JOURNAL OF SCIENCE, TECHNOLOGY AND ENGINEERING RESEARCH

Bilim, Teknoloji ve Mühendislik Araştırmaları Dergisi

ISSN (Online) 2717-8404

Available *online* at *https://dergipark.org.tr/en/pub/jster*

RESEARCH ARTICLE

Investigation of the effect of asphalt and sub-base layer thicknesses on pavement surface deformation by the finite element method

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Citation:

Bayazit, M., Şahinkaya, F. (2024). *Investigation of the effect of asphalt layer and sub-base layer thicknesses on pavement surface deformation by the finite element method*, Journal of Science Technology and Engineering Research, 5(1):24-33. DOI:10.53525/jster.1452916

HIGHLIGHTS

- *Effect and importance of size of loading affects surface permanent deformation.*
- *Sub-base should be added rather than increasing the asphalt concrete layer.*
- *Finite element analysis can perform analyses that cannot be done experimentally.*
- *The study results are important for understanding how layer thicknesses impact the deformation.*

Article Info

Received : 15 March 2024
Accepted : 04 May 2024

DOI:
10.53525/jster.1452916

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ABSTRACT

The layer thickness of flexible pavements is one of the important parameters affecting permanent deformations. In this study, the effect of sub-base thickness and asphalt concrete thickness on the deformations under axial loads was investigated using the Plaxis 2D finite element software. In the study, 100, 200, 300, 400, 500, and 600 kPa pressure were applied to the asphalt pavement surface. In the first case, the base layer of 30 cm thickness was kept constant, and the asphalt layer was changed from 9 to 14 cm. In the second case, the asphalt thickness at 9 cm and the base layer thickness of 30 cm were kept constant, and the sub-base layer thickness was selected at 30, 40, and 50 cm respectively. As a result of the completed analysis, it was observed that the deformations on the pavement surface decreased with increasing thickness of the layers; furthermore, the use of a sub-base layer in the pavement considerably increases the deformation resistance.

Keywords: *Finite element analysis, Pavement, Asphalt, Layer thickness, Sub-base*

I. INTRODUCTION

Flexible pavement is the most widely used road paving material in the world. It is a layered structure of different granular materials. It is important that the pavement provide a safe surface for passengers and vehicles without deforming under traffic loads. The permanent deformation resulting from the traffic loads is an important parameter affecting the service life of the pavement. In addition to the stability of the asphalt concrete; the layer thicknesses, the quality of the material, and the application experience affect the durability of the flexible pavement. The properties of the materials used in the flexible pavement can be determined by experimental methods. However, it is not possible experimentally to investigate the deformations that will occur on the pavement surface under the effect of different material properties, layer thicknesses, and loads. One of the analytical and modeling techniques for various types of structures is the finite element method (FEM). This method is suitable for analyzing the deformation of the pavement surface under different boundary conditions, different material properties, different layer thicknesses, and different loads. [1].

Asphalt concrete has plastic, viscous, and elastic qualities all at once and all of which are significant, particularly when the temperature is high. The use of an elastic model appears inadequate in accurately characterizing the actual behavior of asphalt concrete under high temperatures. Due to this, many researchers employ various rheological models, such as viscoelastic models [2]. In order to estimate the pavement's thermal behavior, ANSYS source code was employed, and the proposed simulation model accurately predicts the pavement temperature at various levels of bituminous layers [3]. Asphalt concrete is also thought to resemble soil because it is composed of air, water, and aggregate. [4, 5]. Thus, asphalt concrete can be modelled as a Mohr-Coulomb material with both cohesive and granular properties at intermediate temperatures [5, 6]. However, linear elastic model is frequently employed for the mechanistic analysis and modelling of asphalt pavement structures. The behavior of asphalt layers at lower temperatures can be accurately determined using this method [2]. Some completed studies used a linear elastic model to represent asphalt concrete [1, 7-9].

