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Original Research

Deformation behavior of flexible pavements by finite element simulation

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ABSTRACT

Flexible pavement is usually designed based on certain axle load limits and climatic conditions. The Iraqi code has specified certain load limits per each axle type that should not be exceeded. However, many trucks violate these limits by carrying additional weights to decrease the transportation cost. These overweight trucks cause severe deterioration to the pavement and thus reduce its life. The Iraqi authorities generally charges the violating trucks a penalty based on their weights. This penalty could be very small compared to the damage occurring to the pavement based on these over weights. Also, some trucks may carry huge weights that the pavement may not support, so unloading such trucks could be a suitable solution rather than paying few amounts of money and deteriorating the pavement. The study aims at studying the effect of axle load increase, and the variation in pavement moduli, on the overall pavement life. It also aims to estimate the overweight truck limits that could be penalized or unloaded. The research uses the ABAQUS software conditions to estimate the tensile strains occurring under the asphalt concrete (AC) layer and the compressive strains above the subgrade surface. These computed strains are incorporated in the fatigue cracking and rutting models to estimate the pavement life for different axle weights. Results showed that violating trucks should be unloaded when their weights exceed certain limits.

Keywords: Finite element, Stresses, Displacement, pavement layer thickness.

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1. Introduction

Among the components of the highway which is the most important transport facility [1-5], flexible pavement is the major component [4, 6-10]. However, flexible pavement is applied to several types of distresses [11-13] affect its serviceability [14, 15]; cracking and permanent deformations are the most distresses types [3, 8, 13]. Permanent deformation is the predominant narrowing of the bituminous surface. This occurs due to the elastic and viscous nature of the bituminous mixture [16]. It results from traffic and plastic path. Flexible paving is mainly formed of four layers which consist of a layer of high bitumen which is in direct contact with the wheel bearing, a base layer for load distribution, and a sub-floor layer for support [17]. The bottom layer includes compressed layer and natural earth layer. The characteristics used in the design consist of elastic modulus and Poisson's ratio. The wheel load is uniformly distributed over the pavement surfaces. The check of the impact of the load is the wheel that is applied to the bore and the flexible pavement is able to respond to the deformation that occurs. The model was prepared and verified in the pavement laboratory with proven data. An analysis of the selected element has been made possible by the ABAQUS program, as the use of the model dimensions, the element types, the linking strategy, and verification of the required grades is of the accuracy of the developed models. It has been done on the finite element model, which is capable of predicting the flexible pavement surface after the load is placed on it [18]. Figure (1) shows the rutting deformation in flexible pavement.

Figure 1. Rutting occurring in pavement (the road located in Iraq)

