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Araştırma Makalesi /Research Article

The Effect of Asphalt Surface Layer Thickness on the Stress Distribution in the Flexible Pavements

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Abstract

Heavy vehicles used for freight transportation cause deformation in road pavements, which are constructed at high cost. To prevent these damages, increasing the thickness of the pavement is one of the factors considered in design criteria. For this reason, using the finite element method to determine the pavement thicknesses and evaluating the data obtained before the road construction in the project design process can provide positive economic contributions. In this study, ANSYS, a finite element software, was used to determine the stresses occurring in the road layers as a result of heavy vehicle loads the flexible pavement according to the pavement thickness change. For 4 different pavement thicknesses, analyses were performed for flexible pavement with 30mm, 50mm, 70mm and 100mm pavement thickness for pavement stress analysis. According to the results of the study; it was observed that the stresses occurring in the loading condition decreased as the pavement thickness increased. It was concluded that flexible pavements with low pavement thickness can be deformed more quickly with the effect of heavy vehicles. Additionally, the study suggests that the most suitable pavement thickness for cost calculations can be determined using the finite element method, thereby allowing for more effective cost-benefit analyses.

Keywords: *Asphalt Pavement, Stress Distribution, Finite Element Analysis*

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Esnek Üstyapılarda Asfalt Kaplama Kalınlığının Gerilme Dağılımına Etkisi

Öz

Yük taşımacılığı amacıyla karayollarını kullanan ağır araçların, yüksek maliyetlerle inşa edilen yol kaplamalarında deformasyona neden olduğu bilinmektedir. Bu zararları önlemek için kaplama kalınlığının arttırılması tasarım kriterlerinde dikkate alınan faktörlerden biridir. Fakat kaplama kalınlıklarının artırılması ile yüksek ekonomik maliyetler ortaya çıkmaktadır. Bu sebeple kaplama kalınlıklarının tayininde sonlu elemanlar yöntemini kullanarak yol yapımı öncesi elde edilen verilerin projelendirme sürecinde değerlendirilmesi ekonomik açıdan olumlu katkılar sağlayabilir. Bu çalışmada; esnek yol üstyapısına uygulanan yükleme sonucu yol katmanlarında meydana gelen gerilmelerin kaplama kalınlığı değişimine göre tespiti için sonlu elemanlar yazılımı olan ANSYS bilgisayar programı kullanılmıştır. 30mm, 50mm, 70mm ve 100mm olmak üzere dört farklı kaplama kalınlığına göre üstyapı gerilme analizleri yapılmıştır. Çalışma sonucuna göre; kaplama kalınlığı arttıkça yükleme durumunda meydana gelen gerilmelerin azaldığı gözlemlenmiştir. Düşük kaplama kalınlığına sahip esnek üstyapıların ağır taşıtların etkisi ile daha fazla deformasyona uğrayabileceği ortaya konulmuştur. Ayrıca yapılan çalışma ile maliyet hesapları için, ihtiyaç duyulacak en uygun kaplama kalınlığının sonlu elemanlar yöntemi ile belirlenebileceği ve böylece fayda-maliyet analizlerinin daha etkili bir şekilde gerçekleştirilebileceği öngörülmektedir.

Anahtar Kelimeler: *Asfalt Kaplama, Gerilme Dağılımı, Sonlu Elemanlar Analiz*

1. Introduction

Flexible pavements are a multi-layered composite system that effectively transfers and distributes traffic loads to the subgrade (Chun et al., 2015). Compressive and tensile stresses occurring in the flexible pavement as a result of traffic loads cause fatigue cracks and rutting on the pavement (Bostancıoğlu, 2019; Mulungye et al., 2007; Abejide and Mostafa 2017; Walubita and Ven, 2000). Overloaded vehicles significantly impact the service life of pavements, necessitating the use of thicker pavement layers (Alwan et al., 2024). But it is known that road construction costs require serious amounts for national economies. For this reason, optimizing the pavement design to achieve the most suitable design at the lowest possible cost can lead to more efficient management of financial resources and contribute to the economy by being utilized in future road construction planning (Tohidi et al., 2023).