In order to evaluate the stresses and deformation on the pavement surface, several numerical studies have been conducted [1]. In the study in which rutting deformation was determined, the axisymmetric two-dimensional finite element approach with varying layer thicknesses and material parameters was used. The results showed that increasing the base layer's thickness and elastic modulus reduced rutting damage but had little effect on fatigue damage. Additionally, the researchers emphasised that the analysis was beneficial for designing a pavement, as it ensures a balance between fatigue and rutting life. [10]. The semi-analytical finite element method (SAFEM program) was utilized to analyze the effects of high traffic loads on stress and strain distribution, surface deformation, and fatigue life. The findings suggested that in order to resist surface deformation, it was necessary to adequately increase the thickness and stiffness of the structural layers of the asphalt pavement when exposed to high levels of traffic. Furthermore, compared to the other pavement layers, the compressive stress on the asphalt binder surface was relatively large and increased more significantly when the axle load was applied. [11]. Wheels and axles of heavy vehicles configurations were modelled in 3D with the finite element (Ls-Dyna) method and dynamic analysis was performed. The study determined that wheels with large contact areas and a single design were the most harmful in terms of causing rutting damage and fatigue cracks. [12]. The Plaxis 3D program was utilized to examine the performance of asphalt concrete pavement without reinforcement and with geogrid reinforcement under different tire pressures. The model was loaded incrementally from 100 to 600 kPa at 50 kPa increments, and critical pavement responses such as total stress and vertical surface deformation were calculated. The study showed that the influence of the geogrid placement at the base of the asphalt concrete surface layer on pavement response was evident during static loading. [8]. The effect of geogrids on the axial stiffness of the pavement in base layers of different thicknesses was investigated using Plaxis 2D software. The base, sub-base, and subgrade layers were modeled with the Mohr-Coulomb model. The study was found that the vertical surface deformations in flexible pavement reinforced with geogrids were less than those in unreinforced flexible pavements. Also, vertical surface deformation was approximately constant when base layer thickness varied from 150 to 200 mm. [1].
The studies have indicated that improving material properties, increasing layer thicknesses, or using geogrid in the layers decreased surface deformation of asphalt pavement. In this study, PLAXIS 2D software was used to do finite element modeling of pavement layer thickness and the deformation of the pavement surface was trying to be determined. Also, the asphalt layer was modelled as linear elastic and the temperature effect was not investigated in the study since the linear elastic model better modelled the asphalt at low temperatures [2].

II. METHOD

For flexible pavement design, a three-layer section consisting of asphalt concrete, base layer, and sub-base layer was chosen. The Plaxis 2D software was utilized to analyze the impact of varying asphalt concrete and sub-base thicknesses on the deformation of the pavement surface under varied levels of axial load. The layers forming of the pavement were selected in two different ways. In the first case, as seen in Figure 1, without sub-base layer, while in the second case, as seen in Figure 2, the sub-base layer was used. In the without sub-base model, the asphalt concrete layer thicknesses were modeled in incremental thicknesses ranging from 9 to 14 cm. In the model using sub-base, the asphalt concrete thickness (ACT) was kept constant at 9 cm, and the sub-base thicknesses (SBT) were modeled separately at 30, 40, and 50 cm. The base layer thickness was selected as 30 cm in both models. Throughout the entire model, the ground layer was selected to consist of soft soil. The models were created separately for each layer thickness in the Plaxis 2D software, and the load was applied to the pavement surface. The pressure of the dual-type tires was applied statically on the pavement. A range of 100–600 kPa was used for the applied pressures [9]. An plane strain model was utilized in the analysis using 15-noded structural solid element with fine refinement. The study employed plane strain modelling to accurately simulate the load exerted by vehicle tyres on the pavement surface. Analyses were performed under similar loading conditions using the plain strain model in the literature. [7]

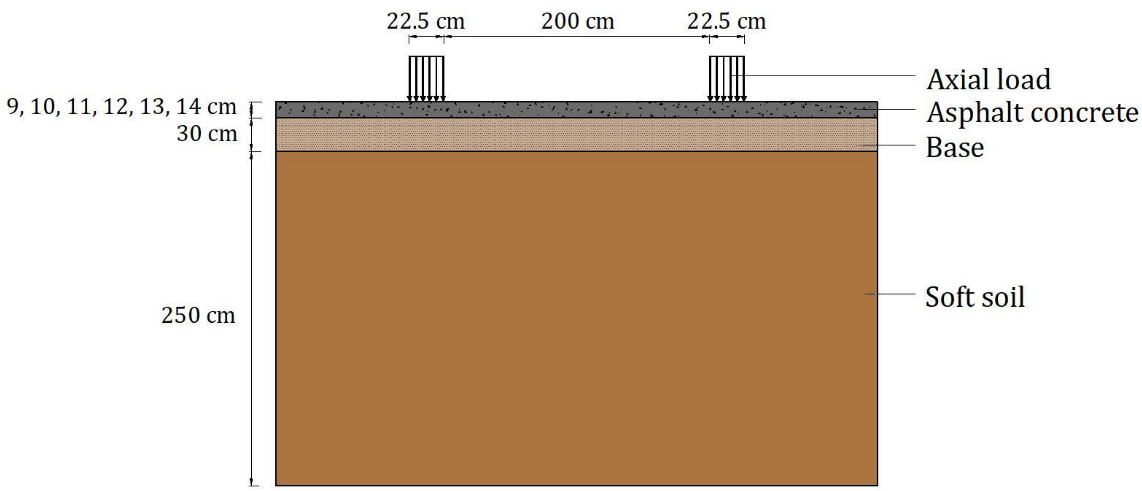


Figure 1. Thickness of layers in pavement without sub-base (ACT range 9-14 cm, Base =30 cm)

