Effect of Repeated Traffic Loads on Most Significant Distresses of Flexible Pavement

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Abstract. Early fatigue and rutting are among the most common types of road damage due to their main relationship with pavement performance. These damages occur due to excessive loads on the axles of the vehicles or improper design of the mixture in addition to the traditional design methods used in paving designs. Therefore, these premature damages must be avoided for the proper performance and service of the road. In order to overcome some traditional design weaknesses, mechanical-empirical design techniques using software like the ABAQUS program are essential. This program determines the exact stresses, strains, and displacement in asphalt pavement, which is then used to predict rutting and fatigue failures. HMA layers behave like viscoelastic materials in actual field conditions, and temperature variations and loading period influence their mechanical response. This study aims to investigate the ABAQUS software's problem-simulation capabilities and compare the findings to experimental work using the mechanical-empirical approach (E-M) to investigate the most valuable features during temperature change and optimize the design of paving constructions. The results highlighted the significance of the impact that increased loads and temperature changes might have on the performance service life of flexible paving with flexible-viscous layers, where life decreases with increasing loads applied to the pavement surface, where life reduces to 50% of age when the loads are increased to twice the standard load. At the same time, both the vertical stress and the percentage of damage increase with both the change in temperature and with the Temperature increases also result in higher tensile and compressive strain values, which might have an impact on the cost of the paving life cycle. Therefore its impact on future maintenance requirements must be verified.

Keywords: Flexible pavement; mechanical-experimental design; verification; ABAQUS; cracks

1. INTRODUCTION

Flexible paving design is one of the essential components in the sustainability of the road network infrastructure, which is closely linked to civil activities such as trade, industry, environment, and others, in addition to its essential role in road quality regarding safety and reducing accidents [1]. It is the transfer of stresses arising from traffic on the road surface through the other layers of the pavement until its effect reaches the soil layer, on which depends the validity of the pavement and the percentage of its bearing these stresses in complex ways that are affected by the stress condition and its value, temperature, humidity, time, loading rate and other factors. An uneven environment leads to more complications, and therefore the goal of paving design is to determine the appropriate thickness of the paving layers above the soil so that it gives a good and flat surface under traffic without deterioration and collapse [2,6]. By making full use of each of the paving materials in the design, it is also necessary to have the ability to resist permanent damage to the road, such as fatigue and rutting during service conditions [7].

At the beginning of the last century, the design of paving layers was limited to determining the thickness of the layers that would provide strength and protection for the weak sub-layers. Then those interested in the field of roads used their experiences based on the successes and failures of previous projects in changing the design parameters by evaluating the pavement condition and predicting the resulting damage that increases from the rate of deterioration of the pavement structures [3]. The repetition of traffic loads that exceed the permissible limits leads to the failure of rutting in the surface layer, which depends on the structural properties of the damaged sub-layers [8]. Flexibility, in addition to the lack of interest in determining the basic components of the paving, would achieve a balance between the failure of rutting and fatigue of the paving layers. Traffic loads impose two types of strain on the road: the vertical stress-strain (εc) and the horizontal tension strain (εt). The first to suggest the use of the vertical stress strain on the surface of the subgrade was (Kerkhoven and Dormon) in 1953 [9], while Rossow [10] recommend the use of horizontal tensile strain in the asphalt layer to reduce the failure of fatigue cracks.

Most of the field observations appeared in Iraq to assess the condition of the pavement surface of the Iraqi road network. We're rutting, and fatigue cracks are among the most important damages installed due to their high intensity and density due to the phenomenon of overloading, and thus its great impact on the pavement condition [7]. To make the best use of material quality in flexible paving design, which was not considered in the 1993 AASHTO designs, the need to develop improved paving design and analysis methods is necessary [11]. Flexible mechanical with traffic loads of proportions (50, 100, 150, and 200%)

of the standard loads according to the Iraqi Standard Specifications [12]. It is used in the design of paving layers, which contains several major destructive patterns of paving layers to determine the failures of rutting and fatigue, where these models are used to determine the life span of the pavement design [13] depending on the program (ABAQUS). The analysis was adopted on the assumption that the layers of the asphalt mixture are Viscoelastic, where the material properties of asphalt paving vary greatly depending on aging and temperature. In contrast, the earth layers can be described as linear elastic [8]. In Iraq and its analysis with studying the effect of the weights of the axles and their increase on the early failure of the paving layers flexes.