Fatigue cracks are among the most significant and significant distresses that have a functional impact on the performance of flexible pavements. The CZM(Cohesive Zone Model) is applied the finite element approach in the ABAQUS 6.14 simulation program for laboratory beam test data [19]. Flexible pavements are designed according to the limits of axle load and the climatic condition and should be constructed to offer a non-skid surface, so the overweight vehicles could cause significant pavement degradation and thus decrease its life, fatigue is one of these types of deterioration, major structural distress that makes a reduction in the serviceability of asphalt concrete pavement [20]. Fatigue is one of the distress models that extensively employ the notion of cumulative damage, and it is concerned with the relationship between the permitted number of repeated loads and the tensile tension at the asphalt layer's base, represented as a damage ratio. Fatigue cracking occurs in 50% of the regions or can be experienced by field performance when the sum of the damage ratios equals 1, indicating that failure risk is 50% [20]. HMA fatigue crack resistance consists of two parts: (1) fracture resistance and (2) the ability to heal. Healing is the occlusion of the Fracture surface that occurs during the rest between loading cycles and it is one of the main components of the laboratory-to-field conversion factor used in the most classical empirical analysis of fatigue models [21]. A viscoelastic heterogeneous composite with thermo-rheological characteristics, like an asphalt mixture, has a complex fracture mechanism. For simulating fracture in asphalt mixtures throughout the past 15 years, many researchers have embraced the use of cohesive zone (CZ) fracture models [22]. The semi-circular bending (SCB) test is gaining popularity as a method for assessing the fracture characteristics of asphalt mixtures. Tensile tension brought on by bending is the mode of failure in SCB samples. Researchers looked at the viability of measuring the fracture qualities of an asphalt mixture using the SCB test [23]. Heavy vehicles, which are used on roads by a variety of vehicle types and are perhaps the most important for freight loading, can lead to paving failure and raise repair and maintenance costs, composite effects for wheel loads and temperature were taken into consideration when analyzing a finite element using ABAQUS 6.14. Two thicknesses of the pavement and a vehicle type 2S-2 were tested. The base and sub-bases were built using Mohr coulomb model to simulate elastic materials [24]. The finite element approach is adopted to investigate the behavior of flexible pavement under the wheel and heat loading conditions. They focused on the stress distribution inside the asphalt concrete pavement and how it affects crack propagation direction. The findings revealed that a maximum stress intensity factor value is obtained at the surface and then decreases with a depth around (0.75 of asphalt layer thickness) due to a decrease in temperature in the asphalt layer, indicating that a crack will begin at the surface and spread throughout the asphalt layer. The horizontal tension in both the top and bottom layers rises when the thermal coefficient expansion factor changes. Stresses at the upper surface are high [25]. It can be noticed an obvious reduction from 0.590 mm to 0.265 mm under the repeated load of 36 Ton. The hardness impact of WPP (Waste Polypropylene) on the asphalt binder causes the rise in asphalt viscosity, which is confirmed by the decrease in penetration values. Increased viscosity values would assist to improve the pavement's resistance to deformations at high temperatures, extending its service life [26]. The simulation was done using finite element software. A geogrid element, which is described as a thin structural element with the capacity to tolerate axial stresses but not resist bending, was used to represent geocell reinforcement [27]. The behavior of bituminous pavements with and without geogrid reinforcement under static and dynamic loads is examined using an axisymmetric finite element model. The findings showed that a static loading had a moderate impact on the pavement's behavior, while dynamic loading had little or no effect [28]. The pavement is subjected to many different pressures during its service life. Pavement that is perfectly designed will execute duly in its operational life and the stresses will not exceed the permitted limit. Proper design is a design that can provide the expected performance and has good aspects for economic consideration. Fatigue cracking is considered the primary kind of structural damage in flexible pavement. Under load repetition of vehicles, pavement asphalt concrete material deterioration is caused by accumulation and microscopic and macroscopic growth cracks that are gradually occurring as shown in Figure (2) [29]. Therefore, this study aims to investigate the deformation behavior of pavement layers using finite element (FE) simulations under given conditions, to predict the fatigue and rutting crack growth under variable-repeated loading, and to develop a model using statistical technique to predict the fatigue and rutting life of asphalt pavement.

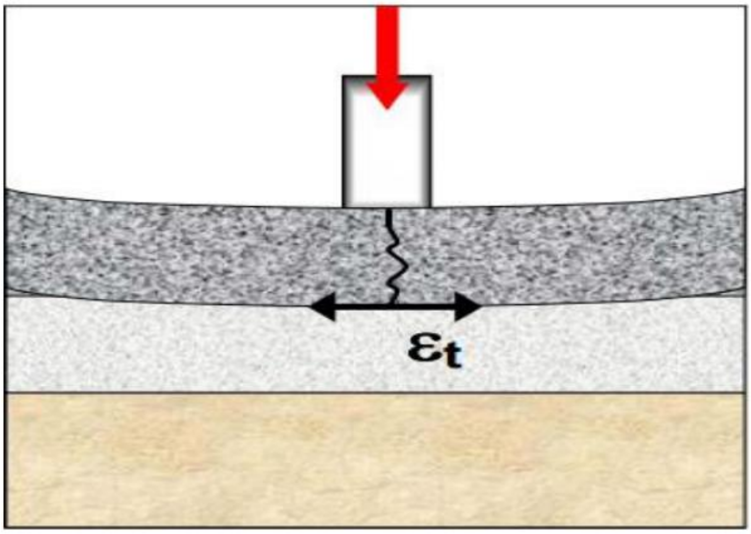


Figure 2. Fatigue cracking mechanism in pavement cross section schematic diagram [29]