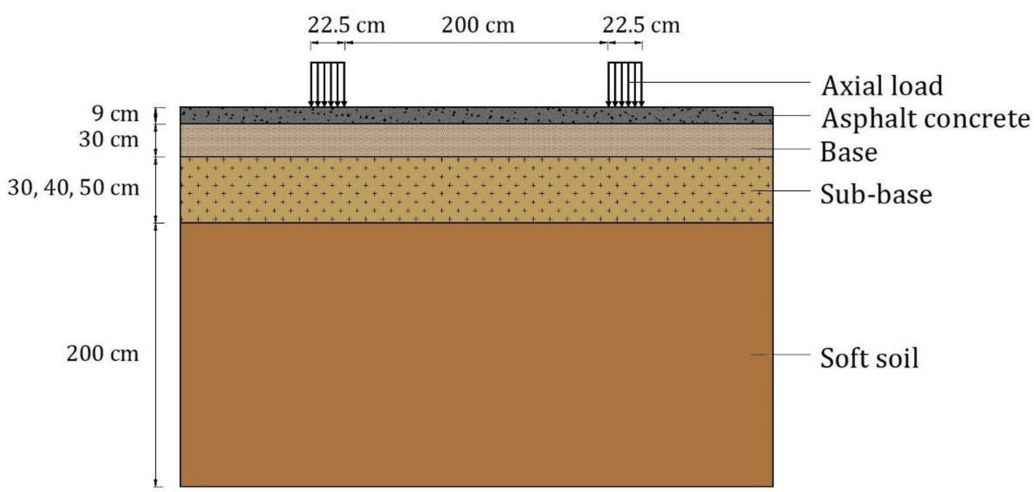


Figure 2. Thickness of layers in pavement with sub-base at 30, 40, and 50 cm (ACT=9 cm, Base=30 cm)

Table 1 lists the material properties utilized in the analysis model, which were chosen based on the completed studies [7, 9].

Table 1. Material properties of pavement layers

Material		Surface Course (Asphalt concrete)	Base Course (Crushed aggregate)	Sub-base (Clay)	Soft Soil (Clay)
Type of Model		Linear elastic	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
Mesh type		Fine	Fine	Fine	Fine
Layer Thickness (cm)	Without sub-base (in the first case)	9, 10, 11, 12, 13, 14	30	-	250
	Added sub-base layer (in the second case)	9	30	30, 40, 50	200
Dry unit weight (kN/m3)		24	22.1	14.5	16.0
Saturated unit weight (kN/m3)		-	23.6	15.5	17.5
Cohesion (kN/m2)		-	1	10	10
Angle of internal friction(Ø°)		-	45	5	1
Elastic Modulus (MPa)		1000	20	10	3
Poisson’s ratio (μ)		0.35	0.35	0.35	0.20
Drainage Type		Undrained A	Undrained A	Undrained A	Undrained A

The models' material properties were then applied, and the mesh was assembled. The model's mesh definition without a sub-base is shown in Figure 3, while the model's mesh definition with a sub-base is shown in Figure 4.

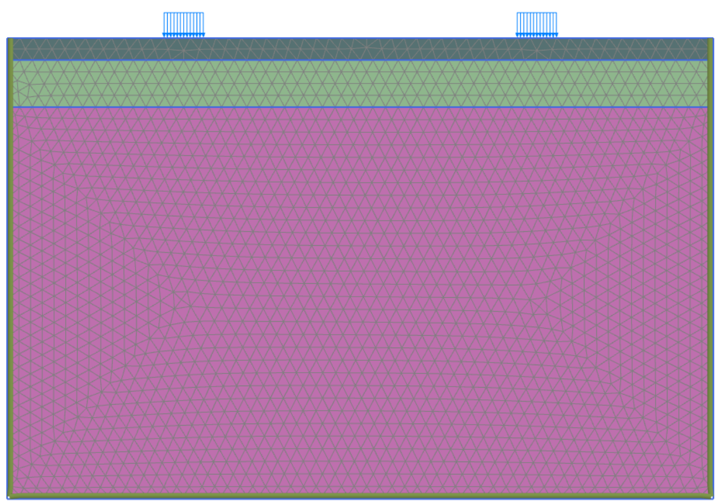


Figure 3. Mesh model of pavement without sub-base (ACT = 9 cm, Base=30 cm)

