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Impact of Subgrade Strength on Pavement Performance

Zemin Taşıma Gücünün Üstyapı Performansına Etkisi

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Abstract

Based on the standard design of flexible pavement structure conducted in Turkey, only subbase course layer is affected by the variation of subgrade strength and other pavement layers (wearing course, binder course, asphalt concrete (AC) base course, and crushed stone base course) are not influenced by the variation of subgrade strength. Therefore, the aim of this study is to investigate the impact of subgrade strength on flexible pavement distresses. To achieve the objectives, firstly, three different flexible pavement structures designed using the Turkish Flexible Pavement Design Guide 2008 were chosen and secondly, the effect of variation of subgrade strength [5 to 50 California Breading Ratio (CBR)] on pavement performance (rutting and fatigue cracking) for three different traffic levels [5000, 10000, and 15000 average annual daily truck traffic (AADTT)] for climatic condition of Izmir region using AASHTOWare Pavement ME Design v2.5.5 were analyzed. The results of the study show that, reducing subgrade CBR values from 50 to 5 CBR resulted in an increase by 3.7mm in total rutting depth and 5.6% in alligator cracking magnitude. Also, results demonstrated that the influence of subgrade strength on rutting within asphalt concrete layers (AC rutting) is negligible. By contrast, increasing subgrade CBR value from 5 to 50 resulted in a significant increase (65.1 to 314.7 m/km) in longitudinal cracking magnitude while thermal (transverse) cracking is not sensitive to the variation of subgrade CBR values. This study can assist highway agencies and individual pavement designers in the design a more practical pavement.

Keywords: *Pavement Performance, Pavement Design, Rutting , Cracking*

Öz

Bu çalışma kapsamında, taban zemin taşıma gücünün esnek üstyapı bozukluklarına etkileri incelenmiştir. Taban zemininin üstyapı performansına etkisini belirlemek için öncelikle, daha önce Karayolları Esnek Üstyapılar Projelendirme Rehberine göre tasarlanmış üç farklı esnek üstyapı seçilmiştir. İkinci adımda, farklı taban zemin taşıma gücünün (5-50 CBR) esnek üstyapı bozukluklarına (tekerlek izi ve yorulma çatlakları) etkileri üç farklı trafik seviyesi [5000, 10000 ve 15000 yıllık ortalama günlük kamyon trafiği (AADTT)] için AASHTOWare Pavement ME Design v2.5.5 kullanılarak İzmir bölgesi iklim koşullarında kapsamlı üstyapı analizleri yapılmıştır. Çalışma sonuçları; taban zemini taşıma gücünün esnek üstyapı bozuklukları oluşması üzerinde yüksek bir etkiye sahip olduğunu ortaya çıkartmıştır. Elde edilen analiz sonuçlarına göre; taban zemini taşıma gücünün 50'den 5 CBR'ye azalması durumunda, toplam tekerlek izinde oturma derinliğinin 9,1 mm'den 12,7 mm'ye artacağı, ayrıca taban zemin taşıma gücünün bitümlü sıcak karışım (BSK) tabakalarında oluşabilecek tekerlek izinde oturma derinliği üzerindeki etkisinin ihmal edilebilir düzeyde olacağı tespit edilmiştir. Analiz sonuçları ayrıca yine taban zemin taşıma gücünün 50 CBR'den 5 CBR'ye düşmesi durumunda, timsah sırtı çatlak oluşumlarını ortalama % 5,6 (% 1,8 ila 7,4) arttıracağını, boyuna çatlakları ise önemli bir derecede azaltacağını göstermektedir (314.7'den 65.1'e). Ayrıca, sonuçlar, enine çatlakların taban zemini taşıma gücünün değişimine duyarlı olmadığını göstermektedir. Bu çalışmanın sonuçları, karayolu kurum ve kuruluşları, belediyeler ve bireysel üstyapı tasarımcılarına daha iyi üstyapı tasarımı yapmalarında yardımcı olabilir.

