Engineering and Technology Journal 40 (05) (2022) 661-667

Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

Finite Element Simulation of Repeated Loading Test of Asphalt Concrete

Noor S. Hatem *, **Miami M. Hilal**, **Mohammed Y. Fattah**

Civil Engineering Dept, University of Technology-Iraq, Alsina'a street, 10066 Baghdad, Iraq.
*Corresponding author Email: mailto:bce.19.23@grad.uotechnology.edu.iq

HIGHLIGHTS

- Abaqus program was used to carry out finite element analysis to predict the rut in the asphalt laboratory model.
- A laboratory test was simulated considering the boundary conditions, load steps, and temperature.
- The numerical and experimental displacement results indicate that the program can simulate the rut that occurs in the model.
- The effect of the temperature was not noticeable.

ARTICLE INFO

Handling editor: Wasan I. Khalil
Keywords: Rutting; finite elements Simulation; asphalt; temperature

ABSTRACT

In this paper, the Abaqus 6.14 version program was used to carry out a three-dimensional finite element analysis to predict the rut in the asphalt laboratory model. In a previous study, a cylinder model of asphalt was tested under the influence of traffic loads and temperature. The test was simulated using the finite element method considering the boundary conditions, load steps, and temperature. The cohesive zone model (CZM) approach was used in the Abaqus program to analyze the spread of the rutting in the model to simulate the fracture and improve the sample structure and the materials used. The Abacus program analysis showed satisfactory results when compared with the experimental results. The numerical and experimental displacement results indicate that the program can simulate the rut that occurs in the model. Using a temperature of 55 ° C showed that the effect of the temperature was not noticeable. XFEM-CZM coupled model provides a suitable numerical tool to represent the rutting tests.

1. Introduction

Rutting is the deformation that occurs due to the applied load on the asphalt. It occurs in any layer of the pavement. Permanent deformation can occur in mixtures of insufficient hardness at high temperatures. Significant rutting normally only occurs during hot weather, especially when the flexible pavement surface temperature is 60 °C or higher [9]. It is also pointed out that the phenomenon of rutting is that the wheel track in the flexible pavement surface is an essential part of the surface degradation process during its construction and service. The rutting problem increases at an early age on the road due to the increase and advancement of heavy transportation. The wide tires of the trucks reduce rolling resistance, thus reducing fuel costs, but they also make excellent rut makers [13]. The combined effect of wheel loads and temperature was considered in the finite element analysis of flexible pavement layers by Fattah et al. [8]. The program (ANSYS V 5.4) was utilized to carry out the analysis. The subgrade layer was modeled as an elastoplastic material following the Drucker Prager model for yielding the isotropic material, while both the asphalt and base layers were considered elastic.

Three different thicknesses for the asphalt layer were tried, namely, 0.05 m, 0.10 m, and 0.15 m, respectively. A temperature rise of 40 °C was considered in addition to wheel pressures. It was found that an increase of wheel pressure from (500) to (700) kN/m^2 leads to an increase in vertical displacement of about (4-8)%. This increase becomes (10-22%) when the wheel pressure becomes 1000 kN/m^2. A Three-dimensional (3D) finite element (FE) model of a reinforced cold bituminous emulsion mixture (CBEM) was built by Shanbara et al. [12] to investigate the effect of static wheel load on rutting formation and flexible pavement response. The preparation and validation of the model were carried out in the pavement laboratory using experimental data. Finite element analyses have been conducted using ABAQUS software. Model dimensions, element types, and meshing strategies were employed to achieve the desired degree of accuracy and convergence of the developed model. The FE model was found capable of predicting surface damage to flexible pavements and their partial recovery following the

http://doi.org/10.30684/etj.v40i5.2128
Received 22 April 2021; Accepted 31 December2021; Available online 5 May 2022
2412-0758/University of Technology-Iraq, Baghdad, Iraq

application of the load. The results demonstrated the capability of the model to simulate the effect of fiber on vertical surface deflection (rutting) and horizontal and vertical displacements. Sadeghnejad et al. [11] tried to predict the impact of temperature and stress on the glasphalt mixture rutting behavior. To achieve the objectives of the study, ABAQUS software was used. The repeated load axial test results were used to model the rutting behavior of asphalt mixtures in the wheel track test. The results showed that the presented models in the study could predict the rutting of asphalt mixtures at different temperatures and stresses. Also, the results of models showed that the waste glass powder could significantly improve asphalt mixtures' performance against permanent deformation.