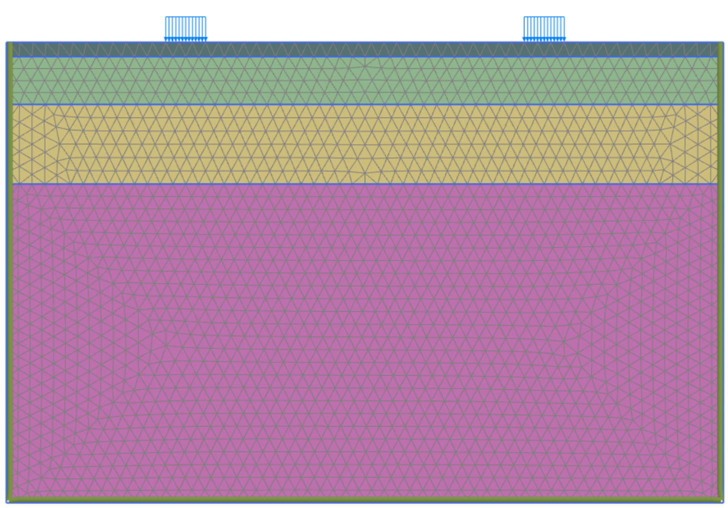


Figure 4. Mesh model of pavement with sub-base

III. RESULTS

The analysis was conducted on each pavement model and loading condition (ranging from 100 to 600 kPa) separately. The total vertical displacement of pavements with and without sub-base is determined for each static loading value. At the end of the analysis, the deformation of the pavement layers without a sub-base under a load of 600 kPa is shown in Figure 5. Similarly, the deformation of the pavement layers with a sub-base thickness of 30 cm is shown in Figure 6.

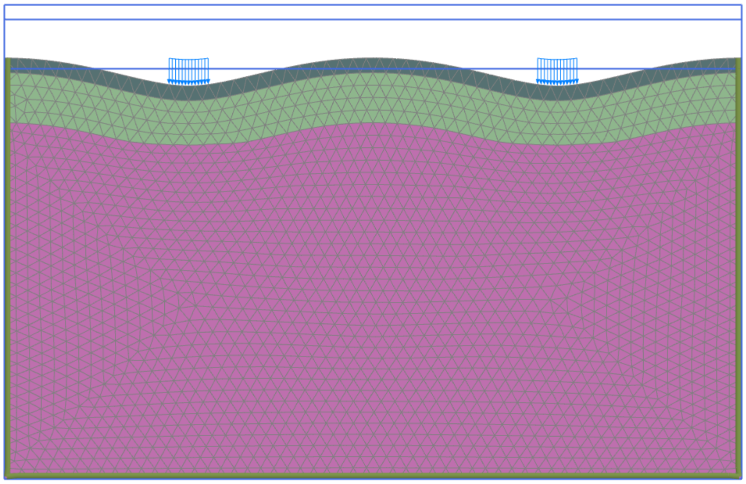


Figure 5. Deformation of pavement layers without sub-base layers (ACT=9 cm, Base=30 cm; Pressure=600 kPa)