2. Methodology

The ABAQUS computer program was adopted to calculate the tensile strain at the bottom of the asphalt layer and the compressive strain at the top of the subgrade soil. These computed strains are incorporated in the fatigue cracking and rutting models to estimate the pavement life for different axle weights. Different axle loads are considered in this research used (40 Ton, 47 Ton and 54 Ton). The design of the asphalt pavement structure with two different thicknesses was adopted. The first design adopted a pavements system of 1000 mm in thickness. This system consists of asphaltic surface of 345 mm, base layer of 180 mm, subbase layer of 280 mm and subgrade layer of 195 mm. The second design adopted a pavements system of 860 mm in thickness. It consists of asphaltic surface of 215 mm, base layer of 200 mm, subbase layer of 250 mm and compacted subgrade layer of 195 mm. The model length was considered to be 16500mm (X-Direction), width of 3600mm (Z-Direction) and the thickness 860 mm and 1000mm (Y-Direction); see Figure 3 and Figure 4. The first step is to define section geometry. For this purpose, the layers of the section should be defined. The properties for pavement of 860 mm thickness and pavement of 1000 mm thickness are shown in Table 1 and Table 2 respectively.

For creating a model to complete the analysis, it’s important to go through most of these modules, as described in the following points:

1. Part module, sketch module, mesh module: build up the geometry of the structure under a set of parts.
2. Property module: create element section, introduce material data, and assign section and material properties to the members.
3. Assembly module: mesh module and interaction module assemble parts to create the entire structure.
4. Step module: create steps and choose analysis method.
5. Load module: introduce load and boundary conditions.
6. Job module: create jobs and submit for analysis.
7. Visualization module: visualize the result.

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 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 elastic viscous and plastic properties that significant at the high temperature specially. Use of viscoelastic model could be sufficient for describing the real response of asphalt layer at high temperature. The bottom layers of the pavement were modeled by Mohr Coulomb material model that used for analyzing the granular material at the low stress level [30].

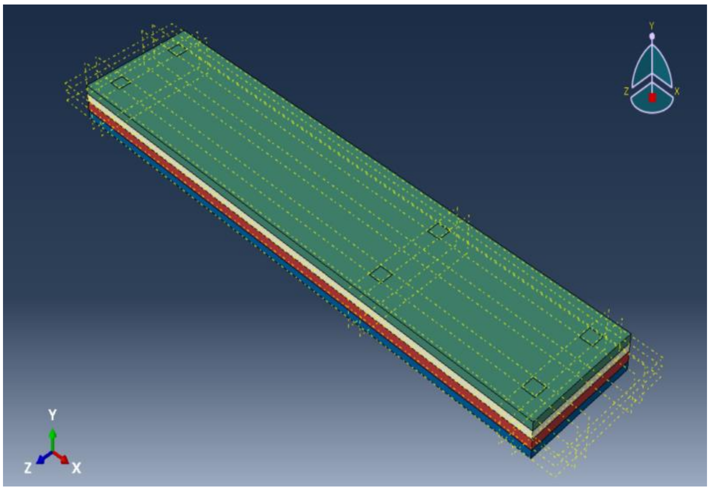


Figure 3. Fatigue cracking mechanism in pavement cross section schematic diagram (thickness: 860 mm)