The stresses in flexible pavements due to the increasing number of vehicles and heavy traffic loads cause the pavement to deform in a short time; therefore, the effect of pavement thickness on these deformations is an important criterion. Increasing pavement thickness generally provides higher resistance to cracking and fatigue, while thinner pavements are subject to deformation more rapidly (Zhang, 2015; Valle and Thom 2020). However, considering that the economic costs will increase with the increase in pavement thickness, it is of great importance to determine the optimum pavement thickness during the project design process. İskender et al., 2022 investigated the effects of pavement thickness on pavement performance by repeated-load-controlled and deformation-controlled bending test on beam specimens and also by Hamburg rutting test. In the flexural test, it was revealed that the load causing fracture increased with increasing pavement thickness and the cracking resistance increased accordingly. In another study investigating the effect of base course and asphalt pavement thickness on road deformation, test road sections with different thicknesses were constructed and data were obtained from these sections. As a result of the study, it was determined that the amount of deformation decreased with increasing pavement thickness (Gevrek, 2008; He and Yang, 2018).

In this study, dynamic loading was applied to the flexible coating with different coating thicknesses and the stresses resulting from the loading were examined. As a result of the study, the most appropriate coating thickness was tried to be determined by examining the stresses that occurred according to the change in coating thickness.

2. Material and Methods

In this study, the finite element method was used to obtain the stress and strain in the road layers. ANSYS computer software was selected for the application of the finite element method. The flexible pavement was modelled in two dimensions. In the created model, a flexible pavement with 4 layers was designed. The geometric model was created according to the values of 30mm, 50mm, 70mm, 100mm for the pavement layer, 200mm for the base layer, 400mm for the sub-base layer and 2000mm for the sub-base layer. Figure 1 shows the cross section of the flexible pavement.

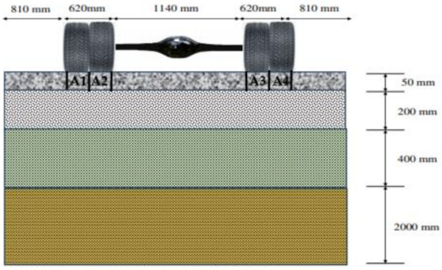

Figure 1. Flexible pavement cross section

Viscoelastic material, which depends on loading and temperature, was used for the pavement layer and elastic material was used for the other 3 layers (Özcanan and Akpınar, 2014). The physical properties (Modules of elasticity, Poisson's ratios and densities) required for these layers are given in Table 1.

Shear modulus and volume modulus values are additionally needed for the definition of viscoelastic material. Shear modulus and volume modulus values are given in Table 2. These values are transferred to the programme during material definition. Operating temperature is entered as 20 °C.

Table 2. Shear and volume modulus values (Mulungye et al., 2007)

Time (s.)	Shear Modulus (MPa)	Volume Modulus (MPa)
2.5	975	2536
5	917	2383
7.5	938	2440
10	937	2437
12.5	950	2469
15	960	2495
17. 5	985	2561
20	972	2528
22.5	952	2475
25	920	2392
50	596	1550
75	585	1521
100	597	1551
125	601	1563
137.5	616	1601
237.5	539	1402
262.5	535	1390
287.5	542	1408
312.5	546	1420
337.5	562	1462
362.5	570	1481
387.5	567	1474
637.5	499	1298
887.5	401	1043
1137.5	227	589
1147.5	212	551

Table 1. Material properties (Al-Azzawi, 2012)

Material	Modulus of Elasticity (MPa)	Poisson Ratio	Density (kg/mm^3)
Pavement Layer	2100,2500,3000,3500	0.40	$2.4e^{-009}$
Foundation Layer	600	0.40	$2.2\ e^{-009}$
Subbase Layer	100	0.30	$2.2\ e^{-009}$
Subgrade	30	0.40	$2.2\ e^{-009}$

The model was divided into elements for analysis by finite element method. Its appearance after being divided into elements is as shown in Figure 2. At the nodes at the bottom of the finite element mesh, movement in both vertical and horizontal directions is not allowed. At the lateral boundaries of the finite element mesh, vertical movement is allowed but lateral movement is not allowed (Ong et al., 1991; Siddharthan et al., 1991; Saltan 1999). In this analysis, these conditions were provided and analysed. The boundary conditions of the model are as shown in Figure 2.