A study was conducted to analyze the effect of the change in the thickness of the asphalt layer and the base layer on the performance of paving on several sections of a specific road using the KENLAYER program. The researchers reached several results, including those related to the mentioned program. The researchers showed the possibility of using the program in the design of paving layers with high reliability. As for the results of the analysis, the researchers indicated that the increase in the thickness of the asphalt layer and the base layer leads to a decrease in the strains while allowing an increase in the frequency of traffic loads for heavy vehicles. In contrast, the decrease in the thickness of the layers leads to an increase in the strain and thus reducing the frequency of loads [14]. At the same time, the researcher Chegenizadeh used the KENLAYER program to model the flexible pavement, where the input of different parameters such as the Poisson's ratio and the elastic modulus were changed, and the output was calculated in the form of stresses, strains, and deflections. The results showed high and medium stress values for the layers with less thickness, while the layers with higher thickness showed less stress [15].

Nidhi and Nagakumar [16] conducted research work in which they used the KENLAYER program to calculate the response of the paving layers. Two linear and nonlinear analyzes were conducted to assess the tensile, compressive, and deflection stresses in the surface layer of the paving. The research results showed that the nonlinear analysis led to a 76.0% increase in compressive stress and a 13.23% decrease in tensile stress. However, similar values were obtained using elastic linear analysis. Accordingly, nonlinear analysis is more accurate and reliable than linear analysis. Abdelrazek [17] conducted a study to clarify a methodology to achieve the required balance between the age of the pavement concerning cracks and its age concerning wear cracks, based on damage analysis using the KENLAYER program to analyze several structural sections of the pavement layers for both cracks and overheating failures. The sections under study consisted of the asphalt surface layer and base layer with the modulus of elasticity for each of them and the modulus of elasticity for the subgrade layer. The results of the analysis of pavement sections showed similar results to the research that the thickness of the base layer and the elastic modulus of the foundation layer is the main factors controlling the balance between the age of the pavement concerning rutting and its age of fatigue because the increase in either of them leads strongly to an increase in the life of the pavement in respect to the cracks damage and has no effect on its age concerning the damage of overheating. The study also showed that the life of the pavement about the two mentioned damages increases significantly with the increase in the thickness of the asphalt layer and increases moderately with the increase in the elastic modulus of the base layer and the asphalt layer.

2. LITERATURE REVIEW

One of the most important types of failures that the road network is exposed to and which greatly affect the serviceability of the pavement are the failures of fatigue and rutting, in addition to their role in reducing the operational life of the roads. This is mostly caused by a growth in the number of trucks, particularly those carrying heavy loads that exceed the permitted limitations, as well as mistakes and weaknesses in the pavement layer designs [18,19]. To obtain adequate performance and overcome traditional design weaknesses while providing good service to the road network, these early causes of failure must be addressed through a new design methodology based on mechanical foundations. Therefore, many studies have been conducted on predicting the failure of fatigue and early rutting in flexible paving using the mechanical-experimental method, some of which can be listed as follows:

In his research (Prediction of Rutting in Flexible Pavements using Finite Element Method), flexible pavement sections are subjected to three-dimensional (3D) finite element analyses over various material qualities, temperatures, and loading conditions. Predicting the rut depth under various temperatures, stress, and material property circumstances is the primary goal of this work. ABAQUS generates a three-dimensional finite element model of flexible pavement to forecast rut depth. The pavement system is considered to be made up of several elastic layers, each of which has a different resilient modulus (Mr) and Poisson ratio. Each layer has a fixed thickness and an unlimited horizontal length, except the bottom subgrade layer [20]. This study examined the pavement system using a cyclic load of 10,000 cycles, or 0.01 seconds, per cycle. Tire contact pressure is 100 psi (0.69 MPa), the wheels are spaced 13.78 in (350 mm) apart, and the Standard Axle Load (ESAL) for an axle with dual pairs of tires is 18 kip (80 kN). Several investigations showed that rut depth increases with increasing temperatures and loads and decreases with the application of a base stabilizer.