Alnedawi et al. [5] investigated the effect of repeated stress rest periods on the deformation behavior of unbound granular materials UGMs experimentally. Experiments were conducted with and without a rest period using basalt and granite crushed rocks from Victoria, Australia. Furthermore, to gain insight into the effect of the rest period, finite element modeling was developed. Both the experimental and modeling results showed that the rest period has a noticeable effect on both resilient and permanent deformation behaviors of UGMs. To develop a finite element model for an existing flexible pavement capable of predicting the stress and strain responses of elastic pavements, the model's output was the prediction of permanent deformation (rutting) to model the rutting behavior of asphalt mixtures in wheel track test. To investigate the parameters affecting the development of rutting; width and depth of the rutting profile are highly dependent upon the pavement structure (layer thickness and quality), traffic matrix and quantity, and the environmental temperature at the site. The objective of the present study is to develop a finite element model for an existing flexible pavement that is capable of predicting the stress and strain responses of elastic pavements.

2. Method of Analysis

One of the most important techniques used for pavement models is the finite element approach. The behavior under traffic loading and combined thermal conditions are simulated using ABAQUS computer program ver. 6.14.1. A 3-D solid structural analysis of a cylindrical specimen of asphalt mixture using element (C3D8R), a general linear brick element, has three degrees of freedom; translations in the nodal x, y, and z directions at each node (Abaqus Manual, 2014).

2.1 Finite element (FE) numerical model using ABAQUS software

In this study, the Critical State ONE Surface Elasticity model was calibrated, verified, and used to simulate the behavior of the base coarse aggregate layer under cyclic loading. Table 1 shows the input parameters of the material.

Table 1: Input of properties of asphalt

Cylinder	Elastic modulus (MPa)	Poisson´s ratio [υ]	Density [gm/m³]	Temperature ºC
Asphalt	3000*	0.35*	2240*	55**

*From Alkaissi (2020).
**From Abed (2010).

Uniaxial compressive repeated loading was applied by Abed (2010) [2] in the form of a rectangular wave with a constant loading frequency of 60 cycles per minute. The aggregate and asphalt were mixed in a mixing bowl by hand on a hot plate for three minutes until asphalt had sufficiently coated the surface of the aggregates. The asphalt-aggregate mixture was then in a short-term oven aged for 2 hours at 135°C for the determination of the maximum specific gravity and 4 hours at the same temperature for compaction in accordance with the Asphalt Institute (2007) [6]. This aging represents the aging that occurs in the field between mixing and placement and allows for absorption of the asphalt binder into the aggregate pores. The mix was stirred every 30 minutes during the short-term aging process to prevent the outside of the mixture from aging more than the inner side because of increased air exposure. Finally, the specimens were compacted by gyratory compactor to nodes to get appropriate air void for the rutting test, as shown in Figure 1.

Figure 1: Specimen compacted by Superpave Gyratory compactor (Abed, 2010)

The specimen should be put in a chamber for the testing machine manufactured by Albayati (2006) for two hours at the desired testing temperature to bring test temperature and allow for a uniform temperature distribution within the specimen. A digital camera was used to cover dial gauge reading upon completion of the test after 10000 load repetitions (or any number for load repetition when the specimen failed earlier). The recording was terminated, and the specimen was removed from the test chamber. Permanent deformation found at the following load repetitions 1, 10, 100, 500, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, and 10000. Permanent strain (ε_p) is calculated by applying the following equation:

$$\varepsilon_p = \frac{Pd}{H} \times 10^6 \quad (1)$$

where:ε_p = axial permanent microstrain,
Pd = axial permanent deformation and
H= specimen height.