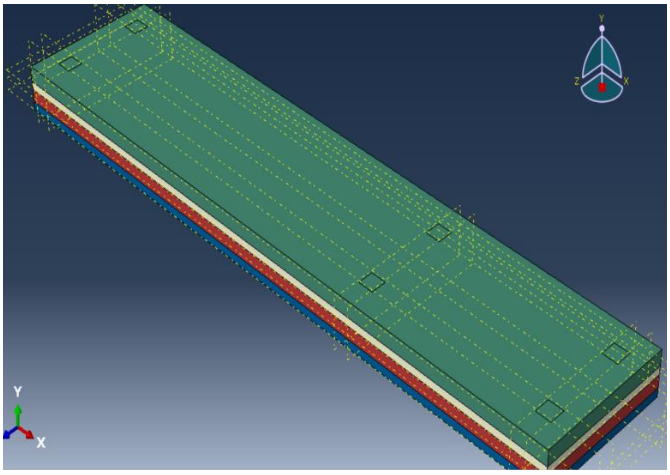


Figure 4. Fatigue cracking mechanism in pavement cross section schematic diagram (thickness: 1000 mm)

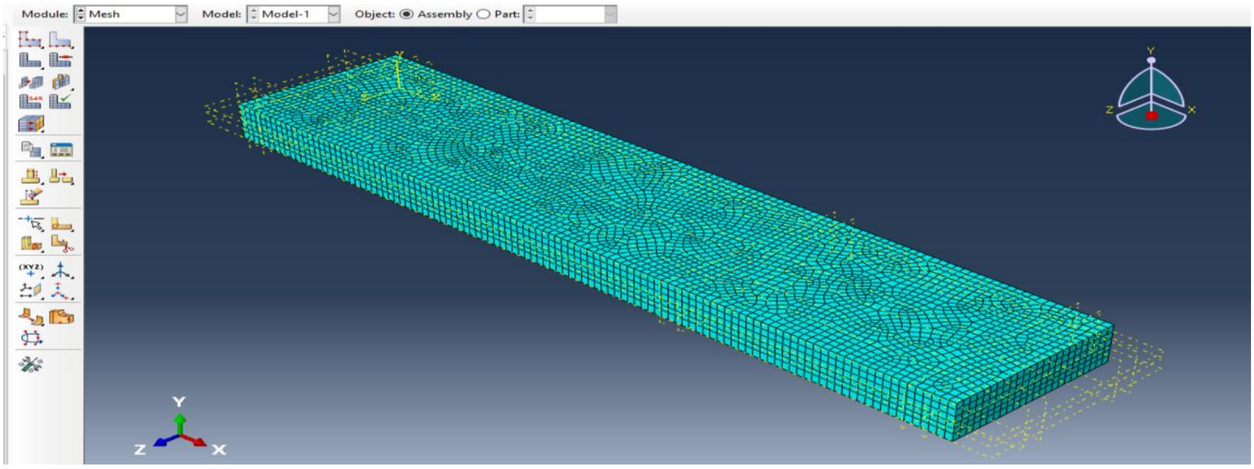
Table 1. Input of flexible pavement layers properties for pavement of 860 mm thickness

Layer	Thickness (mm)	E (MPa)	Density (Ton/m^3)	Poisson's ratio	Temperature (ºC)	Friction angle ϕ	Dilation angle	Cohesion
Asphalt	215	276	2.32	0.35	45	-	-	-
Base	177	193	2.297	0.3	45	38	8	6
Subbase	236	220	2.265	0.3	45	40	10	7
Subgrade	195	179	1.772	0.25	45	-	-	-

Table 1. Input of flexible pavement layers properties for pavement of 1000 mm thickness

Layer	Thickness (mm)	E (MPa)	Density (Ton/m^3)	Poisson's ratio	Temperature (ºC)	Friction angle ϕ	Dilation angle	Cohesion
Asphaltic	345	2760	2.32	0.35	45	-	-	-
Base	180	193	2.297	0.3	45	42	12	6
Subbase	280	172	2.265	0.3	45	40	10	7
Subgrade	195	44	1.772	0.25	45	-	-	-