Anahtar Kelimeler:: *Üstyapı Performansı 1, Üstyapı Tasarımı 2, Tekerlek İzi 3, Çatlaklar 4*

1. Introduction

Based on the standard design of flexible pavement structure conducted in Turkey, only subbase course layer is affected by the variation of subgrade strength. The subbase course thickness increases for lower subgrade strength and decreases in the presence of stiffer CBR value. While, other pavement layers [wearing course, binder course, asphalt concrete (AC) base course, and crushed stone base course] are not sensitive to variation of subgrade strength [1]. The current Turkish flexible pavement design guide was adopted from The American Association of State Highway and Transportation Officials (AASHTO) 1986/1993 design method. This method is not able to predict the pavement distresses such as rutting and cracking and determine the effect of variation of design inputs on pavement performance [1] [2]. Therefore, to overcome on these restrictions, the Mechanistic-Empirical Pavement Design Guide (MEPDG) was developed in 2004 and implemented by AASHTO in 2008. The MEPDG is the state-of-the-practice pavement design method that calculates pavement responses (stresses and strains) and predicts various pavement distresses under the combination of traffic loading and environmental conditions into consideration of extensive detailed material properties [3][4][5]. The MEPDG was transferred into software in 2008 and its commercial software called AASHTOWare Pavement ME Design was released in 2013 [6]. The AASHTOWare Pavement ME Design has a powerful ability to determine and evaluate the sensitivity of pavement distresses on design inputs.

After the development of the MEPDG method, state agencies in the USA and countries have made effort to implement this method based on local conditions. Therefore, they conducted extensive researches such as sensitivity analysis of design inputs on pavement performance, evaluation, and local calibration of the MEPDG [7][8][9][10][11][12] [13][14].

In 2014, the local climate data for Egypt were collected and converted to the MEPDG format and the effect of climate factors were investigated for different climatic zones in this country using AASHTOWare Pavement ME Design. The results of the study shown that for the same material properties and pavement structures as well as same traffic level, the rutting magnitude is higher in southern parts than northern parts of the country. Also, results indicated that alligator fatigue cracking is not sensitive for climate zones in Egypt [8].

In 2014, in order to facilitate the implementation of the MEPDG in the State of Qatar, local data such as bound and unbound material properties, pavement structure, and traffic data were collected and comprehensive sensitivity analysis were conducted using AASHTOWare Pavement ME Design. The analysis results demonstrated the effectiveness in replacing unmodified bitumen Pen 60-70 with modified bitumen PG 76-10 for pavements in Qatar climatic conditions. In particular, longitudinal cracking was significantly less in pavements with modified bitumen PG 76-10 [9].

In 2017, the conventional AASHTO 1993 and MEPDG was compared for Egypt climatic conditions. The result of comparative analysis of these two methods manifested that although all pavement sections in this study were designed using AASHTO 1993 method for the same serviceability level, the MEPDG predicted different pavement distresses. The variation of the predicted distresses using the MEPDG of the AASHTO 1993 designed pavement structures increased with the increase in traffic level and decrease in the subgrade strength. This variation was also different for different climatic conditions[10].

In 2017, for the implementation of the MEPDG in Saudi Arabia, the local data such as material properties, traffic data, climate data, and pavement distresses were collected, analyzed and converted to the MEPDG. The result of study shown that some of the collected local data such as climate data and traffic characteristics cannot be used directly as design inputs in the AASHTOWare Pavement ME Design [11].

In 2018, in order to boost the implementation of the MEPDG in Lebanon, the local traffic data were collected and the sensitivity of traffic characteristics on pavement performance for different climatic zones were conducted using AASHTOWare Pavement ME Design. The findings demonstrated that highway design agencies can rely on available automated traffic counts surveys and apply various assumptions based on their own observations and records of vehicles types to create a reliable truck categorization in accordance with the MEPDG vehicle classification system. On the other hand, using typical values or estimating the growth factor for traffic prediction in cases where continuous data is not available might result in incorrect results, as mild variation in the growth factor significantly affects the predicted pavement distresses[12].