Traffic load conditions are the main factors affecting the pavement system design, depending on axial loads, the configuration of axles, tire contact areas, number of load repetitions, and vehicle speed. Certainly, the heavy vehicular traffic, such as that of the trucks, definitely is a primary cause of pavement distress and failure. Wheel load can be applied on the entire wheel path for the loading area. Generally, the most common way of applying wheel load, in both theoretical and numerical analysis, is to apply tire pressure loads, uniformly distributed, to a circular or rectangular equivalent contact area defined by the function of the wheel load and the tire contact pressure. To simulate the wheel applied cyclic load. Generally, equivalent, pulse, and moving loading are the most common methods [7]. A heavier sine pulse of 0.1-sec load duration and 0.9 sec rest period is applied. History loading results in approximately 10,000 load cycles or when the specimen fracture, as shown in Figure 2 (Abed, 2010). Figure 3 shows boundary conditions selected for the model, including preventing shifting in the x and y directions and movement in the z-direction. The degree of mesh polishing is important for estimating the precise stress field in the pavement road, so the required mesh for the density is the surface layer on which the load is applied. Figure 4 shows the finite element model for the meshed cylinder. The finite element model includes cylindrical specimens used in this work with 150 mm (6 inches) in diameter and 135 mm (5.3 inches) in height.

The separation traction model was used to simulate the crack in this model with an initial tensile strain of 0.00028176 and considering asphalt as a viscoelastic material. The motivation behind the development of this approach was to allow FE modeling of fracture independent of the mesh. The major advantages of this approach are:

The mesh is generated independent of the crack or crack's path, and the location doesn't have to be specified. XFEM is a mesh-independent FE fracture modeling approach in which the FE mesh is generated independent of the crack, and the crack path and location are not specified. The piecewise polynomial function space of conventional FE methods is extended with extra functions. The extra functions enrich the solution space, and hence such functions are called "enrichment functions". XFEM fracture modeling requires two enrichment functions: a Heaviside function to represent the displacement jump across the crack face and a crack tip asymptotic function to model singularity, Figure 4. Ng and Dai [14] studied the ability of XFEM to predict fracture behaviour with infrastructure materials, and it was shown that XFEM is capable of predicting fracture for both homogeneous and heterogeneous infrastructure materials, including asphalt mixtures.