In mesh generation, at the model of pavement structure mesh was created for the use of small step time, the mesh consists of (19878) elements (24136 nodes) as shown in Figure 5. For applying boundary conditions, degrees of freedom on the bottom of model and for both front and rear and lateral surfaces were fixed perpendicular to shear surface, as shown in Figure 6. For realizing pavement behavior under vehicular loading, repeated load of truck (3-S3) 54 ton (7 ton +20 ton+27 ton) was modeled as shown in Figure 7 with first rest period (0.2 sec) and second rest period (0.4 sec) between two subsequent axles of the truck with an average speed of 100 km/hr. (speed = distance /time) and a rest period of 36 sec between two subsequent vehicles (100 vehicles / 3600 sec) Figure 7 as illustrated by Figure 8 which present the idealized load simulated in the numerical analysis.



Module: Mesh Model: Model-1 Object: ● Assembly ○ Part:

Figure 5. Mesh geometry by using ABACUS software for the model of asphalt pavement layers

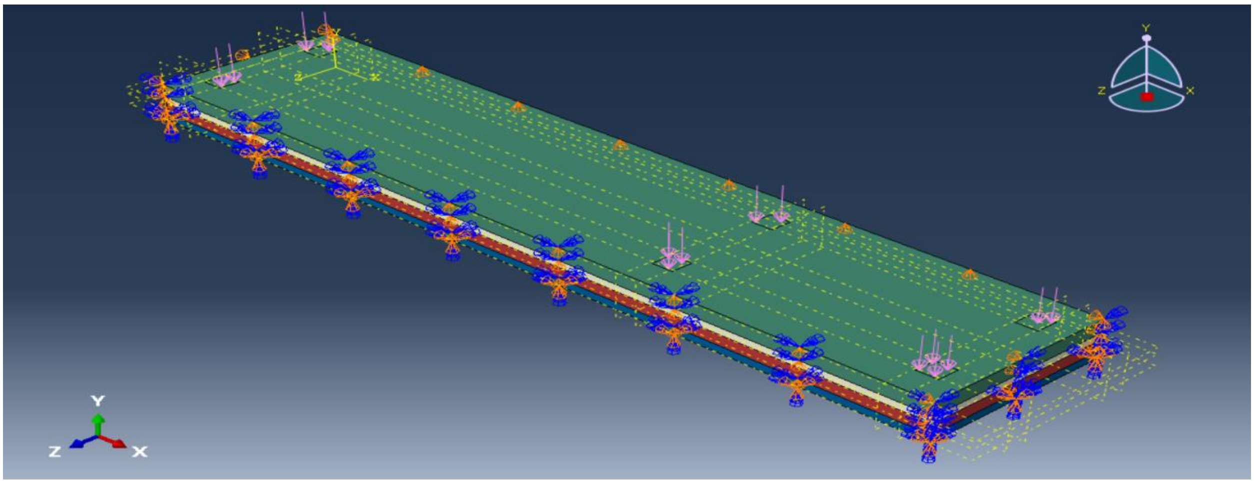


Figure 6. Boundary conditions using ABACUS software for the model of asphalt pavement layers