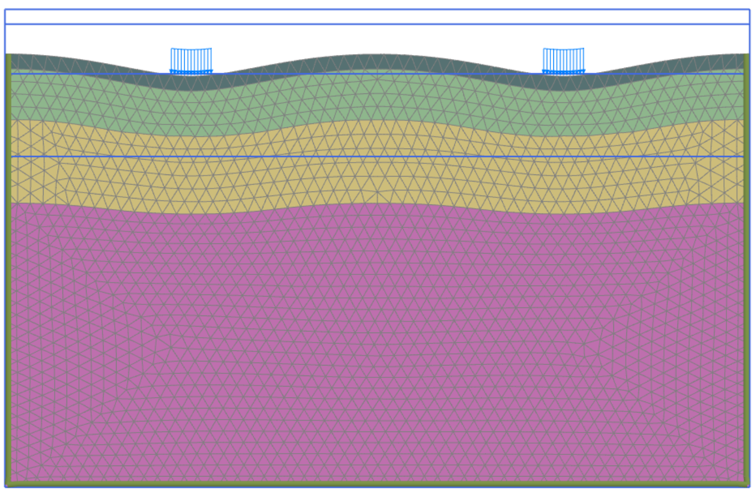
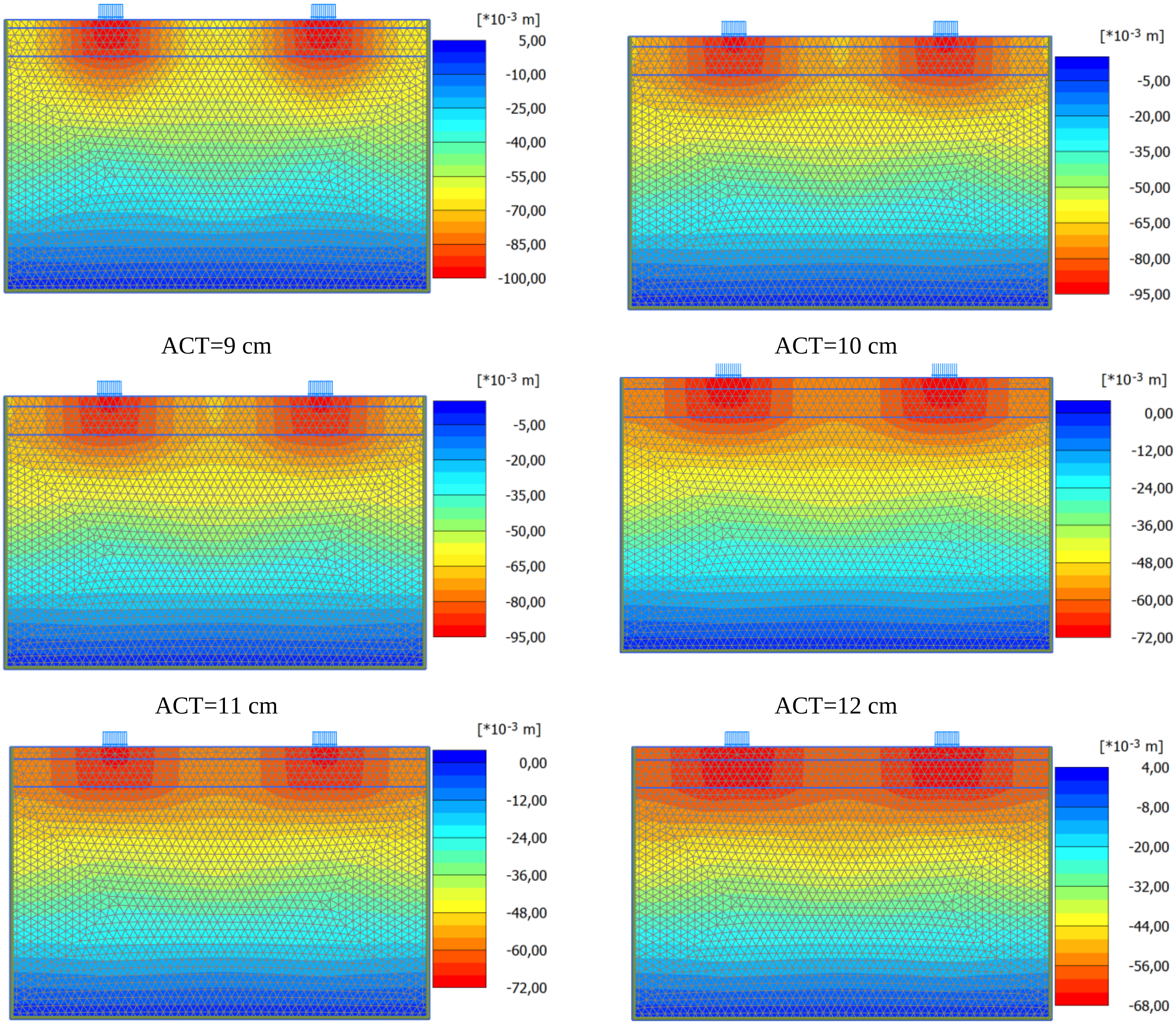


Figure 6. Deformation of pavement layers with sub-base at 30cm layers (ACT=9 cm; Pressure=600 kPa)

The vertical displacement contour diagrams of pavements modeled without sub-base according to asphalt concrete thicknesses (ACT) ranging from 9 cm to 14 cm applied to a 600 kPa load are given in Figure 7.



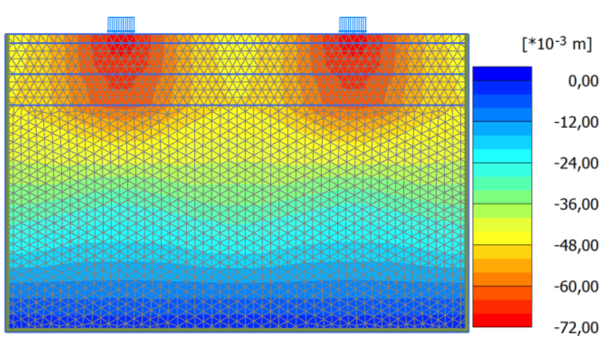
ACT=9 cm ACT=10 cm

ACT=11 cm ACT=12 cm

ACT=13 cm ACT=14 cm

Figure 7. Vertical displacement contour diagram(uy) of pavement without sub-base (Pressure=600 kPa)

The vertical displacement contour diagrams of pavements (ACT=9 cm) modeled with sub-base at 30, 40, and 50 cm SBT applied to a 600 kPa load are given in Figure 8.



