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Influence of Base Layer Thickness and Property on Flexible Pavement Behavior

Sura Kamal Mohamed[1,*], Mohannad Hussain Al-Sherrawi[2]

Department of Civil Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
sura.kamal2101m@coeng.uobaghdad.edu.iq[1], dr.mohannad.al-sherrawi@coeng.uobaghdad.edu.iq[2]

ABSTRACT

When designing the pavement layers, a suitable thickness must be chosen to protect the pavement from environmental conditions and traffic loads and ensure the structure's durability up to the design life. To investigate the behavior of flexible pavement, the characteristics and thickness of each layer are programmed into the finite element method (FEM). The Abaqus program is one of the infinite-element analysis programs. The use of the Abaqus program leads to a reduction in cost and time compared to laboratory tests. In this study, the Abaqus program analyzed a three-dimensional model of a multi-layered road section, and all materials have elastic behavior. The model comprises five layers (wearing, binder, base, subbase, and subgrade). The model was looked at with different base layer thicknesses (15, 25, and 30 cm) and elasticity moduli (1655, 2070, and 3000 MPa). Critical parameters were looked at in the present research: vertical displacement at the wearing layer's top, horizontal tensile strain in the asphalt layer's lowest point, and vertical compressive strain at the subgrade's surface. The outcomes indicated that the pavement is more susceptible to rutting than fatigue as a result of static load. An increase in thickness and modulus of elasticity for the base layer leads to a reduction in rutting risks.

Keywords: Abaqus program, Base layer, Flexible pavement, Finite element, Vertical displacement

*Corresponding author
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تأثير التغير في سمك وخصائص طبقة الاساس على التبليط المرن

سرى كمال محمد *، مهند حسين محسن

قسم الهندسة المدنية، كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة

عند تصميم السمك لطبقات التبليط يجب اختيار السمك المناسب لكل طبقة لضمان حماية المنشأ من تأثير العوامل البيئية والاحمال المرورية ولضمان ديمومته حتى نهاية العمر التصميمي. طريقة العناصر اللامحدودة تستخدم لدراسة طبيعة التبليط المرن من خلال ادخال خصائص وسمك كل طبقة. برنامج الاباكوس هو أحد برامج التحليل للعناصر اللامحدودة. وان استخدام برنامج الاباكوس يودي الى تقليل بالوقت والكلفة بالمقارنة مع الفحوص المختبرية. في هذه الدراسة تم استخدام برنامج الاباكوس لتحليل نموذج ثلاثي الابعاد، متعدد الطبقات لمقطع طريق وجميع المواد كانت ذات طبيعة مرنة. النموذج يتكون من خمسة طبقات (السطحية، الرابطة، الأساس، تحت الأساس، التكوين). تم دراسة النموذج بسماكات مختلفة لطبقة القاعدة (15، 25، 30 سم) ومعامل المرونة (1655، 2070، و 3000 ميجا باسكال). تم النظر في العوامل الحرجة في هذا البحث: الإزاحة الرأسية في الجزء العلوي من الطبقة المتآكلة، وإجهاد الضغط العمودي في الجزء العلوي من الطبقة السفلية، وإجهاد الشد الأفقي في الجزء السفلي من طبقة الأسفلت. أظهرت النتائج أن الرصيف أكثر عرضة للتخدد من التعب نتيجة الأحمال الساكنة. تؤدي الزيادة في سمك ومعامل المرونة للطبقة الأساسية إلى تقليل مخاطر التخدد.

الكلمات الرئيسية: برنامج الاباكوس، طبقة الأساس، التبليط المرن، العناصر المحددة, الهبوط العمودي