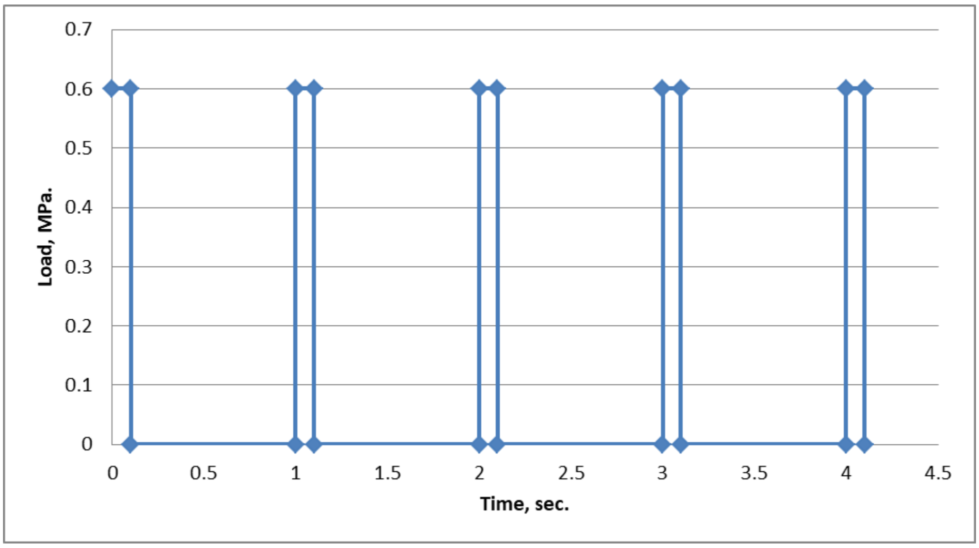

Figure 2: Load-time data for the simulated test

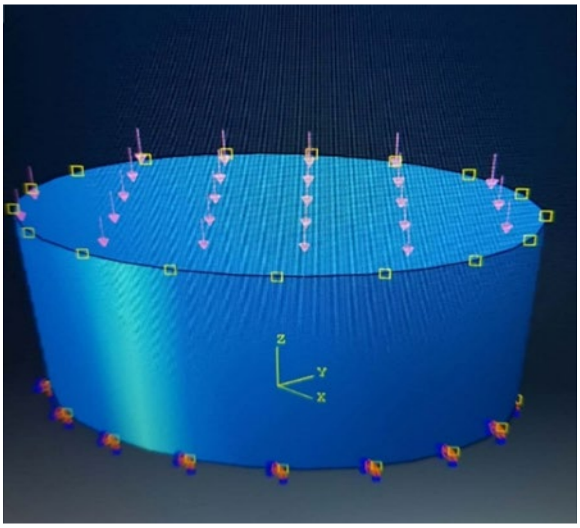

Figure 3: Boundary conditions using ABAQUS Program

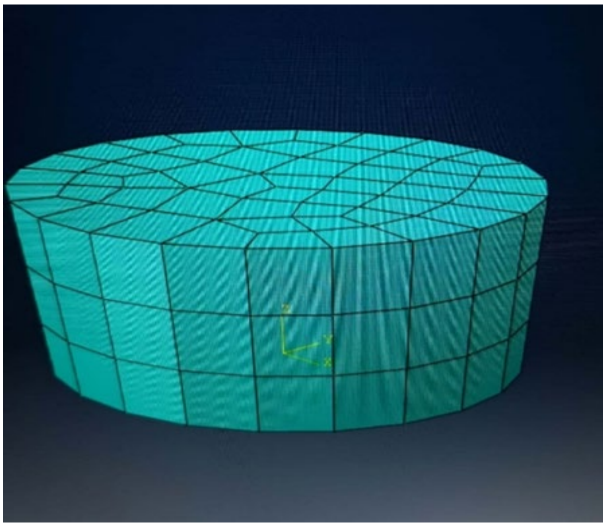

Figure 4: Finite element mesh

Employing the finite elements of the cylinder model was using a three-dimensional model with appropriate materials. The analysis considers the heat load due to the high temperatures in the summer in Iraq. A model was implemented to analyze elastic paving under the influence of traffic load and the influence of temperatures. ABAQUS thermal analysis is based on the law of energy conservation and Fourier's law with temperature-dependent thermophysical properties.

3. Results and Discussion

Figure 5 shows the Mises stress of the cylindrical sample under the effect of traffic loading. Figure 6 shows the results that emerged from shedding traffic loads, which led to the permanent deformation of the flexible pavement. Figure 6 illustrates the results of this simulation in which the displacements are the response of the application of repeated loads and the number of duplicate downloads. Figure 6 shows the deformation that occurs in a section of the flexible pavement (sample) with a diameter of 150 mm, and a height of 135 mm. The displacement processes under the load center reach a maximum value after about 0.1 sec—loading cycle, adding the effect of temperature that is 55 degrees Celsius. From the analysis, the permanent deformation in the flexible pavement layers can be estimated. Figure 7 presents the history loading results of displacement of the center of the sample in approximately 10,000 load cycles or when the specimen fractures.