Using three-dimensional (3-D) finite element analysis), the impact of the geotextile interlayer on the performance of flexible pavement is evaluated. The study's major goal is to assess how applying geo-jute at three specific locations—the interface between the subgrade and the base, the base and the asphalt layer, and inside the asphalt layers. According to the results data, incorporating geo-jute into flexible pavement greatly enhances pavement performance, resulting in decreased stress, strain, and displacement at the top of the subgrade. Additionally, the addition of geo-jute increased the carrying capacity of the subgrade soil by around 20% [21]. The study of the data reveals that despite a 14% increase in stress levels in the leveling course and base course, the rut depth in those layers has increased by 12 and 28%. The pavement system is thought to consist of many elastic layers, each of which has a specific resilient modulus and Poisson ratio. Except for the lowest layer, each layer must have a finite thickness and extend horizontally to infinity [22].

ABAQUS software version 6.12.1 was used to study how cracks spread inside the flexible pavement. The initial crack was identified at the base of the asphalt layer using the X-FEM approach, based on interpolation functions that can quantify displacements close to the crack zone. The crack was propagated upwards from the base to the pavement surface with an inclination of almost 300 in the third upper zone of the asphalt layer [23]. Fatigue cracks are among the most significant and significant distresses that have a functional impact on the performance of flexible pavements. This article (Numerical Simulation of the Effect of Repeated Load and Waste Polypropylene on the Behavior of Asphalt Layers) examines how the cohesive zone model CZM predicts the behavior of cracks in asphalt and concrete pavements. The CZM is applied to the finite element approach in the ABAQUS 6.14 simulation program for laboratory beam test data [24].

A finite element was examined using Abaqus 6.14 while taking into account composite effects for wheel loads and temperature. With two different asphalt layer thicknesses of 140 mm and 250 mm, a vehicle of type 2S-2 was put to the test. The vertical displacement is reduced by around 0.59% when the asphalt layer's thickness is increased from 140 to 250 mm. Additionally, the impact of modified asphalt with polymer on pavement vertical displacement was examined; the results showed an apparent decrease from 0.590 mm to 0.265 mm under repeated loads of 36 tons [25]. 3-D finite element analysis was performed using the ABAQUS 6.14 version program to forecast the rut in the asphalt laboratory model. The test was simulated using the finite element approach while considering the boundary conditions, load stages, and temperature. A 55°C temperature was used to demonstrate that the temperature had no discernible impact [26].

3. PROBLEM STATEMENT AND MODELING USING ABAQUS/CAE

The problem of premature collapse in the flexible pavement is one of the main problems that failed in the paving layers because of its direct impact on the design life and performance in the Iraqi road network due to the overloads of uncontrolled load vehicles and the failure to operate weighing stations at border ports and city entrances and near quarries and sources of building materials. The mechanical-experimental method that evaluates the stresses, strains, and deformations generated in the flexible asphalt layers at each design stage is one of the most important and widely used asphalt pavement design methods [9]. Excess traffic, but also due to environmental conditions such as temperatures, where temperature changes lead to shrinkage of materials and a change in the properties of the viscoelastic materials of the asphalt mixture. Unfortunately, most practitioners currently do not take any of these phenomena into the design of paving structures. Therefore, the effects of high traffic loads on permanent damages represented by the failure of exhaustion and erosion of the flexible paving layers with viscoelastic properties (using the most common method in the design, the mechanical-experimental method) were studied. Using the APAQUS program to find the values of stress, strain, and deformation in the pavement layers, in addition to analyzing the damage generated and determining the design life of the paving.

Since the primary goal of an ABAQUS software user is to represent a specific situation or resolve a particular issue before coming up with a solution, it is required to interact with the program in its own language, which involves building a model and then analyzing it. The geometry, material characteristics, and other physical attributes should be defined using these modules before the model is submitted for analysis. The actions listed below must be taken in Part, Property, Assembly, The Step, Interaction, Load, Mesh, Job, and Visualization modules.