In 2021, in order to improve the accuracy level of distress prediction models of the MEPDG the local calibration of the MEPDG was performed in Saudi Arabia. The study results manifested that local calibration of rutting and International Roughness Index (IRI) models significantly reduced the bias and standard errors between observed and predicted pavement distresses by the national calibrated AASHTOWare Pavement ME Design version [13].

In 2021, in a similar study, the sensitivity of hot-mix asphalt mixtures (HMA) design properties in different asphalt concrete (AC) layers on pavement performance were investigated in Dokuz Eylul University, Izmir, Turkey. The result of the study indicated that HMA mixture design properties (binder content, air voids percentage, and aggregate gradation) in different AC layers have significant different impacts on pavement performance. Higher binder content in top AC layer(s) resulted in poor alligator fatigue cracking performance, in contrast, higher binder content in bottom layer (AC base course) led to significant improvement in fatigue live of the flexible pavement. The effect of variation of air voids percentage on fatigue life of the pavement in terms of alligator cracking is potentially strong in AC base course but negligible in binder and wearing courses [14].

In order to improve pavement performance, having an optimal pavement design and reducing pavement maintenance costs the impact of local design inputs on pavement performance should be determined. But, the MEPDG has not been implemented in Turkey and the sensitivity analysis for all design inputs have not been conducted yet [1]. In the other hand, according to pavement structure standard design made in Turkey shows that only the thickness granular sub-base course is sensitivity to the variation of subgrade strength. Moreover, this standard design has not determined that in what extend the subgrade strength influence on pavement performance (total rutting, AC rutting, alligator cracking, thermal cracking, and longitudinal cracking).

Therefore, within the scope of this study the effect of subgrade strength (5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 CBR) on pavement distresses for Izmir climatic conditions using AASHTOWare Pavement ME Design v2.5.5 was investigated. Moreover, the aim of this study was that the results of this study could facilitate the implementation of MEPDG in Turkey, and could be used as a guide by pavement design highway state agencies and individual pavement designers.

2. Material and Method

In order achieve the objective of this study, in the first step, local design data (pavement structures, hot-mixed asphalt (HMA) and granular material properties, traffic characteristics, and climate data) were collected from General Directorate of Highways annual published reports, Turkish Flexible Pavement Design Guide, and Turkish Highway Technical Specifications [1], [15], and Turkish State Meteorological Service. Then, the collected local data were analysed and converted to suitable formats that can be used as design inputs in the AASHTOWare Pavement ME Design v2.5.5. In the second step, the local data were used as design inputs in the AASHTOWare Pavement ME Design Software in order to investigate the impact of subgrade strength on flexible pavement distresses [e.g., total rutting, AC rutting, alligator cracking, longitudinal cracking, and thermal (transverse) cracking].

2.1. Local Data Collection

Pavement Structure

Based on Turkish Flexible Pavement Design Guide, three different pavement structures were selected for three different traffic levels (5000, 10000, and 15000 AADTT). The pavement layers types, numbers, and thicknesses are presented in Table 1. The pavement structures used in Turkey consist of three AC layers (wearing course, binder course and AC base course), crushed stone base course, and granular subbase course. The thickness of wearing course is 5cm in every pavement structures. The thickness of binder course and AC base course are variable and change according to traffic levels. The crushed stone base thickness is constant (200mm) in every pavement structures. The thickness of granular subbase course is changed based on traffic levels and subgrade types (See Table 1) [1].

Table 1. Pavement structure information [15]

Layers types	AADTT		
	5000	10000	15000
Wearing course (mm)	50	50	50
Binder course (mm)	80	100	100
AC base course (mm)	110	110	140
Crushed Stone Base course (mm)	200	200	200
Granular subbase course (mm)	300	300	350

HMA Material Properties

The HMA mixture material properties were extracted from Highway Technical Specifications. The collected local data is illustrated in Table 2.

