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

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Abstract. Roads are utilized by many vehicle kinds and heavy vehicles among these may be seen as the most essential for cargo loading, causing paving failure and increasing expenses for rehabilitation and maintenance. In this study, in analyzing a finite element employing Abaqus 6.14, composite effects for wheel loads and temperature were addressed. The asphalt layer was designed as an elastic material, while the base and sub-bases were modeled according to the Mohr coulomb model like an elastic material. And studying the impact of wheel loads on flexible pavement settlement and the main output of analyzing pavement structure is almost represented by the vertical stresses and the surface deformation which are considered as the critical response point. A truck type 2S-2 was tried with two thicknesses of asphalt layer 140 mm and 250 mm and considering that base and subbase layer thicknesses remained constant so it does not affect the variation of displacement. It was found that the increase of asphalt layer thickness from 140 mm to 250 mm leads to a decrease in the vertical displacement of about 0.59% and studied the effect of modified asphalt with polymer and how it effect pavement vertical displacement with an obvious reduction from 0.590 mm to 0.265 mm under the repeated load of 36 ton and The vertical stress decreased from 5.036 kPa to 1.899 kPa

Keywords: finite element, polymer, pavement structure, stresses.

1. Introduction

Asphalt pavement fatigue life depends on the mechanical and geometrical properties of the pavement layers, and load conditions are expensive and time-consuming to detect asphalt pavement fatigue in the laboratory, so that numerical approaches and theoretical approaches are better used to study this phenomenon. In structural, geotechnical and pavement analysis, there are numerous complex challenges. Therefore, exact mathematical solutions for their differing equations can be resolved in order to achieve a restricted class of load characteristics and simple geometric forms. And the most often used methodology is the well-known finite element method, utilized to reach a practical problem with the approximate answer. Due to the different temperatures and traffic loading that cause many types of failures in pavement layers, this search studied the effect of different axle loads on pavement behavior and how asphalt layer thickness and the addition of polymers could effect on the performance of the flexible pavement.

Alkaissi and Al-Maliky (2009) 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.

Pais et al., (2013) through the use of truck coefficients in many vehicle cases with different thicknesses of asphalt layers and different subgrade stiffness moduli, studied the impact of overloaded vehicles on the road surface, and how the vehicle caused significant damage to the road surface. The study revealed that increasing the thickness can reduce the vehicle load. The impact of the asphalt layer, when fatigue cracks are the main problem of the pavement, the roadbed has little effect on the vehicle load.

Albayati, a.k and saadi,a., (2017) used kenlayer software to estimate tensile strains at the bottom of asphalt layer and the compressive strains at top of subgrade layer and showed that maximum allowable single axle load during winter season is 15 tons and 9 tons during summer season and permitted 13 tons load for the single axle load with dual tire instead of 9 tons as per current local specification and that result in losing 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, (2018) conducted a study on many realistic models that developed to represent the effect of thickness variation of the asphalt mixtures with respect to 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 affected by the thickness of asphalt and stress induced history.

Sadjad and Yousef (2020) stated that through the finite element analysis in Abaqus, the vertical and horizontal loads of the wheels and their positions relative to the cracks were considered in the analysis, and (SIF), T-stress for a four layered road. The stress was also computed as a fracture parameter, with the vertical and horizontal loads shown in relation to its location. The crack tip parameters (KI, KII, T stress) are affected by the elastic modulus and the thickness of the road layer, and it is discovered that the shear deformation mode of the crack tip when the wheel is close to the crack surface, the opening mode of the wheel away from the crack, and both modes in between are all affected.

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 a data collected from critical national highway to compute the impact of vehicles on vertical displacement of pavement structure to investigate the impact of two different thicknesses were studied by the finite element analysis with building a model of asphalt pavement and studied the effect of adding polymers.

### 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 model and for both front and rear lateral surfaces were fixed perpendicular to shear surface, as shown in figure 3.
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 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 Coloumb material model that used for analyzing the granular material at the low stress level (Mejlun et al., 2017). Table (1) lists the material properties of pavement.

| Layer     | Thickness (mm) * | E (MPa)* | Density (kg/m$^3$) * | Poisson’s ratio* | Friction angle (*)** | Dilation angle ** |
|-----------|------------------|----------|----------------------|------------------|----------------------|------------------|
| Asphalt   | 140              | 508      | 2348                 | 0.35             | -                    | -                |
| Local Base| 300              | 275.79   | 2334                 | 0.35             | 38                   | 8                |
| subbase   | 500              | 211.53   | 2288                 | 0.4              | 40                   | 10               |
| Subgrade  | 2000             | 34.47    | 1789                 | 0.45             | -                    | -                |

* Ministry of Construction, Housing Municipalities and Public Works.
** From Hassan et al. (2018).

