \end{Bmatrix} \quad (12)$$

{Q} $\{Q^{surf}\}$ is the heat flow rates and heat that absorbed through the convection, radiation in the pavement surface.

Volumetric heat capacity can be considered as the specific heat capacity product (c) and density and for finding the relation between temperature of surface with the specific heat capacity, (c). The specific heat capacity ranges between 800 and 1600 j/(kg.k) that present asphalt concrete values and keeping other parameters constant when c increases, the surface maximum temperature decrease, value of c can influence surface temperature and also can be influence in thermal conductivity (k) surface temperature and surface emissivity [11].

The pavement is composed of aggregates and binders (asphalt, cement, etc.). The surface emissivity of these materials is between (0.7-0.95). Considering that many additives can reduce the surface emissivity to a certain extent, the surface temperature of the pavement is emitted with the surface when the emissivity factor increases from 0.5 to 0.9, the highest temperature decreases by about 50℃, and the lowest surface temperature decreases by about 50℃ [11].

For realizing pavement behavior under vehicular loading, a repeated load of single unit truck 18 ton (12 ton +6 ton) with rest period (0.3 sec) between two subsequent axles of the truck with an average speed of 80 km/hr (speed = distance /time) and a rest period of 36 sec. between two subsequent vehicles (100 vehicles / 3600 sec.) AASHTO 2011), Figure (5) as illustrated by Figures (6) and (7) which present the idealized load simulated in the numerical analysis.

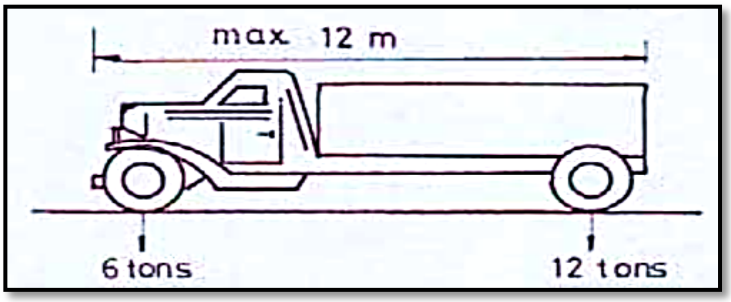


Figure 5: Single unit truck (SU-90) (18 tons) (Iraqi Highway Design Manual, 1980)

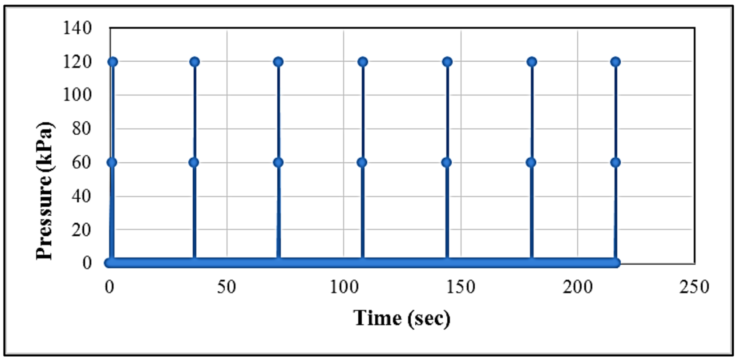


Figure 6: Repeated load function with time for a single unit truck (SU-90)

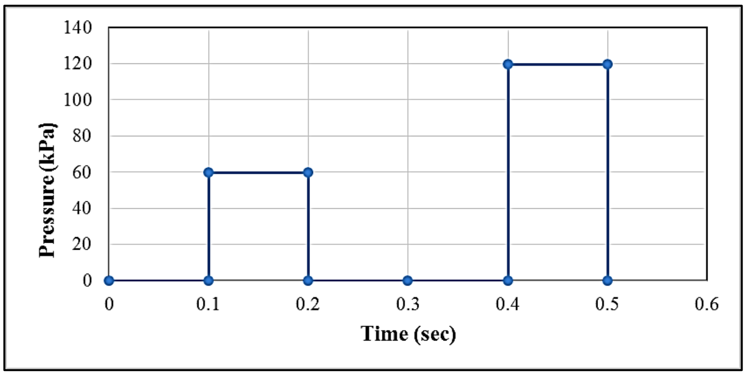


Figure 7: Repeated load function with time (one cycle)

4. Results of Analysis

The main output for the analysis of pavement structure is almost represented by the vertical stresses and the surface deformation which are considered as the critical response points, therefore to examine the displacement trends, single unit truck of 18 tons and its overload value of 36 tons were considered, as shown in the figure below the difference the vertical displacements and the effect of increasing load leads to a considerable increase in the vertical displacement from 0.249 mm after 3600 sec of 18 ton repeated load to 0.518 mm after 3600 sec of 36 ton repeated load in 30 ℃ .