Granular Material Properties

Granular base and subbase course as well as subgrade resilient modulus and CBR values were selected based on Highway Technical Specifications [15] which is shown in Table 3.

Traffic Data

Local traffic data used as design inputs such as monthly adjustment factors (See Table 4), number of axles per truck (See Table 5), vehicle class and class distribution factors (See Table 6), were collected from the General Directorate of Highways [16]. The traffic data were analyzed and found that the current vehicle classification used in Turkey is not suitable to be used as design inputs in the MEPDG because vehicles were classified in five groups based on vehicle types only [1]. While, in the MEPDG vehicles are classified into 10 classes (class 4 to 13) based on vehicle types, axle number and axle types [17]. Therefore, new vehicle classification was developed. In this regard vehicles were aggregated into seven classes (class 4 through 10), however classes 11, 12, and 13 were not observed in Turkey. Therefore, their distribution percentages are taken as zero.

Climate data

The 5-year climate data (temperature, wind speed, precipitation, cloud cover, and humidity) were obtained from the Turkish State Meteorological Service office. As the climate data had not been calibrated in the MEPDG format [18], therefore, the climate data were analyzed, improved, and converted to the text file with ".hcd" extension to be used in the AASHTOWare Pavement ME Design 2.5.5 [19]

Table 2. HMA mixture material properties [15]

Inputs	Wearing course	Binder course	AC Base course
Unit weight, kN/m3	24	24	24
Reference temperature, °C	21.1	21.1	21.1
Poisson's ratio	0.35	0.35	0.35
Binder grade and type	Pen. 60-70	Pen. 60-70	Pen. 60-70
Effective binder content, Vbe (%)	10	10	9
Air voids, Va (%)	4	5	5
% Passing from 19 mm sieve	100	90	80
% Passing from 9.5 mm sieve	81	59	65
% Passing from 4.75mm sieve	47	41	52
% Passing from 0.075mm sieve	5.5	4.5	3.5

Table 3. The resilient modulus of Granular base and subbase layers [15]

Layers and material types	Value
Crushed stone base course, Mr, MPa	225
Non-stabilized granular subbase course, Mr, MPa	125
Subgrade types, (CBR %)	5-50

Table 4. Trucks monthly adjustment factors

Month	Trucks classes									
	4	5	6	7	8	9	10	11	12	13
Jan	0.83	0.84	0.84	0.84	0.8	0.8	0.8	0	0	0
Feb	0.79	0.8	0.8	0.8	0.77	0.77	0.77	0	0	0
Mar	0.88	0.96	0.96	0.96	0.94	0.94	0.94	0	0	0
Apr	0.9	0.99	0.99	0.99	0.96	0.96	0.96	0	0	0
May	1.03	1.07	1.07	1.07	1.05	1.05	1.05	0	0	0
Jun	1.07	1.07	1.07	1.07	1.05	1.05	1.05	0	0	0
Jul	1.25	1.1	1.1	1.1	1.13	1.13	1.13	0	0	0
Aug	1.28	1.08	1.08	1.08	1.12	1.12	1.12	0	0	0
Sep	1.05	1.03	1.03	1.03	1.07	1.07	1.07	0	0	0
Oct	1.04	1.08	1.08	1.08	1.12	1.12	1.12	0	0	0
Nov	0.92	0.99	0.99	0.99	1.04	1.04	1.04	0	0	0
Dec	0.95	0.99	0.99	0.99	0.95	0.95	0.95	0	0	0
Total	12	12	12	12	12	12	12	0	0	0

Table 5. Number of axles per truck

Vehicle class	Single	Tandem	Tridem	Quad
4	1.96	0.04	0.00	0
5	2.00	0.00	0.00	0
6	1.00	1.00	0.00	0
7	1.33	0.33	0.68	0
8	2.00	1.00	0.00	0
9	1.99	0.03	0.99	0
10	1.00	1.00	1.00	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0

Table 6. Vehicle class distribution factors and truck growth rate

Vehicle class	Distribution (%)	Growth Rate (%)
4	15.82	5
5	33.01	5
6	16.59	4
7	10.08	4
8	0.33	4
9	24.10	4
10	0.07	4
Total	100	