SBT=30 cm

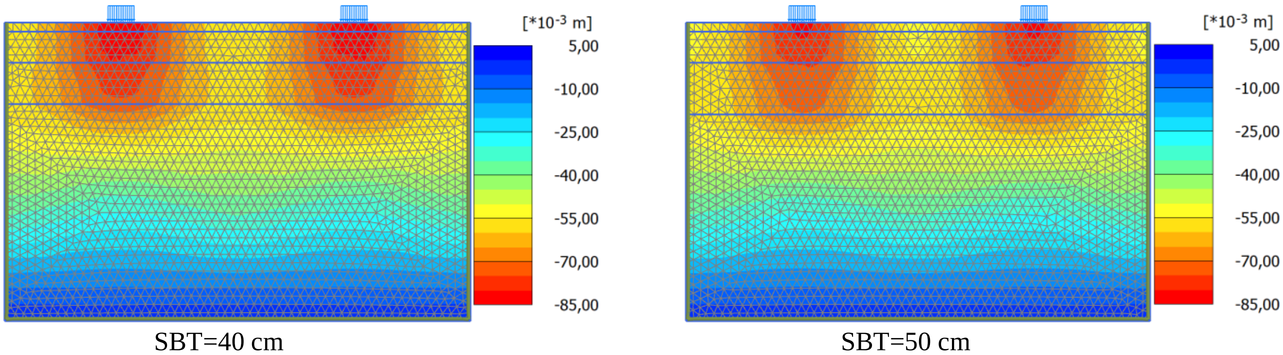


Figure 8. Vertical displacement contour diagram(uy) of pavement with sub-base at 30, 40, and 50 cm thickness (ACT=9 cm; Pressure=600 kPa)

At the end of the analysis, the deformation values on the pavement surface were determined. Figure 9 shows the surface deformation on the pavement without a sub-base layer caused by an increase in asphalt thickness. The deformations on the pavement surface without the sub-base layer are shown in Figure 10, which shows the influence of the ACT. Figure 11 illustrates that the variations in pavement surface deformation resulting from the addition of a sub-base layer of different thicknesses (30, 40, or 50 cm) under a 9 cm layer of asphalt concrete and a 30 cm base layer. Figure 12 shows the differences in deformations on the surface of the pavement (ACT=9 cm) with and without a subbase layer at depths of 30, 40, and 50 cm.

As seen in Figure 9, the deformations on the pavement surface increased due to the increase in the applied load on the pavement without sub-base. At low pressures, such as 100 kPa, the deformations on the pavement surface were close to each other, while it was observed that the deformations on the surface increased as the applied pressure increased.

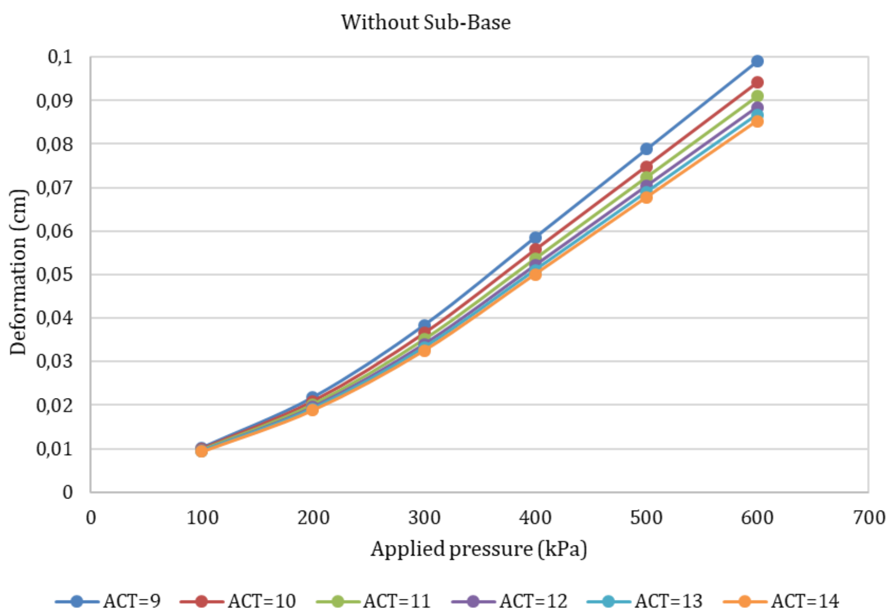


Figure 9. Deformations of different asphalt thicknesses on pavement surfaces without sub-base (ACT=9 cm)

Figure 10 shows that an increase in the thickness of the asphalt concrete layer results in a decrease in deformation. The greatest deformation was observed when the asphalt layer thickness was 9 cm, whereas the smallest deformation occurred at an asphalt layer thickness of 14 cm. Furthermore, it was observed that increasing the asphalt thickness at low loads had no effect on deformation significantly, but at loads of 300 kPa and above, it considerably decreased deformation formation. It can be said that it may be more appropriate to increase the pavement thickness under conditions of large loading on the pavement.