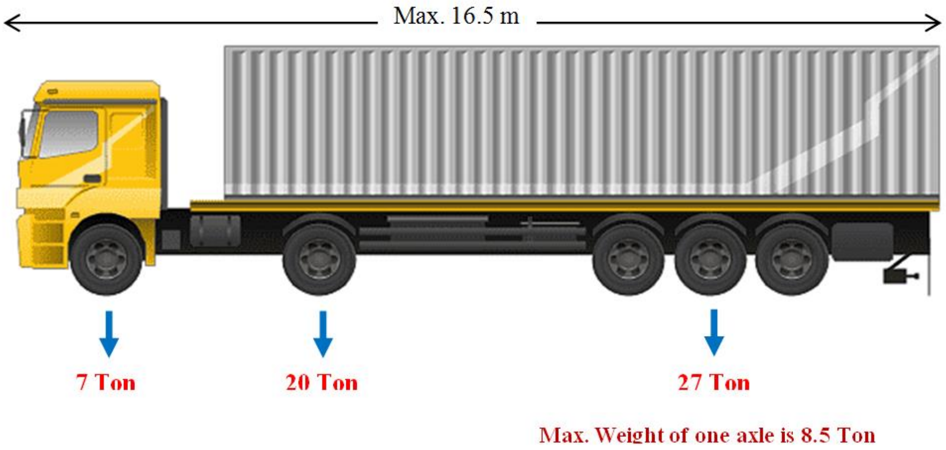


Figure 7. Truck Type 3-S3 (54 Tons) [31]

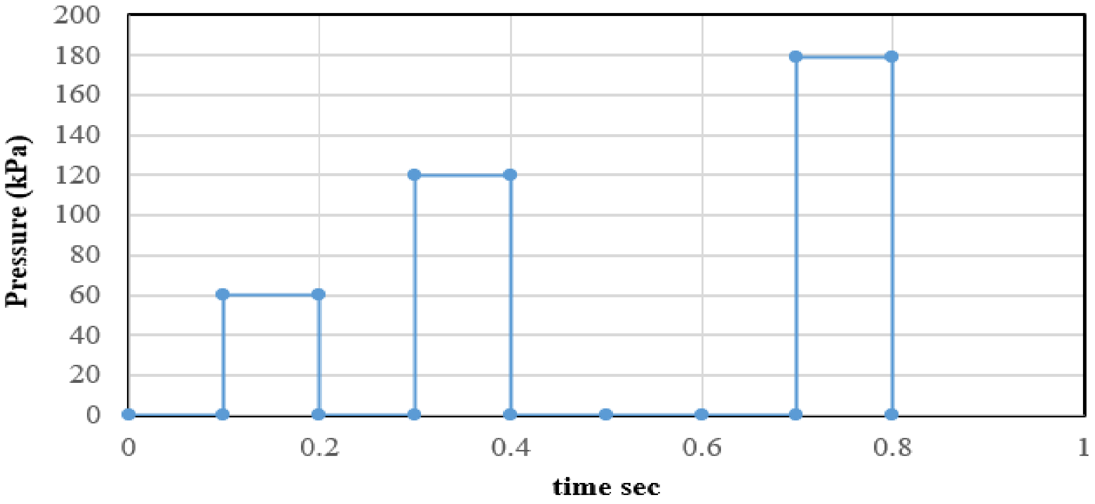


Figure 8. Repeated load function 3 with time (one cycle)

3. Results and 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, Truck Type 3-S3 (54) Ton, as shown in the Figure 9 the difference the vertical displacements and the effect of increasing thickness leads to a considerable decrease in the vertical displacement from 0.4178 mm after 3600 sec to 0.03930 mm after 3600 sec for the same repeated load 54 Ton. For two different thicknesses that were tried; namely, 215 mm and 345 mm, respectively under the effect of repeated load after 3600 sec in 45ºC, a linear elastic analysis of the asphalt layer was carried out. An obvious decrease in the vertical displacement was obtained from 0.4178 mm to 0.03930 mm below the wheel loading area as shown in Figure 10 and Figure 11 when the thickness was increased from 215 mm to 345 mm, this increase in asphalt layer thickness decreased the transmitted load to other layers, so the vertical displacement is reduced to minimum with the asphalt surface layer and remains almost constant with depth down to the subgrade layer. The thinner thickness of layer, the lesser ability to reduce loading pressure [32]. Figures 12 and Figure 13 show the distribution of the vertical stresses (σyy) under repeated load of a wheel pressure with 54 Ton at the top of asphalt layer with different thicknesses and how the vertical stresses decrease from 7.518 kPa to 4.369 kPa as the asphalt layer thickness increases. It should be noted that in the current work, thickness of the base layer and base layer remain 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.