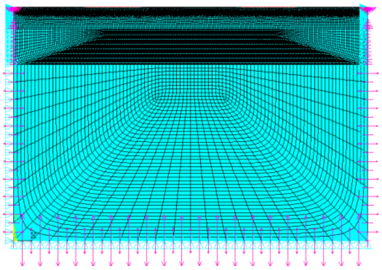

Figure 2. Finite element mesh

The load applied to the flexible pavement is a dynamic loading and an attempt has been made to apply a load equivalent to a moving axle load in real life.

A dynamic loading was applied to the areas with 3 different loading steps by applying a heavy vehicle, whose axle plan is given in Figure 3, to the model of the pavement in Figure 1.

Dynamic load application was also applied with the transient analysis module in the ANSYS programme. 3 different loading steps were applied to the front, middle and rear wheels. According to Figure 1, the first loading was applied for the front tyres. The front wheels were applied to areas A1 and A4. The middle and rear dual wheels were applied to A1, A2, A3 and A4 areas. The numerical data about the force and areas required for loading are given in Table 3.

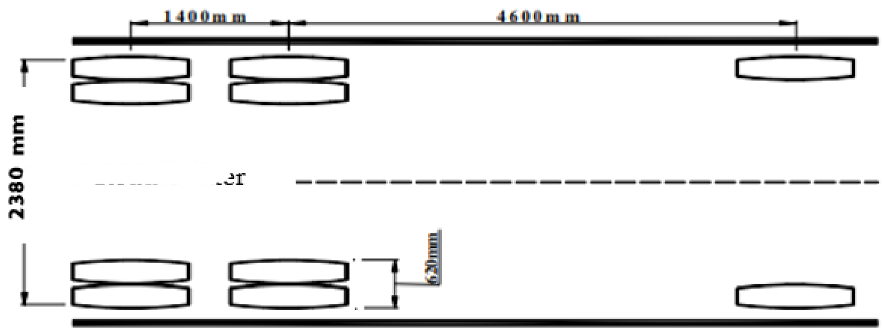

Figure 3. Heavy vehicle axle plan (Mulungye et al., 2007)

Table 3. Installation steps

Time (s)	A1	A2	A3	A4	1. Loading (Mpa)	2. Loading (Mpa)	3. Loading (Mpa)
0,000-0,001							
0,001-0,0015	x			x	0,660		
0,0015-0,252							
0,252-0,266	x	x	x	x		0,637	
0,266-0,338							
0,338-0,352	x	x	x	x			0,630
0,352-0,450							

3. Findings

As a result of the analyses, pavement layers with 4 different pavement thicknesses on the flexible pavement were analysed separately and the stress values occurring in the pavement as a result of these analyses were shown graphically.

3.1. Pavement Stress Analysis

The top layer of the flexible pavement is the surfacing layer. Therefore, since it is located at the top of the pavement, it is the layer most exposed to stresses, deformations and environmental effects. For this reason, the stability of this layer is important for road life. Inaccuracies in the determination of the pavement layer thickness are design errors and some negative consequences may arise as a result of these errors. For example, low pavement thickness leads to excessive reduction of flexibility, excessive shearing between layers and low inertia resistance (displacement resistance of aggregates) of asphalt layers (Tunç 2004). In this study, the same cross-sectional line of the pavement in Figure 1 was influenced by the heavy vehicle whose axle plan is given in Figure 3, and the stress changes in the X direction in those parts were shown.