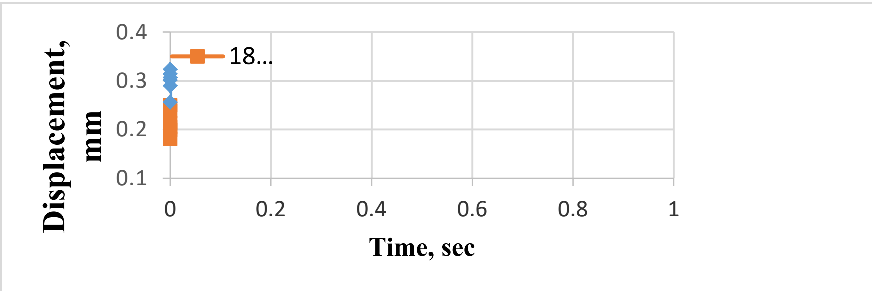
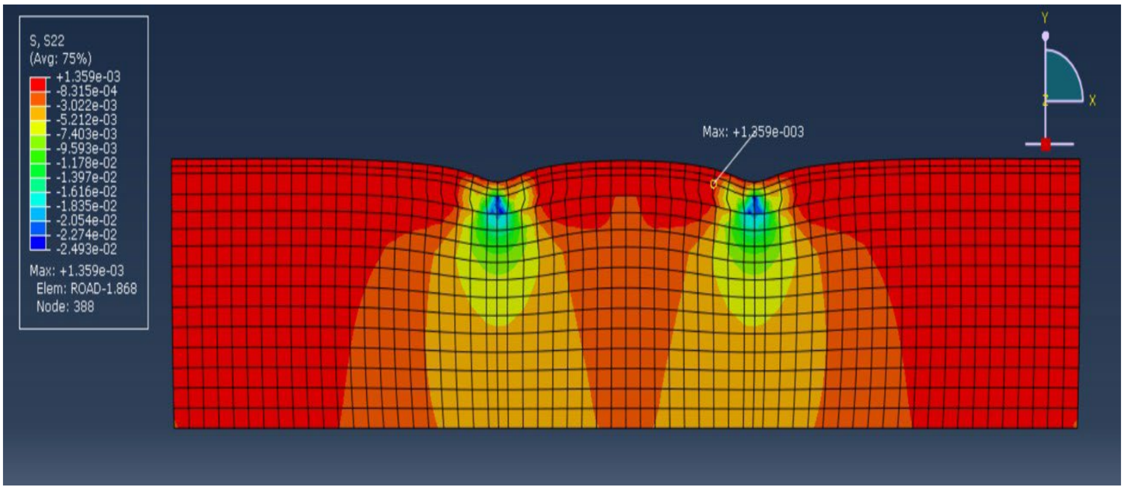


Figure 8: Variation of the vertical displacement at the top of the surface layer below The center of one of the wheels with a repeated load of 18 tons and 36 tons after 3600 sec in 30 ℃

While Figure 9 presents the vertical stresses distribution under the repeated load of passenger car (18 ton) after 3600 sec., the maximum vertical stress is about 1.359 kPa and the increase of wheel pressure to 36 ton leads to an increase in stresses with time and the effect of temperature to 1.825 kPa which means about 0.36% and that cost for the overloaded trucks 30% greater compared to the costs for the legally loaded vehicles and this result that pavement will approximately have just 70% of expected pavement life.

Overloaded axles in the future will lead to a fracture displacement with the increase of stress level and, therefore a probability of failure in these zones becomes larger and failure is expected and could approximately decrease the pavement design life.



a. Wheel load = 18 ton.