To support the results obtained by the computer program ABAQAUS 6.12-1, verification results are worked out to compare the results obtained by the finite element program ABAQUS with those the results of the experimental work, which was conducted by the researcher [27]. Where the test was conducted on the same model that was used by the researcher. Experimental beam specimen dimensions used are 3 in (76.2 mm) high, 3 in (76.2 mm) wide, and 15 in (381 mm) long [27]. The input material characteristics for flexible pavement layers are shown in Table 1. A 3-dimensional segment of flexible pavement is subjected to a pressure of 0.6 MPa. Using 0.1 seconds of load time and 0.4 seconds of rest time on the beam, a repeating flexural stress of 0.6 kPa was applied. Figure 1 shows the flexural deformation recorded at the middle third of the beam during each load repetition at a temperature of 20°C. At the test's first 50 cycles, the initial stiffness was computed. The phase angle denotes the elastic side.

Table 1: Input of flexible pavement properties.

Beam	Modulus of Elastic (MPa)	Poisson ratio (υ)	Density (kg/m^3)	Temperature ° C
Asphalt concrete	508	0.35	2.24	20

A pressure-distributed load was applied at the mid-span and presented in ABAQUS as a function of repeated load, and a macro-crack was assumed before the load began at the bottom part of the beam, as shown in Figure 1. Two lines of nodes were selected for the specimen's lower supports, and the displacement is constrained in a vertical direction, as shown in Figure 2. The characterizations for beam material are presented in Table 1, which is used as input data for the finite element program for the asphalt beam model. According to the method of finite element principles, when refining the mesh is enough ,the effect of the size of the meshing will be smaller than the crack path propagation. The small size of the mesh could be more proper. The computation effectiveness should also be considered in Figure 3. Accordingly, materials and positions were given with different mechanical parameters to these elements.

The analysis considers the heat load since it is significant due to the high temperature in Iraq during the summer by applying the finite elements of the beam model with a three-dimensional model and appropriate materials. A model was used to investigate elastic pavement when traffic load and high-temperature influences are present. The rule of conservation of impacted energy with thermos physical properties dependent on the impressed temperatures is known as thermal analysis, and it has a huge portion in the ABAQUS software.

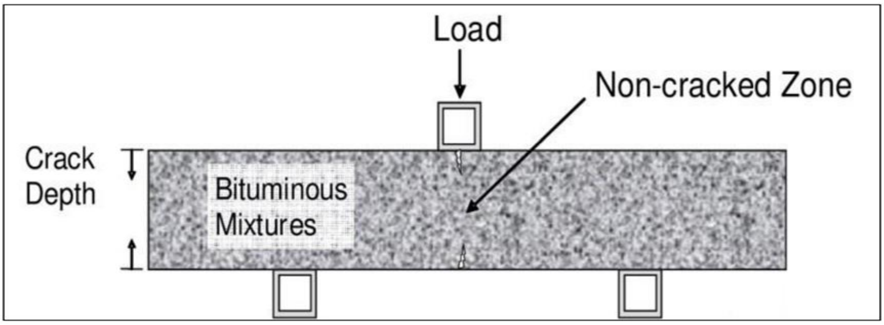


Figure 1: Beam under repeated flexural stress [27].

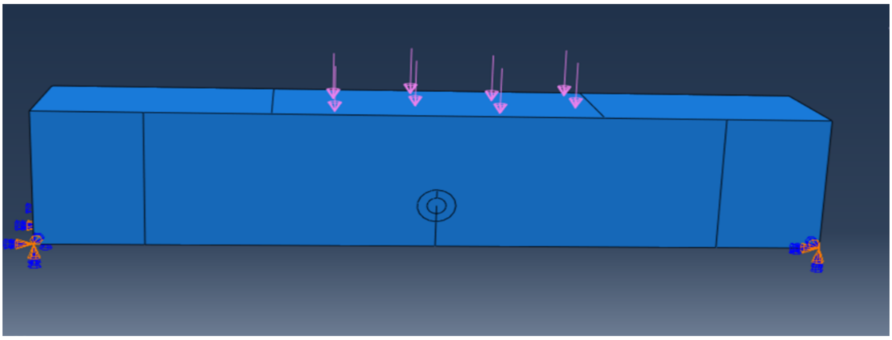


Figure 2: Boundary conditions for pavement model using ABAQUS program.