For realizing pavement behavior under vehicular loading, repeated load of truck (2-S2) 36 ton (6 ton +12 ton+18 ton) was modeled as shown in figure (4) 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 80 km/hr (speed = distance /time) and a rest period of 36 sec between two subsequent vehicles (100 vehicles / 3600 sec) figure (4) as illustrated by figures (5) and (6) which present the idealized load simulated in the numerical analysis.
**Figure 4.** Truck Type 2-S2 (36 tons) (Iraqi Highway Design Manual, 1980).

**Figure 5.** Repeated load function 3 with time for truck type 2S-2.
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, Truck Type 2-S2 36 ton and its over load value 72 ton were considered, as shown in the figure (7) below the difference the vertical displacements and the effect of increasing load leads to a considerable increase in the vertical displacement from 0.559 mm after 3600 sec of 36 ton repeated load to 1.284 mm after 3600 sec of 72 ton repeated load in 40 °C.

Figure 7. 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 36 ton and 72 ton after 3600 sec in 40 °C.

While figure (8) presents the vertical stresses distribution under the repeated load (36ton) after 3600 sec., the maximum vertical stress is about 5.036e-3 mPa and the increase of wheel pressure to 72 ton leads to increase in stresses with time and the effect of temperature to 1.185e-2 mPa which means about 0.36% and that cost for the overloaded trucks 30% greater comparing to the costs for the legally loaded
vehicles and this result that pavement will approximately have just 70% of expected pavement life (Pais et al., 2013)
Overloaded axles in 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.
Behiry (2012) concluded that the fatigue damage generally increases in an increasing rate (diverging) with increasing the axle load. While the rutting damage increases with a decreasing rate (converging). Furthermore, with increasing asphalt layer elastic modulus the fatigue and rutting damage decrease.

![Figure 8](image)

Figure 8. Distribution of the vertical stresses at the surface of pavement layer with different repeated axle loads at temperature of 40 °C at 3600 sec.

For two different thicknesses that were tried; namely, 140 mm and 250 mm, respectively under the effect of repeated load after 3600 sec in 40 °C, a linear elastic analysis of the asphalt layer was carried out. An obvious decrease in the vertical displacement was obtained from 0.559 mm to 0.251 mm below the wheel loading area as shown in figure (9) when the thickness was increased from 0.140 mm to 0.250
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 (Aarabi, 2018).

![Graph showing variation of vertical displacement at the top of the surface layer](image)

**Figure 9.** Variation of the vertical displacement at the top of the surface layer below the center of one of the wheels with two different thicknesses of asphalt layer and different repeated loads after 3600 sec in 40 °C.

Figures (10) show the distribution of the vertical stresses (σyy) under repeated load of a wheel pressure with 36 ton at the top of asphalt layer with different thicknesses and how the vertical stresses decrease from 5.036 kPa to 3.235 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.
Even though the extent to which material properties can affect crack initiation and growth varies, material properties are always considered to be critical in determining the resistance of pavement under different modes of cracking. Material properties can influence different stages of cracking. The first stage is the formation of micro cracks in asphalt film around the aggregates. In the second stage, these micro cracks grow further to initiate the macro crack, in which material properties, structural characteristics and external factors dictate the level of energy or driving force available for initiating a crack. The third stage is crack propagation, which represents crack growth or propagation speed within the structure. Crack propagation is affected by material properties, pavement structure and traffic loading. The two critical material characteristics that define the role of material in the two crack stages are modulus and fracture, or damage resistance properties as stated by Ozer et al. (2018).

One of the important solutions for the asphalt pavement distresses problem is making an asphalt mixture with modified characteristics. In this study, to increase the stiffness of the asphalt mixture and decrease the vertical displacements and stresses in the pavement structure, a Waste Polypropylene (WPP) was
added to the asphalt layer with a ratio of 5%. The properties of the asphalt modified with WPP are listed in Table (2).

Table 2. Properties of the modified asphalt by WPP polymer.

|                        |       |
|------------------------|-------|
| Modulus of elasticity (MPa)* | 1300  |
| Poisson’s Ratio**       | 0.25  |
| Viscosity (pa.s)* at 135 ℃ | 0.662 |

*From Aabdalkhabeer, 2020
**Assumed.

It can be noticed from figure (11) that the decrease in the values of vertical displacements is due to the hardness effect of WPP on the asphalt stiffness and that would help improve the resistance to fatigue cracking and increase the service life of the pavement.