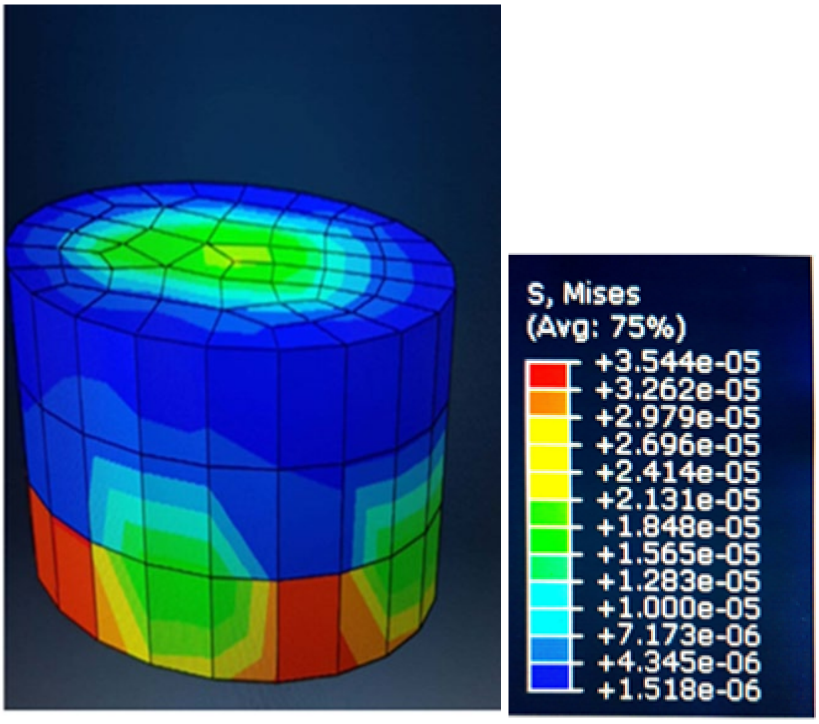

Figure 5: Mises stress of a cylindrical sample under the effect of traffic loading

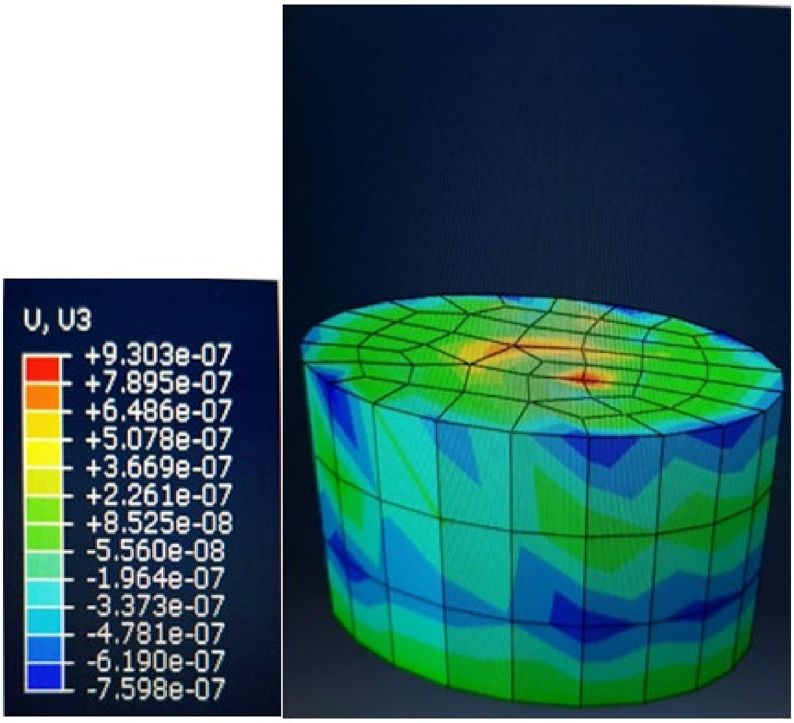

Figure 6: Vertical displacement of a cylinder sample under repeated load

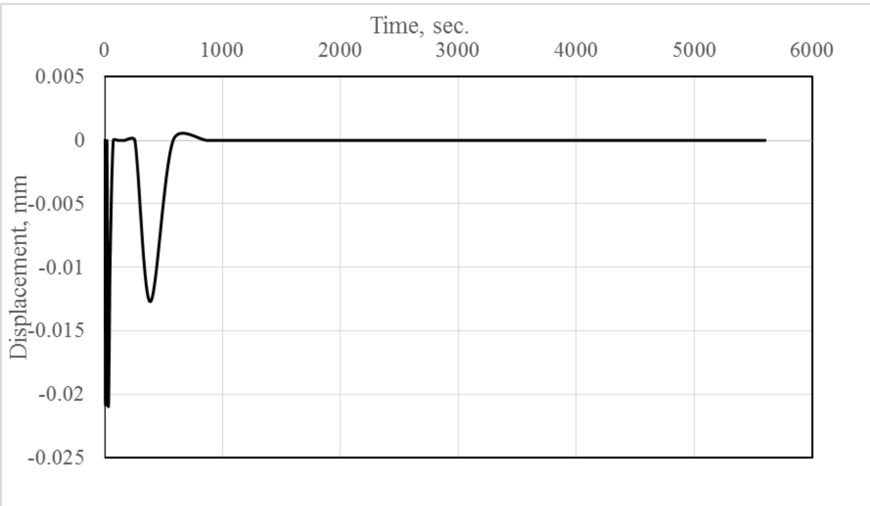

Figure 7: Vertical displacement time history at the center point of the asphalt sample