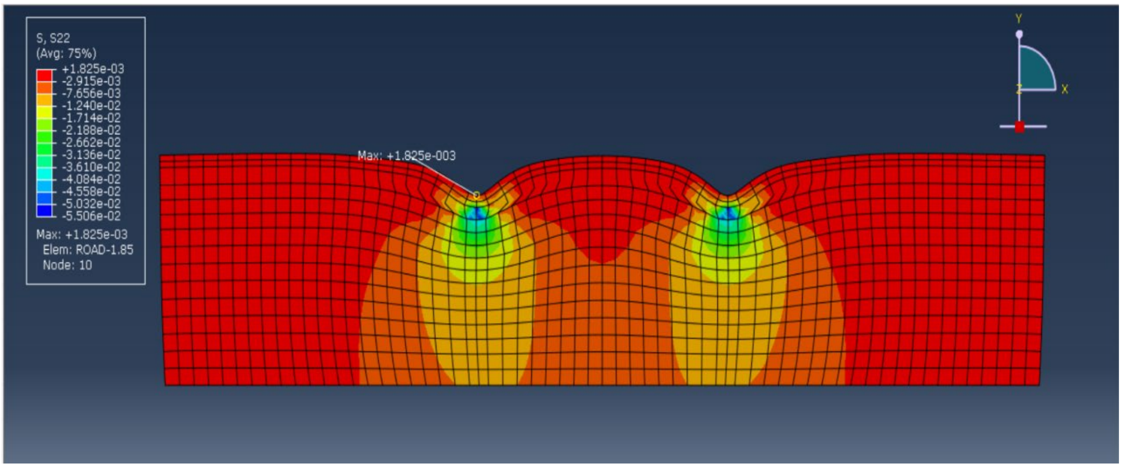


Figure 9: Distribution of the vertical stresses at the surface of the pavement layer with a thickness of 14 cm of the asphalt layer with two different repeated loads at the temperature of 30 ℃ after 3600 sec

A linear elastic analysis of the asphalt layer was carried out for two different thicknesses, namely, 144 mm and 250 mm, respectively, under the effect of repeated load after 3600 sec in 30 ℃. An obvious decrease in the vertical displacement was obtained from 0.249 mm to 0.156 mm below the wheel loading area, as shown in Figure 10. When the thickness was increased from 0.14 m to 0.25 m, this increase in asphalt layer thickness caused a decrease in the transmitted load to other layers, so the vertical displacement is reduced to a minimum with the asphalt surface layer and remains almost constant with depth down to the subgrade layer. The thinner layer thickness, the lesser the ability to reduce loading pressure Aarabi [1].

Figures (11a) and (11b) show the distribution of the vertical stresses (σyy) under the repeated load of a wheel pressure with 18 tons at the top of an asphalt layer with different thicknesses and how the vertical stresses decrease from 1.359 kPa to 0.9495 kPa as the asphalt layer thickness increases. In the current work, the thickness of the base layer and base layer remains unchanged, so it does not affect the change of the stress value of the subgrade layer. According to the results, the thinner the asphalt layer, the smaller the ability to reduce the loading pressure.