The graph shown in Figure 4 shows the stress graph of the flexible pavement with 4 different pavement layer thicknesses. This graph shows the stress values at the first loading moment, i.e. when the front tyres contact the areas. In this graph, it is seen that the road with low pavement layer thickness is exposed to more compressive and tensile stresses. As the pavement thickness increases, stress values decrease. (Cao et al., 2022; He and Yang 2018; Özcanan and Akpınar, 2014; Walubita and Ven, 2000).

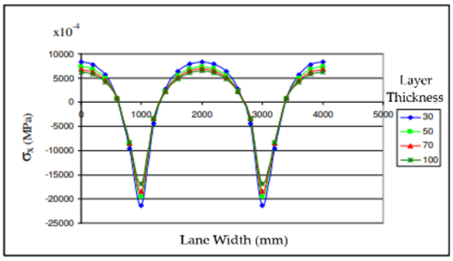

Figure 4. X direction stress graph at the first loading (front single wheel)

Figure 5 shows the stress values of the centre double axles at the second loading moment of the vehicle. Although the values are very close to each other in this graph, the lowest stress value is seen in the pavement layer with a thickness of 100 mm.

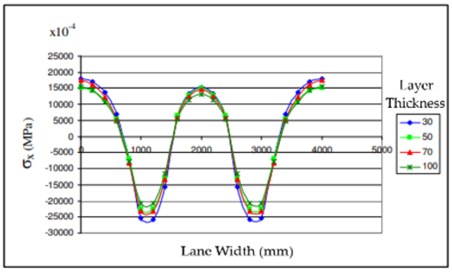

Figure 5. X-directional stress graph at the second loading (middle double wheels)

The stress graph at the moment of final loading, that is, when the rear double wheels contact the areas, is as shown in Figure 6. Here, the high stress value occurring in the pavement with a thickness of 30 mm stands out with a big difference. Again, as in the other loadings, the lowest stress value in this loading was observed in the road with a pavement thickness of 100 mm. In general, what stands out in all 3 loads is that less stress occurs in the layer with higher thickness.

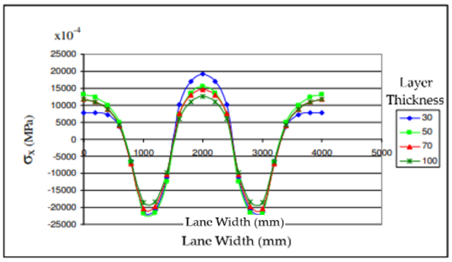

Figure 6. X-directional stress graph at final loading (rear double wheels)

The graphs in Figure 7, Figure 8 and Figure 9 show the y-direction stress values occurring in the pavement after the load applied to the flexible pavement with different pavement thicknesses. In Figure 7, the y-directional stress values occurring at the moment when the front tyres of the vehicle contact the areas are given in the graph. In this graph, it is seen that the flexible pavement with low pavement thickness reaches high compressive and tensile stresses.

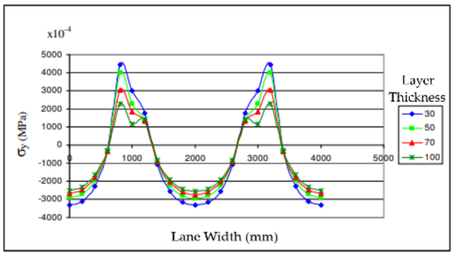

Figure 7. Y direction stress graph at the first loading (front single wheel)

It is seen in the graph in Figure 8 that the highest values of compressive and tensile stresses are reached in the pavement layer with a thickness of 30 mm during the passage of the middle two-wheeled axle of the heavy vehicle. It is seen that 50- and 70-mm thick pavements are close to each other. In the 100 mm thick flexible road structure, it is seen that both compressive and tensile stresses are at low values.