1. INTRODUCTION

Because roads and pavements are essential for modern societies' economic and communicational activities, scholars are always looking for new methods to analyze pavement behavior **(Shafabakhsh et al., 2013).** For roads, airports, and industrial yards with flexible pavement, the thickness of the pavement is determined by calculating the stresses and strains that happen in the structure as a result of the traffic loads and comparing them to the stresses and strains that are allowed **(West et al., 2005).** Boussinesq performed the first research on pavement structure **(Duncan and Chang, 1970).** The bond between the pavement layers must be appropriate to ensure the durability of the pavement. Weak bonding leads to the pavement layers slipping, especially in vehicle braking areas **(Nonde, 2014).** Surface deflection is essential for understanding how well pavement structures can stand up **(Zhang and Wang, 2011).** Each pavement layer has different properties and deformability so it's harder to analyze **(Kumela, 2018).** The base layer is essential as it transmits and distributes the traffic loads imposed on the pavement surface to the subgrade. Currently, In China, asphalt pavement with a semi-rigid base is the most popular choice for more than 90% of roadways. When the Hot Mix Asphalt (HMA) surface shows inadequate bonding with the underlying layers, it can result in the ability of the upper pavement layer to slide or shift when subjected to vehicular traffic **(Mehta, 2008).** Insufficient transfer of loads to the lower layers of the asphalt pavement, coupled with stress absorption by the upper sliding layers, can result in the formation of ruts **(Lushinga and Xin, 2015).** The most common causes of damage to flexible pavements are fatigue cracking and rutting that take place on the pavement surface due to the effects of traffic and weather **(Qadir, 2013; Al-bayati and Lateif, 2017; Lateif, 2019; Al-Azawee and Lateif, 2020; Samor and Sarsam, 2021)**. Creating a flexible conventional pavement system that requires less maintenance and lasts longer requires an understanding of the primary causes of rutting and pavement fatigue. **(Saad and Poorooshasb, 2005).**

Prove finite element (FE) programs, such as ABAQUS and ANSYS, have proven effective in accurately predicting the response of pavements under various traffic load conditions. These programs take into account a wide variety of constitutive laws for the different layers of the pavement. **(Zaghloul and White, 1993; Uddin and Ricalde, 2000; Kuo and Darter, 1995; Dondi, 1994).** The flexible pavement's reaction to shifting loads is predicted using a finite element model. Implicit dynamic analysis was used to investigate inertia's effect on the reaction of pavement structures **(Al-Qadi and Tutumluer, 2010).** Three-dimensional finite element analysis tools were the best way to deal with important issues in constructing pavements **(Chen and Soltani, 1995; Cho and Weissmann, 1996; Kuo and Darter, 1995).** There is a shift towards mechanical design techniques to reduce the constraints in calculations of stress, strain, and deflection in pavement analysis. The use of finite elements to examine the mechanical behavior and performance of pavement, which is subject to different traffic factors: type of axle, the inflation pressure of the wheel, the contact area of the wheel, vehicle speed, the number of load repetitions, heavy vehicles, such as trucks, significantly influence pavement distress, failure, etc. The earliest publication on finite element method (FEM) analysis of a pavement structure was documented in 1968 **(Duncan and Wilson, 1968)**. There is a shift towards mechanical design techniques to reduce the constraints in calculations of stress, strain, and deflection in pavement analysis**. (Ahirwar and Mandal, 2017)** used finite element analysis with PLAXIS 2D software to look into what would happen if geogrid material was used in the base layer at different depths and loads to make the pavement, base, and subbase last longer. According to the findings, using geogrids reduces the vertical displacement of the pavement layers as compared to not using them. Similarly, as the geogrids' axial stiffness increases, there is a decrease in vertical displacement. **(Yin et al., 2022)** used the Abaqus software to evaluate a three-dimensional model using FEM and investigated the impact of geogrids on reinforcing pavement. employed three different kinds of geogrids: firm, medium, and soft. Every variety has a unique modulus of elasticity. These materials were employed beneath the asphalt layer as well as between the base and subgrade. By putting the geogrid between the base and the subgrade in a single layer, the authors concluded that permanent deformation is reduced. The stress generated at the top of the subgrade will be reduced by using the geogrids in two layers: one between the base and the subgrade and the other beneath the asphalt layer. **(Saad and Al-Baghdadi, 2021)** used the Abaqus software to evaluate a three-dimensional model using FEM and investigated rutting depth. They used two types of asphalt mixtures: ordinary and those containing rubber. They concluded that the rubber asphalt mixture reduces the rutting depth by 37% compared to the ordinary. **(Alkaissi and Al Khafagy, 2009)** The researchers conducted a study to analyze the mechanics and spread of cracks generated on the surface of the composite pavement. The two-dimensional model was analyzed using FEM in ANSYS software. The researchers stated that the cause of cracks in the surface layer is high vertical stress and shear stress from the vehicle's tires. These cracks move downward due to the tensile stress below the layer of asphalt and the tension generated at the tip of the crack. The authors assumed the presence of a crack in the underlying concrete layer. The crack in the asphalt and concrete layers was represented in