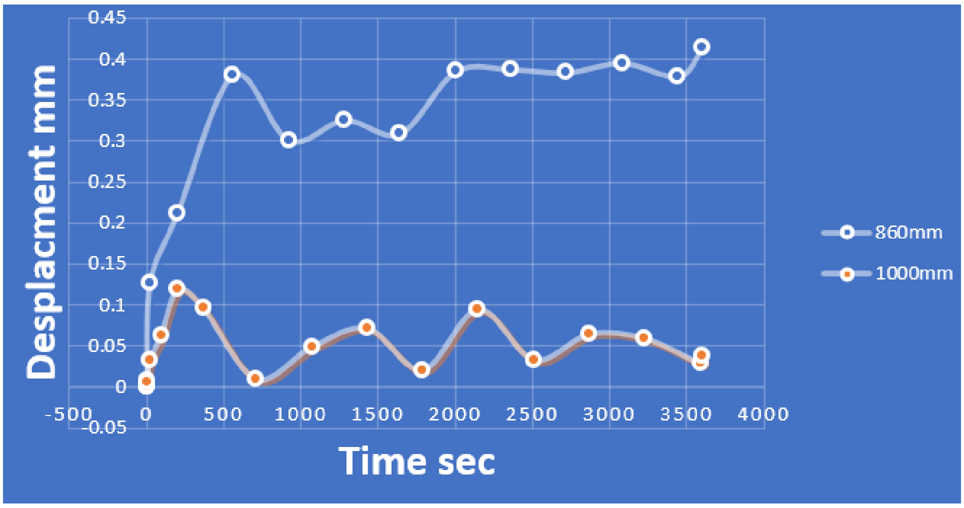


Figure 9. Variation of the vertical displacement at the top of the surface layer below the center of one of the wheels with a repeated load of 54 Ton after 3600 sec

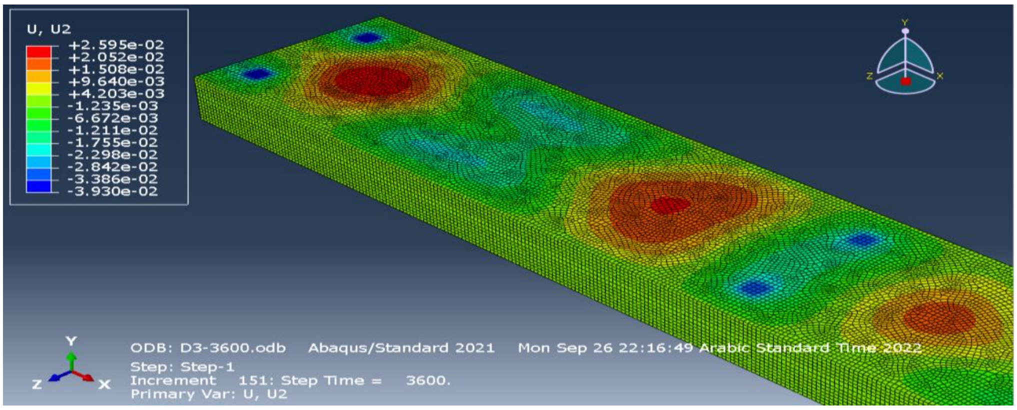


Figure 10. Distribution of the vertical stresses at the surface of pavement layer with repeated axle loads at 3600 sec (1000 mm thickness)