Abed (2010) proposed the displacement interpolation function as follows:

$$\log \varepsilon^p = -9.473 + 0.532 \log N + 1.798 \log T - 0.672 \log \eta + 0.448 \log Ac \quad (2)$$

where: N = 1, T= 55, σ = 41.137, η =0.516, Ac=4.6

ε^p = permanent strain, N = load cycle, T = temperature, °F, η = the binder viscosity at 70°F, 106 poise, Ac=asphalt content [2].

According to Eqs. (1) and (2), Abed (2010) [2] found that after 10000 cycles, the maximum rutting displacement is close to that predicted by the finite element simulation, which is about (-0.02) mm and is compatible with that found from the numerical results. The results demonstrated the capability of the model to simulate the effect of traffic load on the vertical surface deflection (rutting).

Rutting in paving materials develops gradually with increasing load applications, usually appearing as longitudinal depressions in the wheel paths accompanied by small upheavals to the sides. It is caused by a combination of densification (decrease in volume and, hence, increase in density) and shear deformation. It can occur in anyone or more pavement layers and the subgrade.

Load is one of the crucial factors in the rutting deformation of asphalt pavement. The more overloaded vehicles, the more severe the deformation of the rutting is. Keeping the thickness and the corresponding material of each layer constant, analyzing the rutting caused by different tire pressures under the condition of many cycles and high temperature is expected to reveal larger strains than static tire pressures.

The cyclic loading responses show rate-independent damage increases with the maximum deformation. The results also demonstrate that most of the loss in material stiffness occurs during the first cycle of deformation, and both linear and damaged viscoelastic behavior reaches a steady state after very few cycles. In the initial stage of trafficking, the increase of irreversible deformation below the tires is distinctly greater than the increase in the upheaval zones. In this initial phase, therefore, traffic compaction has an important influence on rutting.

After the initial stage, the volume decrement beneath the tires is approximately equal to the volume increment in the adjacent upheaval zones. This indicates that compaction under traffic is completed for the most part and that further rutting is caused essentially by displacement with the constancy of volume. Therefore, this phase represents the deformation behavior for the greater part of the lifetime of a pavement.

Rutting is distinguished as a depression in asphalt pavement with side upheavals occurring along the wheel path, which is basically caused by the accumulation of unrecoverable plastic strains, as indicated in Figure 6.

When increasing the frequency and load amplitude, it is noticed that there is a small decrease in displacement since the major deformation occurs at early cycles [15].

Asphalt concrete pavement performance depends on the bitumen properties, asphalt concrete mixtures, volumetric properties, and external factors such as traffic volume and environment. Higher traffic volume produces high stress within the pavement layer, which is one of the main causes of pavement distress. Rutting and fatigue cracking is considered the most important type of distress affecting the performance of asphalt concrete pavements on major state highways [16]. This distress reduces the pavement's service life and increases the maintenance cost. So, it is recommended to control the vehicles loads to ensure longer lives of pavement layers.

4. Conclusions

1) The finite element method was used to simulate a rutting test in which a sample was taken in the shape of a cylinder, and a load of 0.6 MPa was projected. A schedule of repeated loads starting from 0.1 to 5600 cycles per second was applied. The (CZM cohesive zone model) was used for the sample. The Abacus program results showed satisfactory results when compared with the experimental results.
2) The numerical and experimental displacement results indicate that the program can simulate the rut that occurs in the model.
3) Using a temperature of 55° C showed that the effect of the temperature was not noticeable in the range of temperature adopted.
4) The cohesive zone model (CZM) approach was used in the Abaqus program to analyze the spread of the rutting in the model to simulate the fracture and improve the sample structure and the materials used. XFEM-CZM coupled model provides a suitable numerical tool to represent the rutting test.

Author contribution

All authors contributed equally to this work.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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.