the form of a gap whose length is the same as the length of the crack. In this study, the stress intensity factor (SIF) and the stress at the upper and lower layers of the asphalt layer, As well as shear stress at the asphalt layer's base, were examined. The asphalt layer is used at various thicknesses by the researchers, ranging from 2.5 to 15 cm. The researchers found that increasing the thickness of the asphalt layer leads to a decrease in shear stress, stress, and the stress intensity factor (SIF). A decrease in these parameters leads to a reduction in the risk of the crack spreading downward.
Using ABAQUS 6.14-2, this study models and examines the behavioral response of the pavement system. This study aims to investigate a three-dimensional model using the method of finite elements. There will be three different base layer thicknesses used: 150, 250, and 300 mm, and three different elastic moduli (1655, 2070, and 3000 MPa).
The objectives of this work are:

- investigate the impact of changing the base layer's thickness and modulus of elasticity on the performance of asphalt pavement in terms of strain and displacement.
- Also, the study aims to study the sensitivity of pavement to thickness and property changes and its effect on layers of pavement to reduce surface deflection and soil stresses.
- To scale the life of rutting and fatigue and take cost issues into account, pavement analysis serves as essential to improving the structural design of pavement.
- With this program, one can select an appropriate base layer to reduce deformation values.

2 MATERIALS AND METHODS

2.1 Material Properties

The wearing, binder, base, subbase, and subgrade layers are considered to have linear elastic behavior in this study. a certain Poisson ratio and modulus of elasticity. The layered properties of the pavement section, as shown in **Table 1.** below **(Abed and Al-Azzawi, 2012)**, were used to simulate the Abaqus program.

Table 1. Material property of layers of flexible pavement **(Abed and Al-Azzawi, 2012)**

Layers name	Thickness (mm)	Modulus of elasticity (MPa)	Poisson ratio
Wearing	50	2689	0.35
Binder	80	2206	0.35
Base	150	1655	0.35
Subbase	300	110	0.4
subgrade	2000	35	0.499

2.2 Finite element Model

According to **(Bohagr, 2013)**, the flexible pavement is modeled as a multilayer structure subjected to static loading. The 3D model of the flexible pavement, as shown in **Fig. 1**, was created with the ABAQUS software program and included the following layer properties: wearing course (50 mm thickness), binder course (80 mm thickness), base course (150 mm thickness), subbase course (300mm thickness), and subgrade soil (2000mm thickness), as shown in **Table 1**. Using an appropriate size horizontal projection (4000 mm x 5000 mm) in longitudinal and transverse directions reduces the error caused by the edge effect **(Alkaissi and Al-Badran, 2018).** Only half of the axle was modeled and simulated to reduce effort and time.

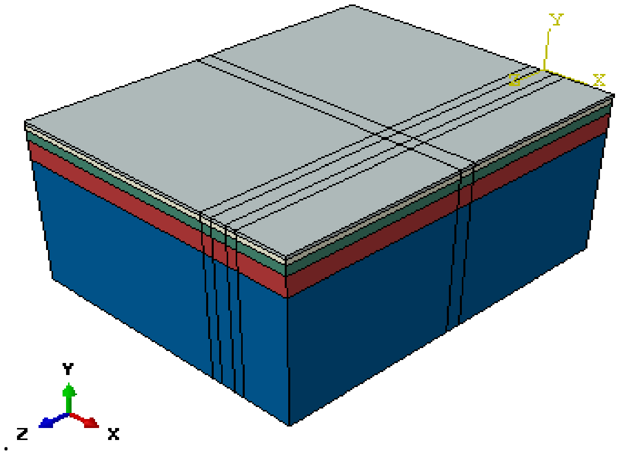


Figure 1. The 3D multilayer model of flexible pavement

This research studied the effect of changing thickness and modulus of elasticity of the base layer on vertical displacement at the wearing layer's top, horizontal tensile strain in the asphalt layer's lowest point, and vertical compressive strain at the subgrade's surface. Several thicknesses of the base layer was used: 15, 25, and 30 cm, and Several modulus of elasticity , which are1655, 2070, and 3000 MPa while maintaining the same thickness and modulus for the rest of the layers,

2.3 Wheel Load

Assumed standard axel load. Load value of 80kN with dual tires with contact pressure of 0.65 MPa shown in **Fig. 2**, with the contact radius of the tire being 9.89 cm.