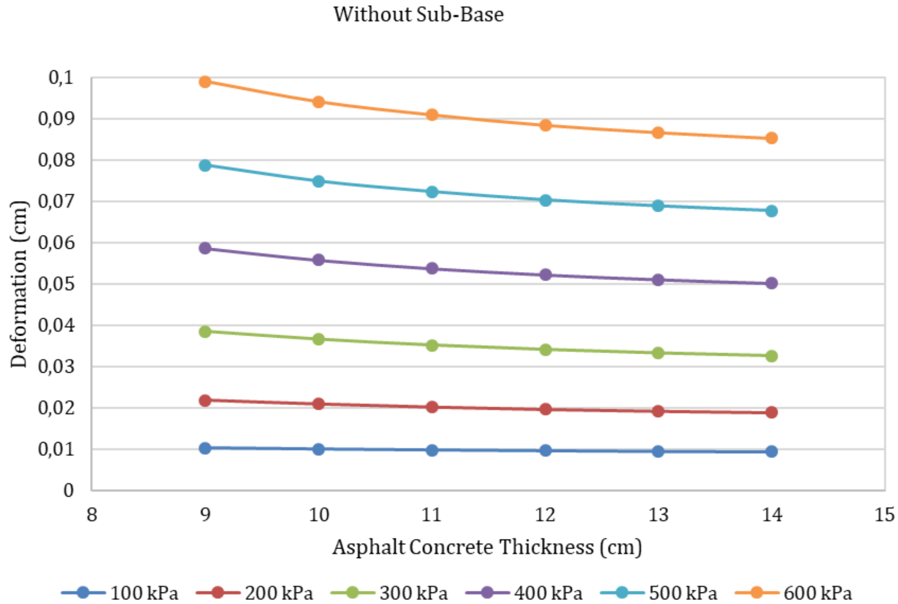


Figure 10. Effect of asphalt layer thicknesses on pavement surface deformation (without sub-base)

As seen in Figure 11, it was observed that the deformation decreased with increasing sub-base thickness. Similar to the without sub-base pavement, the thickness of the subbase has little influence on deformation at low pressures but a greater effect at pressures of 300 kPa and above.

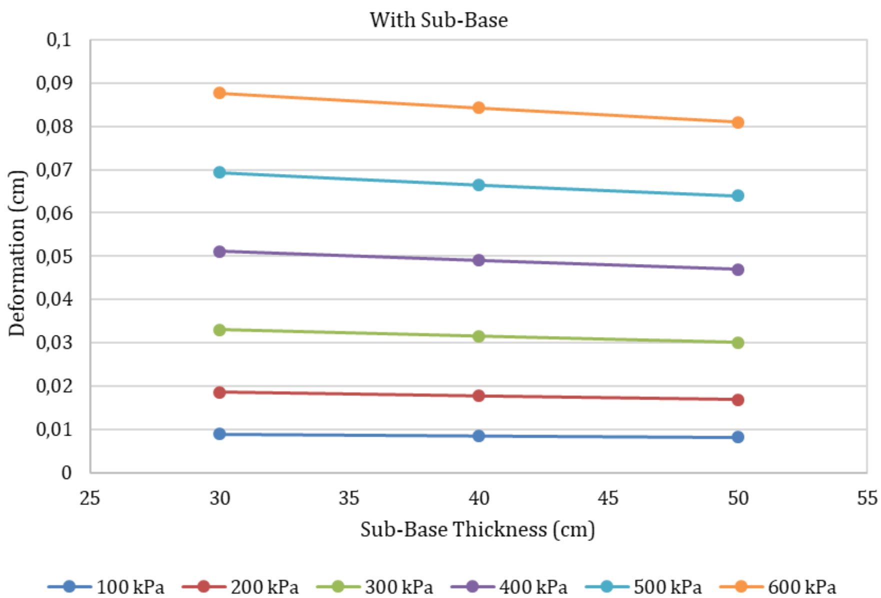


Figure 11. Effect of sub-base layer thicknesses on pavement surface deformation (ACT=9 cm)

The use of a sub-base layer in the pavement considerably increases the deformation resistance, as shown in Figure 12, when the effect of sub-base layer thickness and the absence of sub-base on deformation is examined. It was also observed that adding a 30 cm thick sub-base layer to the pavement improved the deformation resistance more than increasing the asphalt thickness without using sub-base.