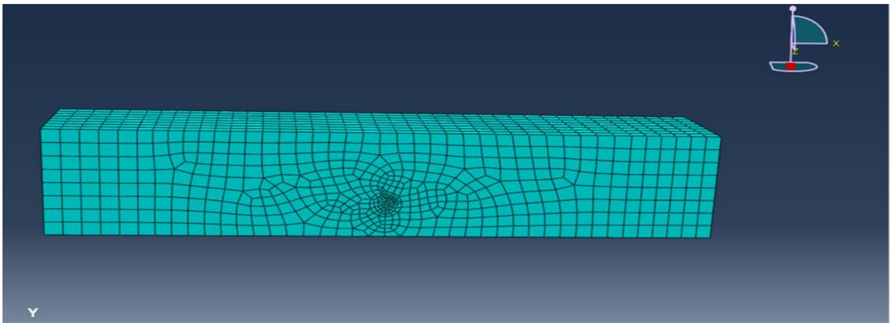


Figure 3: Pavement model finite element mesh.

4. RESULTS AND DISCUSSIONS

The obtained results demonstrate a small difference between the experimental test and ABAQUS. The application of finite element software ABAQUS using the CZM assumes that the specimens' materials are homogenous. However, there would be differences between the modeling and the tests due to the inhomogeneity of the asphalt materials. The results of the sample were verified in this study. These samples fail at different numbers of cycles and stiffness. Figure 4 explains the transverse and longitudinal distribution of vertical strain within the beam of the asphalt. The repeated load effects increased the vertical strain as shown in Figure 4, the initial strain is 0.002693 at cycle number one.

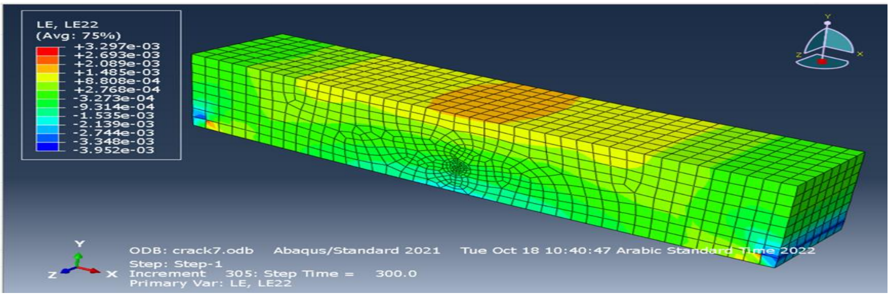


Figure 4: Vertical strain (ε_{yy}) distribution of the beam under the effect of repeated loading at 300 sec.

Figure 5 presents the maximum principal stress within the beam. A high value (257 MPa) was observed at the side of the crack at node 1151, then decreased laterally with horizontal distance .In Figure (6), the maximum tensile vertical stresses (σ_{yy}), which represent the critical values for vertical compressive stresses, are just under the load as shown in the Figure; they are concentrated at the top of the beam almost under the point of the load which is about 0.6 MPa at node 948. The tensile response of stresses immediately underneath the load may be considered as a critical response for cracking in the asphalt beam and Figure 7 Vertical displacement (U2) distribution of the beam under the effect of repeated loading at 300 sec.

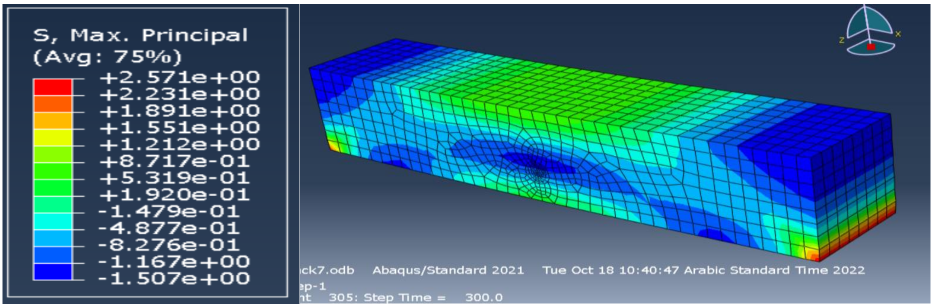


Figure 5: Maximum principal stress of the beam at 300 seconds under the influence of repeated loading.