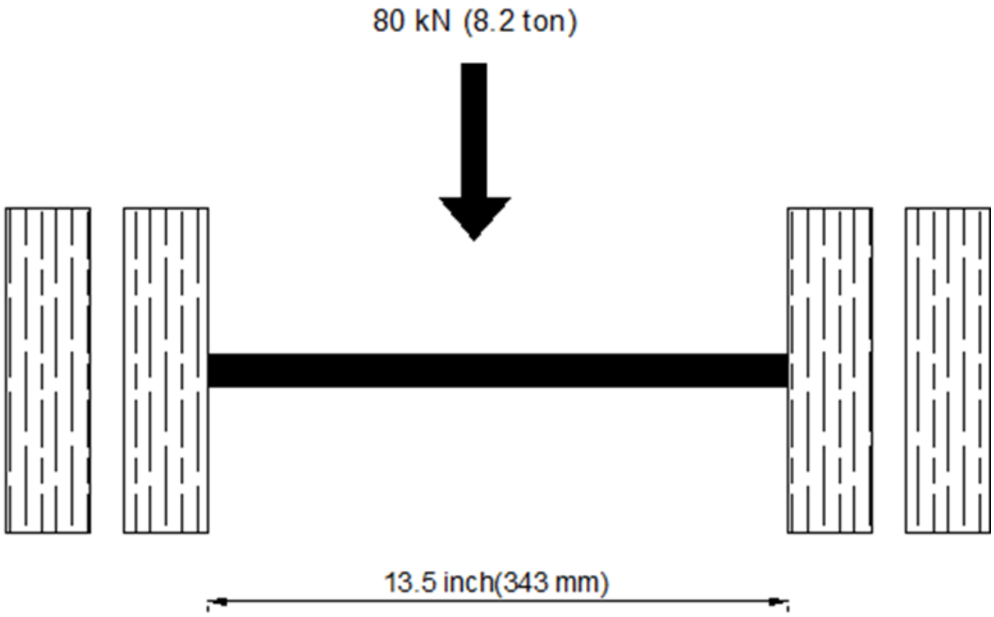


Figure 2. Standard axle (Huang, 2003)

The simulation process with ABAQUS software for the model depends on defining the value of the applied load as a pressure load, representing the effect of the vehicle's wheel. The axle's load is transferred to the pavement surface through the uniform contact area of each tire is calculated by Eq. (1) **(Khodary et al., 2020).** Uniform contact pressure of each tire (0.65 MPa) While disregarding the tire wall's stiffness effect, the contact pressure will equal the tire pressure **(Huang, 2004).**

$$Contact\ radius\ (cm) = 100 * \sqrt{\frac{load\ on\ singlet\ ire\ (kn)}{\pi * tire\ pressure (kpa)}} \quad (1)$$

The contact area is the contact region between the wheel and the top layer of asphalt while a vehicle moves above a section of pavement. It depends on tire pressure, which rises as tire pressure lowers. The contact area is irregular in shape, consisting of two semicircles and a rectangle in the middle **(Huang, 2003)**. The contact area simulated by ABAQUS using the rectangle shape with an area of 0.5227 L2 is shown in Eq. (2) and **Fig. 3 (Huang, 2003)**. The wheel load is distributed over a contact area of 210*145 mm in the longitudinal and transverse directions. A rectangle footprint for the wheel was utilized to improve agreement with finite element meshing.

$$Lc = * \sqrt{\frac{load\ on\ singlet\ ire\ (N)}{0.5227 * tire\ pressure (MPa)}} \quad (2)$$

where:
Lc = length of Tire footprints, mm
For convert to a rectangular area, the length L=0.8712 Lc (in the direction of moving) and width B =0.6Lc **(Zhang et al., 2017).**