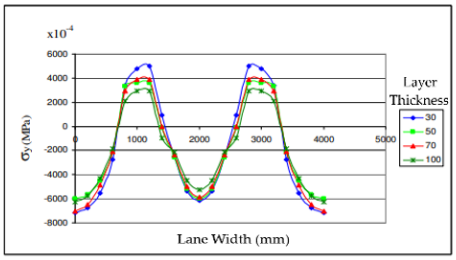

Figure 8. Y direction stress graph at the second loading (middle double wheels)

Figure 9 shows the stress graph during the passage of the last double axle of the vehicle. In this graph, the highest tensile stress value occurred in the layer with a thickness of 30 mm. However, in compression, the stress values of the 30- and 50-mm thick pavements are very close to each other and are higher than the others. The flexible pavement subjected to the lowest compressive and tensile stresses is the flexible pavement with pavement layer having a thickness of 100 mm.

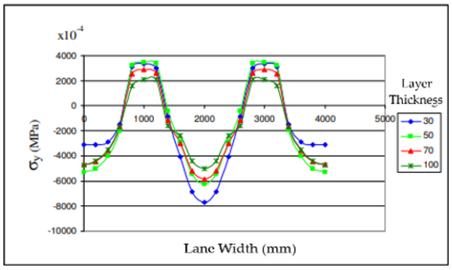

Figure 9. Y direction stress graphic at final loading (rear double wheels)

3.2 Strain for Different Pavement Thicknesses

In the deformation graphs shown in Figures 10, 11, 12 and 13, which were obtained as a result of the analyses made according to different pavement thicknesses; as the pavement thickness increases, the amount of deformation between the foundation and subbase, where the maximum deformation occurs under the areas where the wheels contact, decreases. Figures 14, 15, 16 and 17 show the y-directional deformations of the flexible pavement with different pavement thicknesses. When these graphs are considered, it is seen that the y-directional deformations are less deformed in the flexible pavement with 100 mm pavement layer. However, when y-directional deformations are compared with x-directional deformations, it is seen that the effect of y-directional deformations on the flexible pavement is not as different as x-directional deformations.

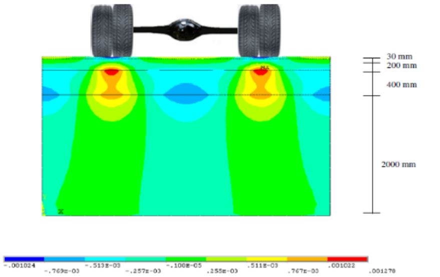

Figure 10. X-directional strain of flexible pavement with 30 mm asphalt pavement thickness

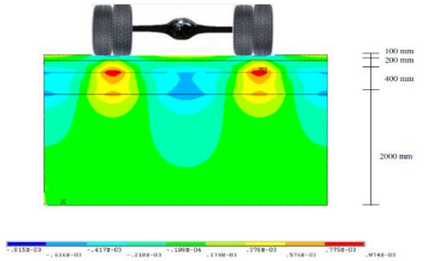

Figure 13. X-directional strain of flexible pavement with 100 mm asphalt pavement thickness

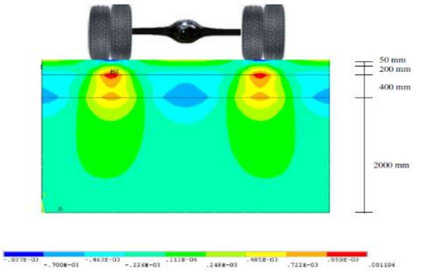

Figure 11. X-directional strain of flexible pavement with 50 mm asphalt pavement thickness

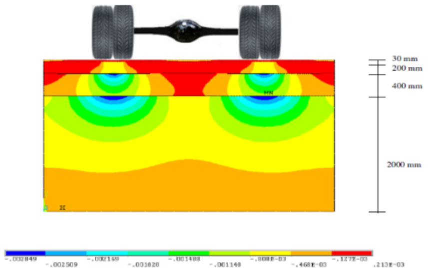

Figure 14. Y-directional strain of flexible pavement with 30 mm asphalt pavement thickness