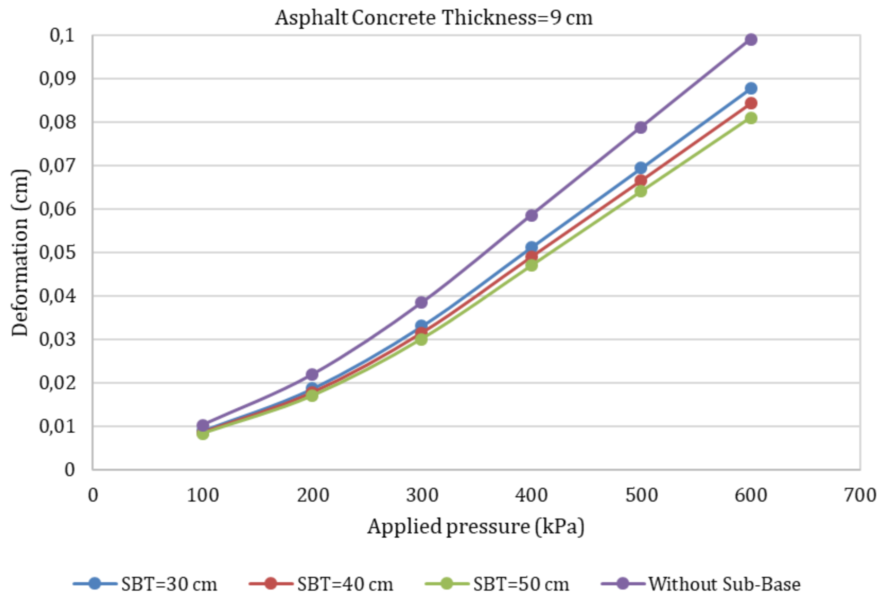


Figure 12. Effect of with and without sub-base layer on deformation (SBT= 30, 40, 50 cm, ACT=9 cm)

IV. CONCLUSION

In this study, the effect of the layer thicknesses used in the pavement deformation was investigated using Plaxis 2D software. The following findings were obtained as a result of the completed study:

1. The analyses were conducted on a pavement model with asphalt thicknesses ranging from 9 cm to 14 cm, specifically on the base layer. It was observed that the deformation of the pavement surface decreased with increasing asphalt thickness.
2. It was noted that increasing the asphalt layer thickness at lower loads did not have a significant impact on deformation. However, at loads of higher than 300 kPa, it notably reduced deformation formation. Under high loading conditions, it might be more suitable to consider increasing asphalt layer thickness.
3. The deformations obtained from 9 cm and 14 cm asphalt layer thickness of the models without subbase were compared in percentage. As a result, it was observed that 8.89%, 13.57%, 15.22%, 14.48%, 14.09% and 13.90% reduction in deformation occurred at 100, 200, 300, 400, 500 and 600 kPa loadings, respectively. According to this result, it is seen that 300 kPa load is the critical load as stated in result number 2.
4. In the without subbase model under 600 kPa loading, depending on the 1 cm increase in the coating thickness, the deformations decreased by 4.96%, 8.17%, 10.71%, 12.49%, and 13.90%, respectively, compared to the 9 cm coating thickness.
5. In the other model, where the sub-base was added at 30, 40, and 50 cm, the asphalt pavement thickness was 9 cm, it was observed that the deformation of the pavement surface decreased with increasing sub-base thickness. However, the results showed that the deformation resistance of the pavement surface increased more with the addition of sub-base compared to the increase in asphalt thickness in the pavement layer.
6. The deformations obtained from 30 cm and 50 cm subbase thickness of the models were compared in percentage. As a result, it was observed that 5.62%, 6.84%, 6.78%, 6.28%, 5.95% and 5.80% reduction in deformation occurred at 100, 200, 300, 400, 500 and 600 kPa loadings, respectively.
7. According to all the analysis results, it is understood that the increase in subbase thickness shows better performance in reducing deformation than the increase in the thickness of the asphalt pavement.

Consequently, this type of analysis is beneficial for designing a pavement, as it provides an equilibrium between the fatigue and rutting lifetimes [10]. This study included the modelling of asphalt behavior under low temperature conditions. However, as the temperature increases, the deformations on the asphalt surface also increase. Therefore, it is recommended to investigate the effect of temperature, different loading conditions, different material properties on the deformation of asphalt pavement in future studies. Investigating the effect of soil properties on the deformations that will occur on the pavement surface will also contribute to future studies.

CONFLICTS OF INTEREST

They reported that there was no conflict of interest between the authors and their respective institutions.

RESEARCH AND PUBLICATION ETHICS

In the studies carried out within the scope of this article, the rules of research and publication ethics were followed.

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