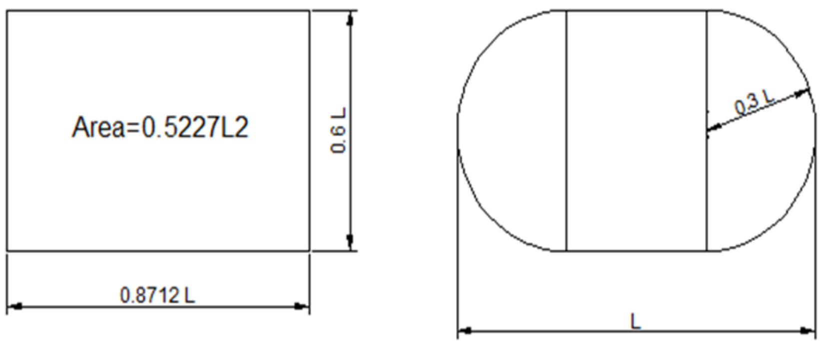
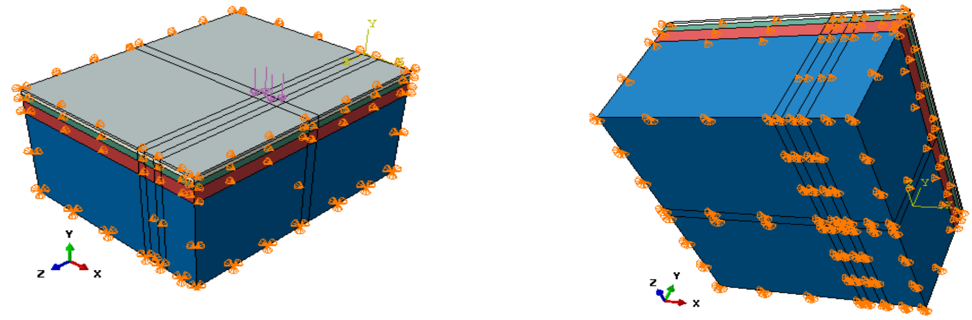


Figure 3. The contact area of tire pressure with a surface of flexible pavement **(Huang, 2003)**

2.4 Boundary Conditions

The displacements in each pavement model layer were controlled by specified boundary conditions. **(Khodary, 2020)**. In predicting the model response, boundary conditions have a significant impact **(Hadi, Al-Sherrawi, 2021)**. The boundary conditions were used to imitate the actual boundary conditions. Abaqus uses rotation and displacement as types of boundary conditions. The bottom of the subgrade is considered to be fixed, meaning it cannot move in either a horizontal (x, z-axis) or vertical (y-axis), which is represented by (U1, U2, U3 = 0) in the ABAQUS program results **(Shanbara et al., 2016)**. The pavement's four sides' edges assume horizontal displacement constraints and freedom in the vertical displacement direction **(Alkaissi and Al-Badran, 2018)**. **Fig. 4** shows the boundary conditions used in the analysis.



(a) Edges of the pavement model (b) Bottom of the subgrade

Figure. 4 The different cases of boundary conditions of the model

2.5 Interaction Modeling Techniques

Two different regions can be combined by interaction, as seen in **Fig. 5**; the tie-contact type is utilized in the FEM to imitation of the way that flexible pavement layers interact **(Alkaissi and Al-Badran, 2018)**.

2.6 Mesh and Element Type

Mesh is the process of dividing the model into groups of finite elements (FE) and depends on the type of design and its requirements. This study used a type of element: the linear element C3D8R (8-node continuum three-dimensional brick element with reduced order numerical. C3D8R may depict significant deformations as well as geometrical and material nonlinearities. Three degrees of freedom are available for translations in the nodal x, y, and z directions for the solid element C3D8R at each node. By adopting a smaller mesh, FEM simulation accuracy is better **(Liu and Glass, 2013).** Therefore, the fine mesh was utilized in the loading area along the tire path. To reduce the amount of time needed to do the analysis, a sufficiently coarse mesh is employed in both vertical and horizontal directions far from the loading region, as demonstrated in **Fig. 6**.