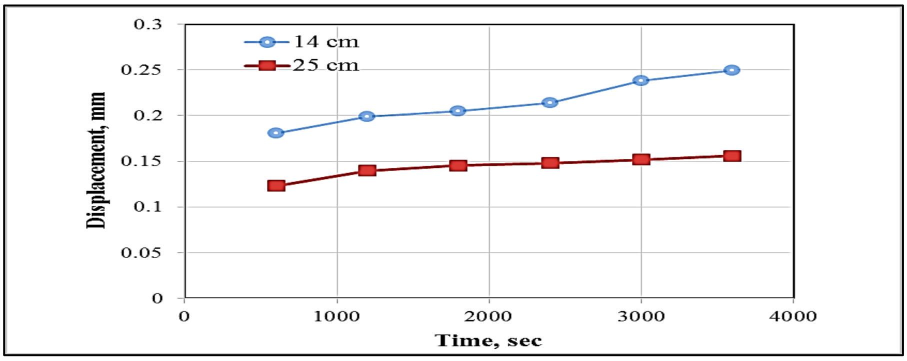
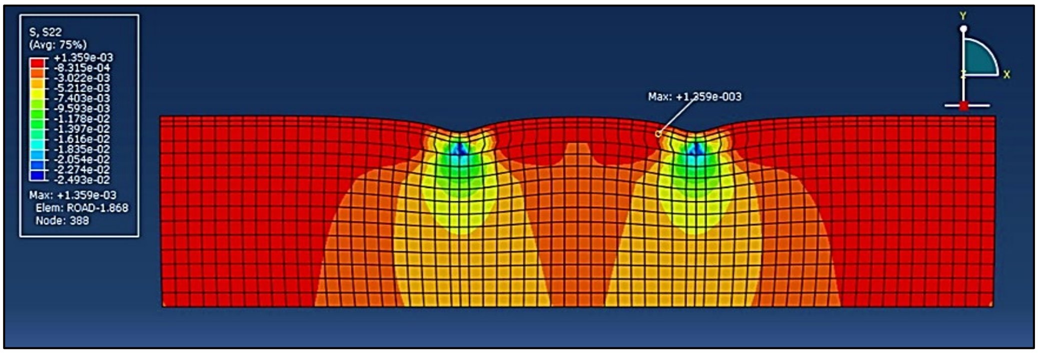
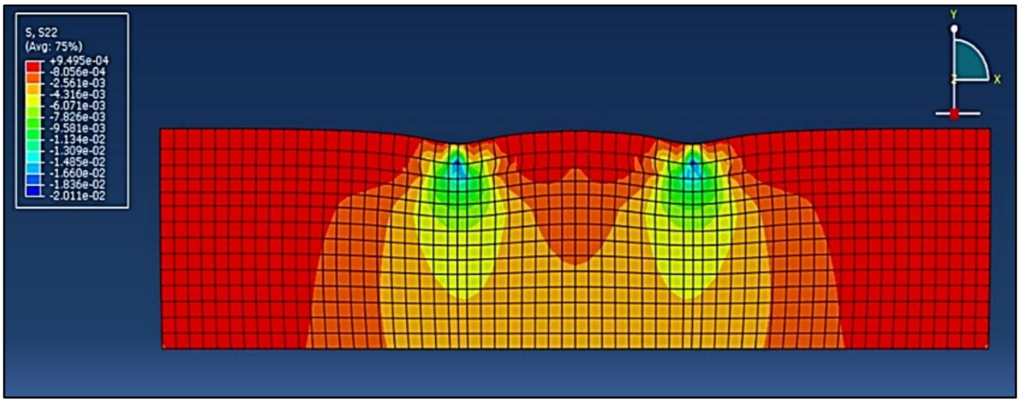


Figure 10: Vertical displacement variation at the surface layer with two thicknesses (14 cm and 25 cm) with a repeated load of 18 tons after 3600 sec in 30 ℃



a.15 cm



b.25 cm

Figure 11: Distribution of the vertical stresses at the surface of pavement layer with different thicknesses of the asphalt layer with a repeated load of 18ton at the temperature of 30 ℃ after 3600 sec

Three different temperatures were studied by finite element analysis to investigate the impact of temperature change during the day and its long-term influence on pavement fatigue life. A model of asphalt pavement was built by a field of thermal stresses and studied the effect of changing parameters: elasticity. In addition, the thickness of the asphalt layer and the effect of increasing the wheel load with various temperatures are also considered.

The temperature field is influenced by many factors. These factors are divided into external and internal factors. The first is composed mainly of wind speed, solar radiation, and air temperature. Other factors include the flexible pavement's mechanical and thermal properties, such as wave reflection, emissivity, and specific heat capacity [16].

As temperature rises from 30°C to 50°C, it is apparent that the vertical displacements are affected and increased under the repeated load after 3600 sec. from 0.249 mm to 0.441 mm, which was caused by a change in the asphalt properties like the reduction in asphalt stiffness and higher viscosity as illustrated in Figure 12. In addition, greater deflection is noted with higher temperatures on the pavements surfaces. This is because of the importance of viscous properties, smaller coefficient of viscosity, and smaller elastic modulus at a higher temperature.