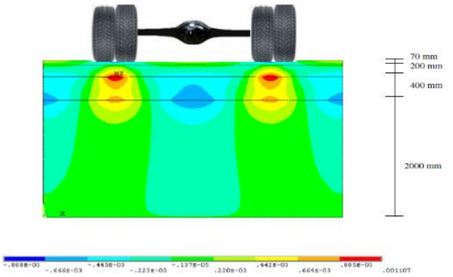

Figure 12. X-directional strain of flexible pavement with 70 mm asphalt pavement thickness

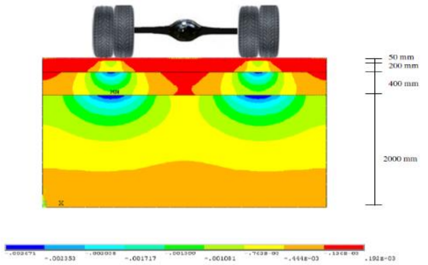

Figure 15. Y-directional strain of flexible pavement with 50 mm asphalt pavement thickness

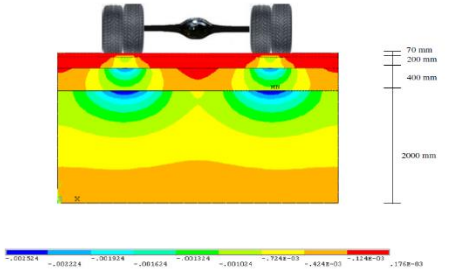

Figure 16. Y-directional strain of flexible pavement with 70mm asphalt pavement thickness

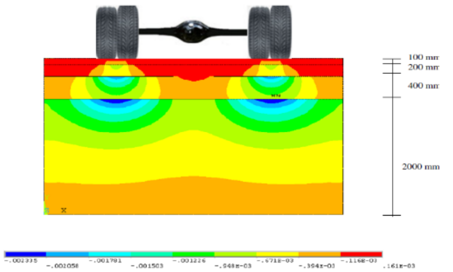

Figure 17. Y-directional strain of flexible pavement with 100 mm asphalt pavement thickness

4. Conlusion

As can be seen in the stress graphs resulting from the analyses performed with four different pavement thicknesses, there is a decrease in compressive and tensile stress values as the pavement thickness increases. In addition, in the x-directional stress graphs in the analysis, it is seen that the compressive stresses caused by the axle load at the front single wheel, middle double wheel and rear double wheel transitions are not very far from each other. According to the analysis, when the y-directional stress graphs are analysed, it is seen that the stresses caused by the double wheel passages are 2 times higher than the single wheel passage at all pavement thicknesses. It is observed that the maximum strain between the base and subbase layers decreases with increasing pavement thickness. At the same time, when y-directional deformations were compared with x-directional deformations, it was observed that the effect of y-directional deformations on the flexible pavement was not as different as x-directional deformations. By increasing the pavement thickness, the stress sensitivity of the asphalt pavement can be reduced and the amount of strain can be reduced. As a result, it is seen that the probability of deformation of the pavement layer with high thickness can be reduced. Of course, at this point, the idea that the thicker we make it, the longer it will last is not very appropriate. At this point, it is also necessary to consider the economic dimension of the work. Increasing the thickness of the pavement layer too much can be a burden in terms of cost. For this, it is necessary to design the pavement layer with the optimum thickness and cost. Although the optimum asphalt thickness is determined to be in the range of 50-70 mm based on the conditions considered in the article (Gevrek, 2008), future studies should incorporate factors such as cyclic loads. It is recommended to conduct various modeling studies with these considerations. It is believed that incorporating cost analyses into future studies on this topic will yield more comprehensive results.

Declaration of Ethical Standards

In this article, the principles of scientific research and publication ethics were followed.

Credit Authorship Contribution Statement

Author-1: Conceptualization, investigation, methodology and software, visualization and writing – original draft, supervision and writing – review and editing.

Declaration of Competing Interest

There is no conflict of interest with any person/institution in the prepared article.

Data Availability

All data generated or analyzed during this study are included in this published article.

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