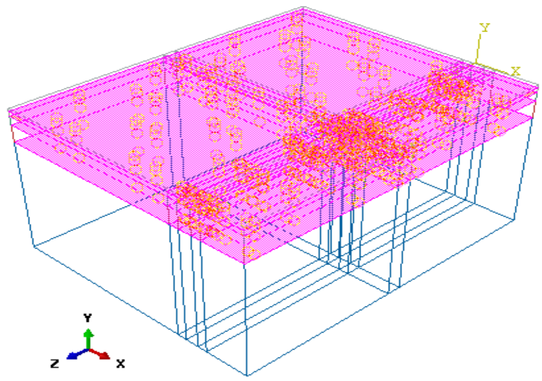


Figure 5. The interaction between all layers of 3D model

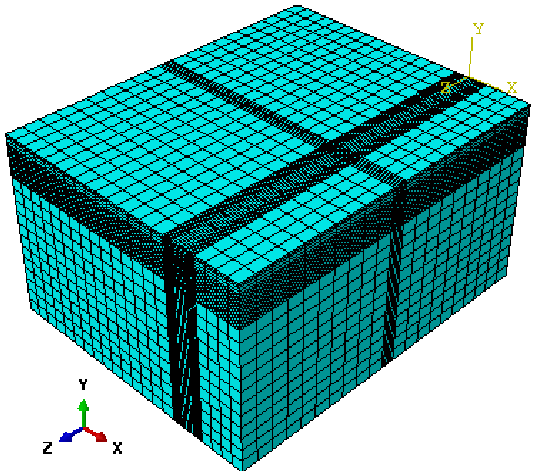


Figure 6. Mesh for the 3D model

3. RESULTS AND DISCUSSION

The study focuses on the vertical displacements at the top of the wearing layer, the vertical compressive strain at the top of the subgrade, and the horizontal tensile strain at the asphalt layer's lowest point of the pavement while considering various thicknesses and moduli of elasticity for the base layer. **Fig. 7** shows the critical strains in the flexible pavement.

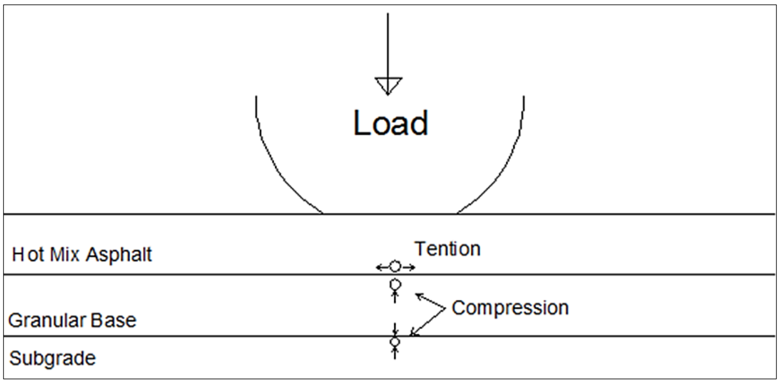


Figure 7. Failure modes and critical strains **(Huang, 2003)**

When a stationary load affects the pavement structure, the peak deformation is observed at the load's center, and the displacement distribution displays a nearly circular and symmetrical pattern. By examining the results, it turns out that the value of the vertical compressive strain at the top of the subgrade is greater than the horizontal tensile strain at the asphalt layer's bottom. Therefore, pavement subjected to static loads is more at risk of collapse due to rutting than fatigue.

3.1 Vertical Displacements

Fig. 8 shows the variation of the value of vertical displacement with changes in thickness and modulus of elasticity. As the thickness of the base layer rises from 150 to 300 mm and the modulus of elasticity remains constant at 1655MPa, the magnitude of vertical displacements varies from 0.3643 to 0.243 mm, indicating a 33% decrease as the increase in thickness leads to a decrease in the concentration of the vertical load. The results of the vertical displacement are consistent with the findings by (**Khodary et al. 2019**) who concluded that increasing the thickness of the base layer from 10 to 30 cm leads to a decrease in the vertical displacement by 45.8% at the top of the surface layer of the asphalt pavement. (**Hadi and Al-Sherrawi, 2021**) examined the impact of varying the thickness of the base layer. Who concluded that increasing the thickness of the base layer from 10 to 30 cm leads to a decrease in the vertical displacement by 37% in the top of the wearing layer below the center of the tire. When the base layer's thickness was set at 150 mm and the modulus of elasticity was modified from 1655 to 3000MPa, there was a 9.9% decrease in the value of vertical displacements, which varied from 0.364 to 0.328 mm. Consequently, vertical displacement at the wearing layer's top has a greater effect by increasing the thickness of the base layer than by raising the modulus of elasticity.