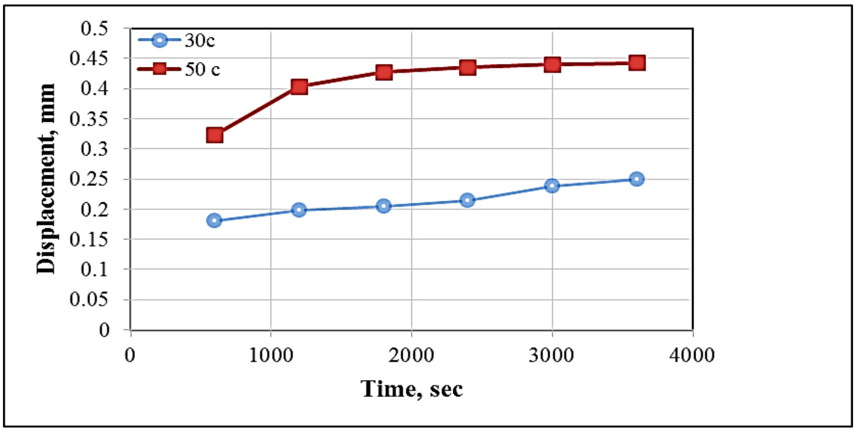


Figure 12: Vertical displacement variation at the surface layer with a repeated load of 18 tons after 3600 sec in 30 ℃ and 50°C

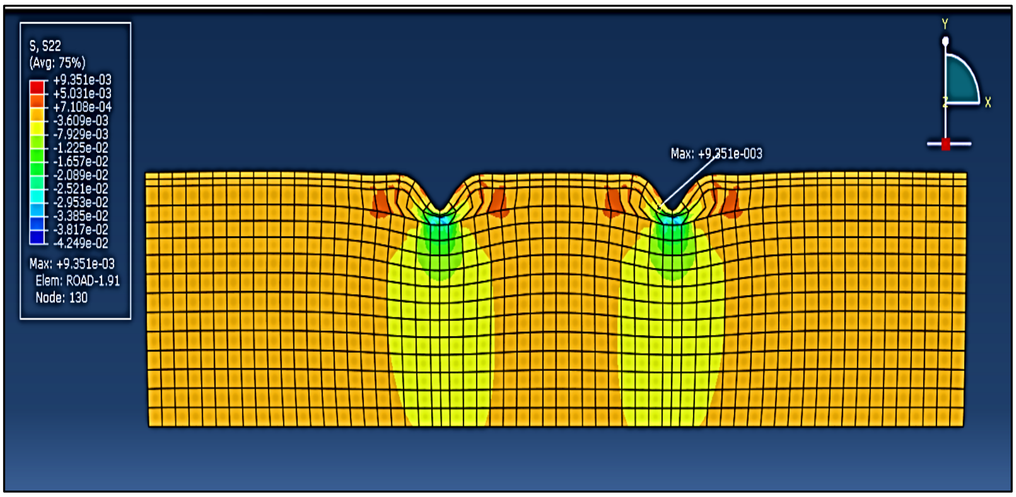


Figure 13: Distribution of the vertical stresses at the surface of the pavement layer with a repeated load of 18 tons at the temperature of 50 ℃ after 3600 sec

Figure 13 explains and reveals that the distribution of vertical stresses (σ_{yy}) is highly affected by the thermal loading. The stress is concentrated in the asphalt layer under the tire print. From the analysis of ABAQUS, an increase in the vertical stresses from 1.35 kPa to 9.35 kPa at the top of the pavement structure can be seen as the temperature rises to 50 ℃ with the effect of wheel pressure due to repeated load after 3600 sec.

5. Conclusions

This research was carried out to investigate the deformation of a pavement structure modeled by finite element analysis (ABAQUS 6.14) software. Test circumstances included pavement structure with two different temperatures and two different thicknesses for asphalt layer (144 cm and 250 cm) and applying a load of 18 tons (single unit truck).

Based on program analysis results, the following conclusions are drawn:

1. With the increase of asphalt layer thickness from 0.144 m to 0.250 m, the vertical displacement of the pavement layer decreased from 0.249 mm to 0.156 mm. It is also has been observed the vertical stresses of the pavement gradually decrease from 1.359 kPa to 0.9495 kPa with a thicker asphalt layer after 3600 sec because the increase in asphalt layer thickness decreases the loads transmitted to the underlayers.
2. As the temperature was raised from 30℃ to 50℃, an obvious deformation in pavement layers occurred, and the vertical displacement increased from 0.249 mm to 0.441 mm.
3. It should be noted that the obtained results shouldn't be treated as a rule in other cases for various pavements structures with different models and different loads conditions, temperatures, and parameters of layers.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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