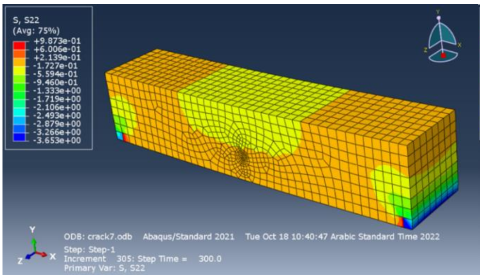


Figure 6: Vertical stress (σ_{yy}) distribution of the beam under the effect of repeated loading at 300 sec.

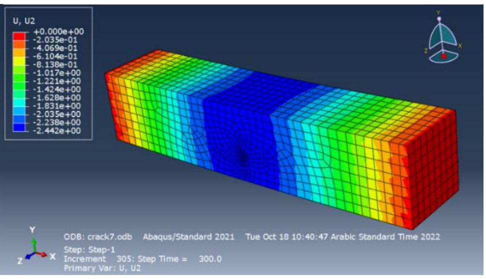


Figure 7: Vertical displacement (U2) distribution of the beam under the effect of repeated loading at 300 sec.

Figure 8 depicts the deformation behavior for the beam model. It's obvious from the Figure the distribution of the beam deformation; repeated load effects have more stresses in fatigue failure. A comparison was made between the initial strain of 18 specimens under stress of 0.61 MPa of the experimental work of [27] and finite element simulation results using ABAQUS. The correlation coefficient is 0.87, as shown in Figure 9.

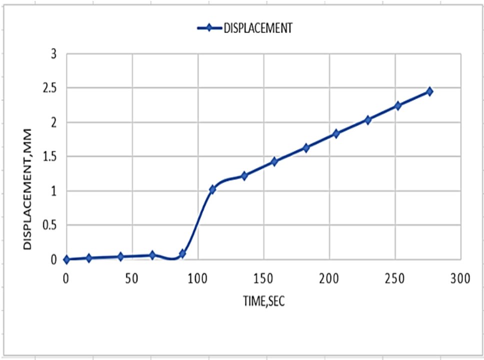


Figure 8: Vertical deformation of the beam under the effect of repeated loading.

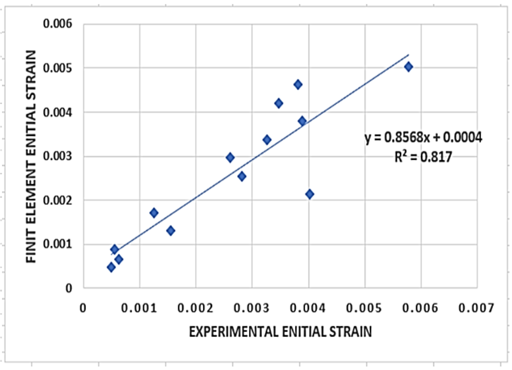
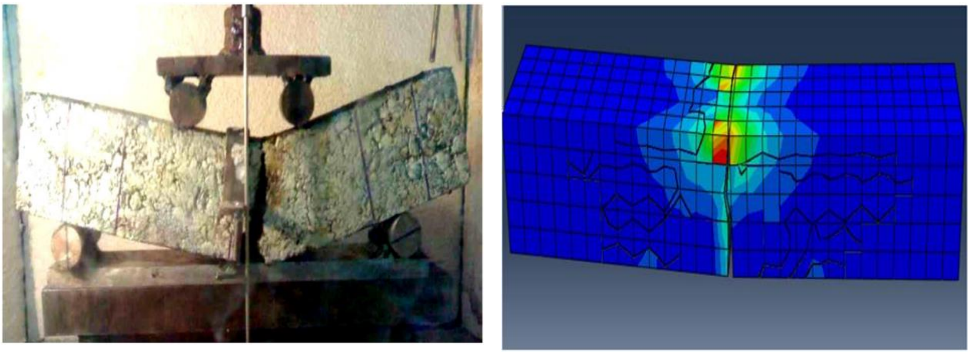


Figure 9: Correlation between initial strains measured experimentally and predicted numerically.