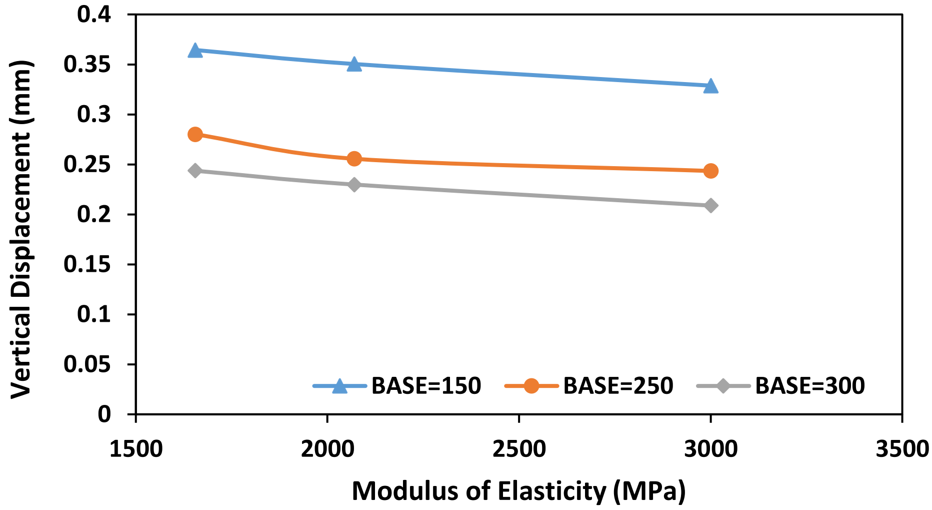


Figure 8. The vertical displacement for all attempts

3.2 Fatigue Criterion

The fatigue criteria incorporate the outcomes of the horizontal tensile strain on the lowest part of the asphalt layer to calculate the fatigue life. **Fig. 9** shows the variation of the value of horizontal tensile strain at the asphalt layer's bottom with changes in thickness and modulus of elasticity. When the base layer's thickness increases from 150 to 300 mm and the modulus of elasticity at 1655 MPa, the value of horizontal tensile strain on the lowest part of the asphalt layer changes from $5.087*10^{-5}$ to $4.6201*10^{-5}$ mm, indicating a 9.17% decrease. When the base layer's thickness was constant at 150 mm, and the modulus of elasticity was increased from 1655 to 3000 MPa, there was a 34.1 % decrease in the value of horizontal tensile strain at the asphalt layer's bottom, which changed from $5.087 *10^{-5}$ to $3.35 *10^{-5}$ mm. increasing the thickness of the base layer affects the horizontal tensile strain at the asphalt layer's bottom less than increasing its modulus of elasticity. This is completely consistent with the findings by **(Ranadive and Tapase, 2016)** who stated that increasing the modulus of elasticity of the base layer reduces the collapse of the pavement resulting from fatigue.