![Figure 11. Variation of the vertical displacement of modified asphalt at the top of the surface layer with thickness of asphalt layer equal to 140 mm under different repeated loads after 3600 sec in 40 ℃.](image)

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 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. This result is in agreement with the findings of Abdalkhabeer, (2020).
The addition of WPP improves the properties of the asphalt mixtures by increasing the stiffness and viscosity of the asphalt. Furthermore, the distribution of vertical stresses is shown in figure (12). The vertical stress decreased from 5.036 kPa to 1.899 kPa, this indicates that polymers improve the performance of asphalt by increasing the stability and viscosity value.

**Conclusion**

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 for asphalt layer (144 mm and 250 mm) and the influence of polymer addition and applying a load of 36 ton (Truck Type 2-S2). Based on program analysis results the following conclusion are drawn: With the increasing of asphalt layer thickness from 0.140 mm to 0.250 mm, the vertical displacement of the pavement layer decreased from 0.559 mm to 0.251 mm. It is also has been observed the vertical stresses of the pavement gradually decrease from 5.036 kPa to 3.235 kPa with a thicker asphalt layer after 3600 sec. because the increase in asphalt layer thickness decreases the loads transmitted to the under layers. With the addition of WPP (Waste Polypropylene) to the asphalt layer, the finite element analysis showed a higher resistance to the repeated load after 3600 sec and a decrease in vertical stress distribution. 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.
References

[1] Ł. Mejłun, J. Judycki, and B. Dołżycki, “Comparison of Elastic and Viscoelastic Analysis of Asphalt Pavement at High Temperature,” Procedia Engineering, vol. 172, 2017, doi: 10.1016/j.proeng.2017.02.095.

[2] Z. A. Alkaiss and S. E. S. Al-Maliky, “Combined effect of wheel and thermal load conditions on stress distribution in flexible pavement,” Engineering and Technology Journal, University of Technology, vol. 27, no. 12, pp. 2257–2267, 2009.

[3] J. C. Pais, S. I. R. Amorim, and M. J. C. Minhoto, “Impact of Traffic Overload on Road Pavement Performance,” Journal of Transportation Engineering, vol. 139, no. 9, Sep. 2013, doi: 10.1061/(ASCE)TE.1943-5436.0000571.

[4] A. K. Albayati and A. Saadi, “Influence of Axle Overload on the Performance of Local Flexible Pavement”, 7th Scientific Engineering and 1st International Conference “Recent Trends in Engineering Sciences and Sustainability (pp. 17–18). Baghdad.

[5] S. Aarabi and S. A. Tabatabaei, “Viscoelastic analysis of thickness variation of asphaltic pavements under repeated loading using finite element method,” International Journal of Pavement Engineering, vol. 21, no. 2, Jan. 2020, doi: 10.1080/10298436.2018.1450504.

[6] S. Pirmohammad and Y. Majd-Shokorlou, “Finite element analysis of road structure containing top-down crack within asphalt concrete layer,” Journal of Central South University, vol. 27, no. 1, Jan. 2020, doi: 10.1007/s11771-020-4292-3.

[7] Abd Al-khabeer, W. N., “Determination of Dynamic Modulus of Modified Asphalt Mixtures” Baghdad, 2020.

[8] Hassan, W. H., Fattah, M. Y., Rasheed, S. E., (2018), "Numerical Analysis of the Effect of Geocell Reinforcement above Buried Pipes on Surface Settlement and Vertical Pressure", Engineering and Technology International Journal of Geotechnical and Geological Engineering, Vol. 12, No. 3, pp. 221-227, World Academy of Science, International Scholarly and Scientific Research & Innovation.

[9] Ozer, H., Al-Qadi, I. L., Singhvi, P., Bausano, J., Carvalho, R., Li, X. and Gibson, N., (2017), “Prediction of pavement fatigue cracking at an accelerated testing section using asphalt mixture performance tests”, International Journal of Pavement Engineering, vol. 19, No. 3, 264–278. https://doi.org/10.1080/10298436.2017.1347435.

[10] Highway Design Manual. Republic of Iraq (1982), Ministry of Housing & Construction, State Org. of Roads & Bridges.

[11] Behiry, A. E. A., (2012), “Fatigue and rutting lives in flexible pavement”, Ain Shams Engineering Journal (2012), vol. 3, 367–374, http://dx.doi.org/10.1016/j.asej.2012.04.008.

[12] Lavanya, K., J Obaid, A., Sumaiya Thaseen, I., Abhishek, K., Saboo, K., Paturkar, R. (2020). Terrain Mapping of LandSat8 Images using MNF and Classifying Soil Properties using Ensemble Modelling. International Journal of Nonlinear Analysis and Applications, 11(Special Issue), 527-541. doi: 10.22075/ijnaa.2020.4750.