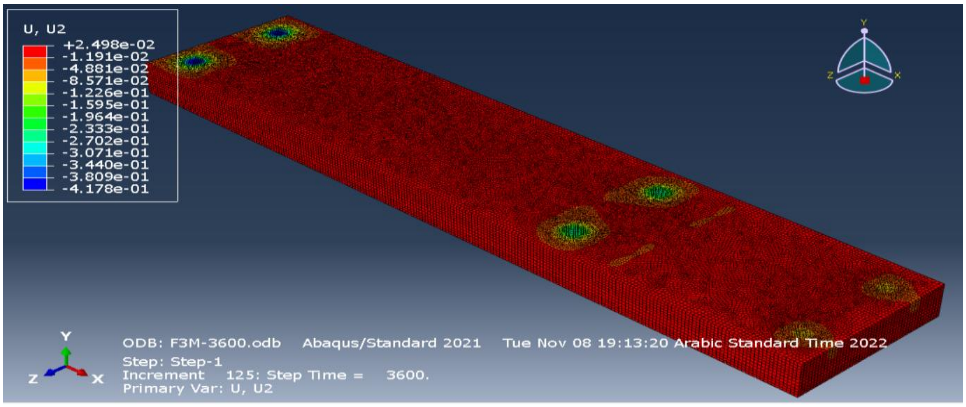


Figure 11. Distribution of the vertical stresses at the surface of pavement layer with repeated axle loads at 3600 sec (860 mm thickness)

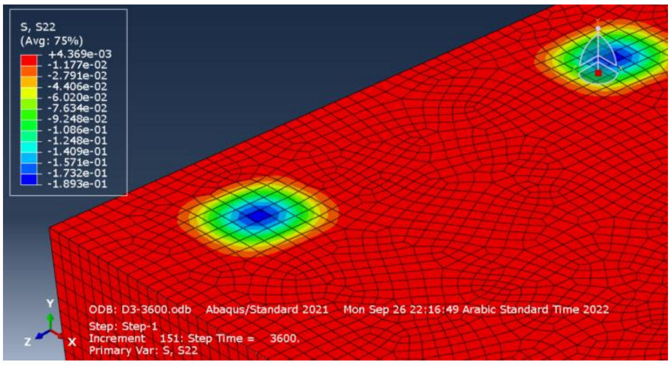


Figure 12. Distribution of the vertical stresses at the surface of pavement layer with different thicknesses of the asphalt layer with repeated load of 27ton at temperature of 45°C after 3600 sec (1000 mm thickness)

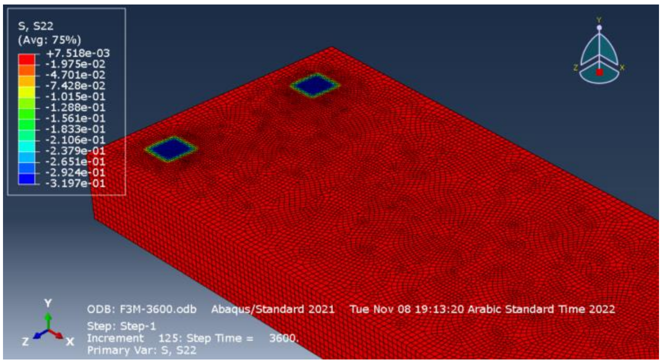


Figure 13. Distribution of the vertical stresses at the surface of pavement layer with different thicknesses of the asphalt layer with repeated load of 27ton at temperature of 45°C after 3600 sec (860 mm thickness)

4. 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 thicknesses and applying a load of 54 ton (Truck Type 3-S3).

Based on program analysis results the following conclusions are drawn:

1. With the increasing of asphalt layer thickness from 215mm to 345 mm, the vertical displacement of the pavement layer decreased from 0.4 mm to 0.03 mm. It is also has been observed the vertical stresses of the pavement gradually decrease from 7.518 kPa to 4.396 kPa with a thicker asphalt layer after 3600 sec. because the increase in asphalt layer thickness decreases the loads transmitted to the under layers.
2. In other situations it should be noted that for various pavement constructions with different models and varied load conditions, temperature and layer characteristics, the findings achieved should not be treated as a matter of principle.

Declaration of competing interest

The authors declare that they have no any known financial or non-financial competing interests in any material discussed in this paper.

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