References

[1] ABAQUS. Finite Element Computer Program, User’s Manual. Version 6.14-4, Karlsson and Sorensen, Inc., Pawtucket, USA, 2014.

[2] Abed, A. H. Required Criteria for Implementation of the Superpave System in Local Pavement Design, Ph.D. thesis, Civil Engineering Department, University of Baghdad, 2010.

[3] Albayati, A., Permanent Deformation Prediction of Asphalt Concrete Under Repeated Loading, Ph.D. Thesis, Civil Engineering, University of Baghdad, 2006.

[4] Z. A. Alkaissi, Effect of High Temperature and Traffic Loading on Rutting Performance of Flexible Pavement, J. King Saud Univ. Eng. Sci., 32 (2020) 1–4. https://doi.org/10.1016/j.jksues.2018.04.005.

[5] A. Alnedawi, K. P. Nepal, R. Al-Ameri, M. Alabdullah, Effect of Vertical Stress Rest Period on Deformation Behaviour of Unbound Granular Materials: Experimental and Numerical Investigations, J. Rock Mech. Geotech. Eng., 11 (2019) 172-180. https://doi.org/10.1016/j.jrmge.2018.05.004

[6] Asphalt Institute, Asphalt Hand Book, Manual series No. 04, Six Edition, Kentucky, USA,2007.

[7] L. S. Calvarano, R. Palamara, G. Leonardi, N. Moraci, 3D-FEM Analysis on Geogrid Reinforced Flexible Pavement Roads, IOP Conf. Ser. Earth Environ. Sci., 95, 2017, 022024. https://dx.doi.org/10.1088/1755-1315/95/2/022024

[8] M. Y. Fattah, S. Abd. El-Ghany, A. S. Abdaljabbar, Analysis of the Performance of Flexible Pavement under the Effect of Wheel and Thermal Loads, Eng. Technol. J. , 28 (2010) 5782-5802. http://dx.doi.org/10.30684/etj.28.18.14

[9] Y.H. Huang, Pavement Analysis and Design, 2nd edn., Prentice Hall, Englewood Cliffs, New Jersey, USA, 2003.

[10] V. D. Rosenthal, P. Lynch, W. R. Jarvis, I. A. Khader, R.. Richtmann, N. B. Jaballah, A. Apisarnthanarak, Socioeconomic impact on device-associated infections in limited-resource neonatal intensive care units: findings of the INICC, Infect, 39 (2011) 439–450. https://doi.org/10.1007/s15010-011-0136-2

[11] M. Sadeghnejad, M. Arabani, M. Taghipoor, Predicting the Impact of Temperature and Stress on the Asphalt Mixtures Rutting Behavior, Int. J. Pavement Res. Technol., 11 (2018) 300–310. https://doi.org/10.1016/j.ijprt.2017.10.006

[12] H. K. Shanbara, F. Ruddock, and F. Atherton, Rutting Prediction of a Reinforced Cold Bituminous Emulsion Mixture Using Finite Element Modelling, Procedia Eng., 164 (2016) 2016-229 .https://doi.org/10.1016/j.proeng.2016.11.613

[13] Verstraeten, J. Bituminous Materials with High Resistance to Flow Rutting, PIARC Technical committee on Flexible Roads, Belgium,1995.

[14] K.Ng, and Q. Dai, Investigation of Fracture Behavior of Heterogeneous Infrastructure Materials with Extended Finite Element Method and Image Analsis, J. Mater. Civ. Eng., 23 (2011) 1662-1671.https://doi.org/10.1061/(ASCE)MT.1943-5533.0000337

[15] F. F. Jebur, M.Y. Fattah, A.S. Abduljabbar, Function and Application of Geogrid in Flexible Pavement under Dynamic Load, Eng. Technol. J., 39 (2021) 1231-1241. http://doi.org/10.30684/etj.v39i8.1771

[16] M.Y. Fattah, K. H. I. Al Helo, Z. I. Qasim, Prediction Models for Fatigue Resistance of Local Hot Mix Asphalt, Road Mater. Pavement Des.,17 (2016) 793-809. https://doi.org/10.1080/14680629.2015.1119711