The results obtained from the experimental work and finite element program numerical studies show a good agreement, as shown in Figure 9. For more accuracy and to enhance confidence in ABAQUS results, the strain values are calculated by ABAQUS 6.12-1, and the same results are obtained. This indicates that these results, which are from the ABAQUS 6.12-1 program, are accurate and can be adopted practically. Also, the strain and displacement model findings align with the measured author values. The cohesive zone model in ABAQUS assumes a specimen with homogeneous material. While Figure 10 illustrates how differences between examinations and simulations would result from the inhomogeneity of asphalt materials (25). Fattah et al. [28] displayed that for strain-controlled testing, an increase in terms of aging causes a decrease in the mix stiffness and an increase in the laboratory fatigue life. In contrast, an increase in test temperatures within the tested range causes an increase in the laboratory fatigue life and a decrease in the mix stiffness. Hu et al. [29] displayed that for strain-controlled testing, an increase in terms of aging causes a reduction in the mix stiffness and an increase in the laboratory fatigue life, while an increase in test temperatures within the tested range causes an increase in the laboratory fatigue life and a decrease in the mix stiffness.



a- Crack in the test. b- Crack in simulation (distribution of stresses).

Figure 10: Comparison between crack test and crack simulation.

5. CONCLUSIONS

A drop in mixing stiffness and a reduction in laboratory fatigue life will follow increased porosity content within the test range. The model is used for investigating the crack propagation in the flexural fatigue test and for predicting experimental results simulations. According to the study results, the following conclusions were made:

- The model of coupled XFEM-CZM successfully simulated the flexural fatigue test process with the crack propagation and a linear regression $R2$=0.817.
- Analysis of crack propagation shows that the mechanism of the beam failure is principally attributed to the tensile stresses.
- The model of XFEM-CZM gives a proper numerical way of representing the flexural fatigue test.

REFERENCES

[1] Pereira P, Pais J. Main flexible pavement and mix design methods in Europe and challenges for the development of a European method. Journal of Traffic and transportation engineering (English edition). 2017 Aug 1; 4(4):316-346.

[2] Asphalt Institute. Thickness Design--asphalt Pavements for Highways and Streets. Asphalt Inst. 1981.

[3] Montuschi A, Dondi G, Pettinari AR. Flexible pavement design using Mechanistic-Empirical methods: the Californian approach. Doctoral dissertation, MSc thesis, Department of Civil, Chemical, Environmental and Material Engineering, Alma Mater Studiorum University of Bologna. 2012. Available at: https://amslaurea. unibo.it/4914/1/tesi_file_unico.pdf.

[4] Karkush MO, Jabbar A. Improvement of soft soil using linear distributed floating stone columns under foundation subjected to static and cyclic loading. Civil Engineering Journal. 2019 Mar 19;5(3):702-11.

[5] Karkush MO, Ahmed MD, Sheikha AA, Al-Rumaithi A. Thematic maps for the variation of bearing capacity of soil using SPTs and MATLAB. Geosciences. 2020 Aug 20;10(9):329.

[6] Karkush MO, Yassin SA. Using sustainable material in improvement the geotechnical properties of soft clayey soil. Journal of Engineering Science and Technology. 2020 Aug;15(4):2208-22.

[7] Jasim AA. Effect of Pavement Layers Properties on Optimum Performance by Mechanistic–Empirical Method. Journal of University of Babylon. 2015; 23(2).

[8] Huang YH. Pavement analysis and design. Upper Saddle River, NJ: Pearson Prentice Hall. 2004.

[9] Kerkhoven RE, Dormon GM. Some considerations on the California bearing ratio method for the design of flexible pavements. Shell Petroleum Company. 1953.