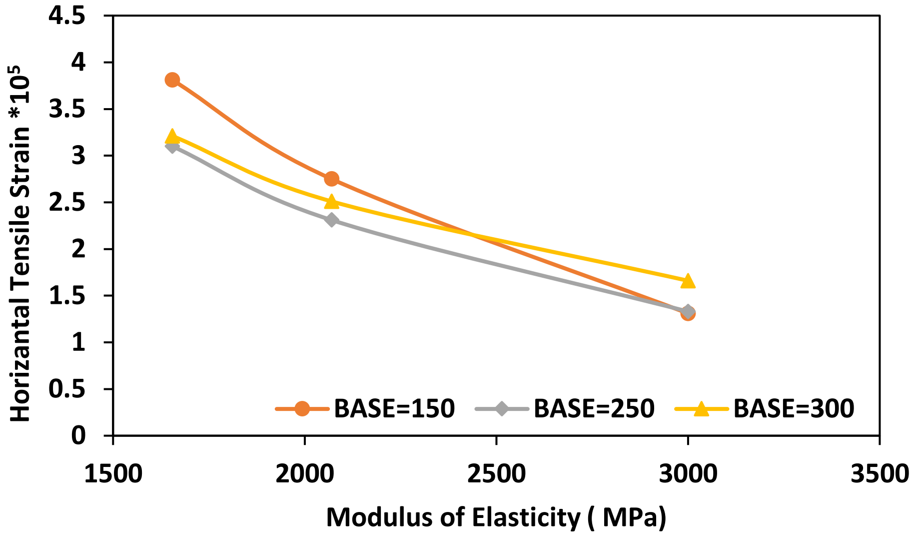


Figure 9. Horizontal tensile strain for all attempts

3.3 Rutting Criterion

The rutting criteria incorporate the outcomes of the vertical compressive strain at the subgrade's surface. **Fig.10** shows the variation of vertical compressive strain at the top of the subgrade with changes in thickness and modulus of elasticity. When the base layer's thickness increases from 150 to 300 mm and fix the modulus of elasticity at 1655 MPa, the magnitude of vertical compressive strain at the top of the subgrade varies from 0.00024 to 0.00014 mm, indicating a 41.6% decrease. When the base layer's thickness was set at 150 mm and the modulus of elasticity was modified from 1655 to 3000 MPa, there was a 14.2% decrease in the value of vertical compressive strain at the top of the subgrade, which varied from 0.00024 to 0.00021 mm. Consequently, increasing the thickness of the base layer affects the vertical compressive strain at the top of the subgrade more than increasing its modulus of elasticity.

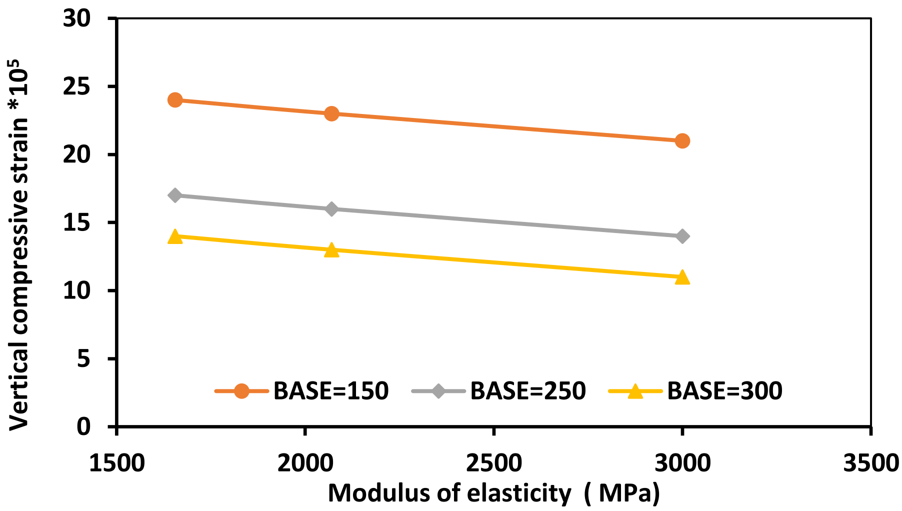


Figure 10. Vertical compressive strain for all attempts

This is completely consistent with the researchers **(Tapase and Ranadive, 2016)** concluded that Rutting-related damage is decreased by deepening the base layer and raising its modulus of elasticity. A perfect subgrade condition is a base layer that is 300 mm thick with an elasticity modulus of 3000MPa and is suitable for asphalt conditions, an improvement in rutting and Fatigue criteria by 54%, 33.7% about the original condition.

4. CONCLUSIONS

The most common deformations occurring in asphalt pavement rutting and fatigue were discussed and suggestions for the best way to reduce these deformations were obtained. The model comprises five layers (wearing, binder, base, sub-base, and subgrade). The model was looked at with different base layer thicknesses (15, 25, and 30 cm) and elasticity moduli (1655, 2070, and 3000MPa). Critical parameters were looked at in the present research: vertical displacement at the top of the wearing layer, horizontal tensile strain at the lowest part of the asphalt layer, and vertical compressive strain at the surface of the subgrade. According to this study, the following can be concluded:

- The pavement subjected to static loads is more at risk of collapse due to rutting than fatigue.
- The vertical displacements at the peak of the surface layer are more affected by raising the thickness of the base layer than by increasing its modulus of elasticity.
- increasing the thickness of the base layer affects the horizontal tensile strain at the asphalt layer's bottom less than increasing its modulus of elasticity.
- Raising the base layer's thickness has a greater impact on the subgrade's top vertical compressive strain than raising its elastic modulus.

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Credit Authorship Contribution Statement

Mohannad H. Al-Sherrawi: Writing – review & editing, Writing – original draft, Validation, Software, Methodology. Sura Kamal: Writing – review & editing, Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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