[10] Rossow, M. Introduction to geotechnical issues in pavement design, Geotechnical Aspects of Pavements. 1960.

[11] Samad, E. Sensitivity analysis in flexible pavement performance using MechanisticEmpirical Method. Civil Engineering Forum. 2011.

[12] Highway Design Manual, Ministry of Reconstruction & Housing, State Corporation for Roads & Bridges, Iraq. 2nd edition. 2005.

[13] Muniandy R, Aburkaba E, Thamer N. Comparison of flexible pavement performance using Kenlayer and Chev PC software program. Australian Journal of Basic and Applied Sciences. 2013; 7(9):112-119.

[14] Rind, T. A., Jhatial, A. A., Sandhu, A. R., Bhatti, I. A., and Ahmed, S. Fatigue and rutting analysis of asphaltic pavement using "KENLAYER" Software. Journal of Applied Engineering Sciences. 2019; 9(2): 177– 182. https://doi.org/10.2478/jaes-2019-0024

[15] Chegenizadeh A, Keramatikerman M, Nikraz H. Flexible pavement modelling using Kenlayer. Electronic Journal of Geotechnical Engineering. 2016; 21(7):2467-2479.

[16] Nidhi M, Nagakumar MS. Applications of Layered Theory for the Analysis of Flexible Pavements. International Journal of Research in Engineering and Technology. 2013; 2(1):200.

[17] Abdelrazek MA. Flexible Pavement Components for Optimum Performance in Rutting and Fatigue. Mansura University-Egypt. 2007.

[18] Taher BM, Mohamed RK, Mahrez A. A review on fatigue and rutting performance of asphalt mixes. Scientific Research and Essays. 2011 Feb 18; 6(4):670-682.

[19] Subhy A. Advanced analytical techniques in fatigue and rutting related characterisations of modified bitumen: Literature review. Construction and Building Materials. 2017 Dec 15; 156(1):28-45.

[20] Asim M, Ahmad M, Alam M, Ullah S, Iqbal MJ, Ali S. Prediction of Rutting in Flexible Pavements using Finite Element Method. Civ. Eng. J. 2021 Aug 1.

[21] Rahman MM, Saha S, Hamdi AS, Alam MJ. Development of 3-D finite element models for geo-jute reinforced flexible pavement. Civil Engineering Journal. 2019 Feb 26; 5(2):437-446.

[22] Abed AH, Al-Azzawi AA. Evaluation of rutting depth in flexible pavements by using finite element analysis and local empirical model. American Journal of Engineering and Applied Sciences. 2012 Aug; 5(2):163-169.

[23] Alkaissi ZA. Modelling Of Crack Propagation in Flexible Pavement Using X-FEM Method. In IOP Conference Series: Earth and Environmental Science. 2022; 961(1): 012014.

[24] Akram HA, Hilal MM, Fattah MY. Numerical Simulation of the Effect of Repeated Load and Waste Polypropylene on the Behavior of Asphalt Layers. In IOP Conference Series: Earth and Environmental Science 2022; 961(1): 012039).

[25] Akram HA, Hilal MM, Fattah MY. Numerical Investigation of Fatigue Crack in Asphalt Concrete Pavements Using Cohesive Zone Model. In IOP Conference Series: Earth and Environmental Science 2022; 961(1): 12039.

[26] Hatem NS, Hilal MM, Fattah MY. Finite Element Simulation of Repeated Loading Test of Asphalt Concrete. Engineering and Technology Journal. 2022 May 25; 40(5).

[27] Almudhadi TH. Some Requirements to Control Reflective Cracking of Overlay Asphalt Pavement. Doctoral dissertation, Ph. D. Thesis, Baghdad University. 2007.

[28] Fattah MY, Al Helo KH, Qasim ZI. Fatigue cracking performance of local superpave asphalt concrete mixtures. Eng Technol J. 2014 Nov 28; 32(12):2904-2920.

[29] Hu J, Liu P, Wang D, Oeser M. Influence of aggregates' spatial characteristics on air-voids in asphalt mixture. Road Materials and Pavement Design. 2018 May 19; 19(4):837-55.