2.1. Investigation of subgrade strength impact on pavement distressd

To determine the impact of variation of subgrade strength on predicted pavement distresses, three different pavement structures (See Table 1) were analyzed for various subgrade CBR values (5, 10, 15, 20, 15, 30, 35, 40, 45, and 50 CBR) for Izmir climatic conditions using AASHTOWare Pavement ME Design 2.5.5. Each analysis was conducted for three different traffic levels (5k, 10k, and 15k AADTT). The rest of the design inputs were kept constant in all analysis. All analyses were conducted for 20-year of design life at 90% reliability level.

3. Results and Discussion

The results of study are given and evaluated in different figures such as total rutting, AC rutting, alligator cracking, longitudinal cracking, and thermal (transverse) cracking at the end of design life (20-year).

3.1 Effect of Subgrade Strenth on Total Rutting

The analysis results revealed that for all traffic levels, total rutting is highly affected by the variation of subgrade CBR values (See Figure 1). The Figure 1 shows that the reduction of subgrade strength from 50 to 5 CBR led to an increase by 3.7 mm (9.1 to 12.7 mm) in average total rutting depth.

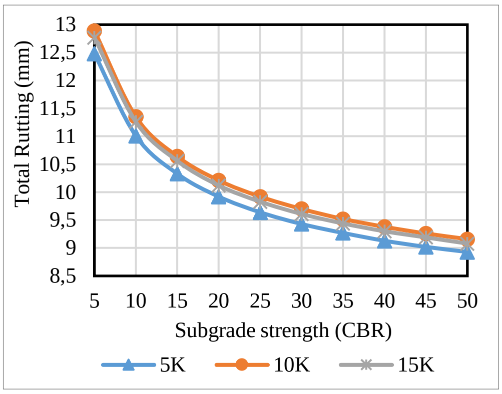

Figure 1. Effect of subgrade strength on total rutting

3.2. Effect of Subgrade Strenth on AC Rutting

The analysis results demonstrated that for all traffic levels the variation of subgrade CBR values has a negligible effect on rutting AC rutting depth. The AC rutting depth slightly increased (0.1 mm) when the subgrade strength was changed from 5 to 50 CBR (See Figure 2).

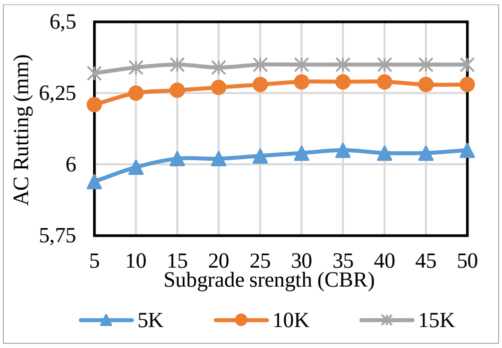

Figure 2. Effect of subgrade strength on AC rutting

3.3. Effect of Subgrade Strength on Alligator Cracking

The analysis results indicated that for all traffic levels, alligator fatigue cracking is sensitive to the variation of subgrade strength. Figure 3 shows that alligator cracking magnitude is remained almost unchanged in the presence of stiffer subgrade (higher than 20 CBR). In contrast, for lower subgrade CBR values (lower than 15 CBR) the alligator cracking increased rapidly. It can be concluded that alligator cracking would be critical in flexible pavements in the presence of lower subgrade CBR values (lower than 15 CBR) only. Generally, when the subgrade strength decreased from 50 to 5 CBR the average alligator cracking increased by 4.51%. Also, Figure 3 shows that for higher traffic levels such as 10000 and 15000 AADTT, reduction in subgrade CBR values from 15 to 5 resulted in an increase by 3.11 and 10.15 % in alligator cracking magnitude, respectively. Also, it can be concluded from Figure 3 that for 5000 AADTT, the impact of subgrade CBR value is negligible.

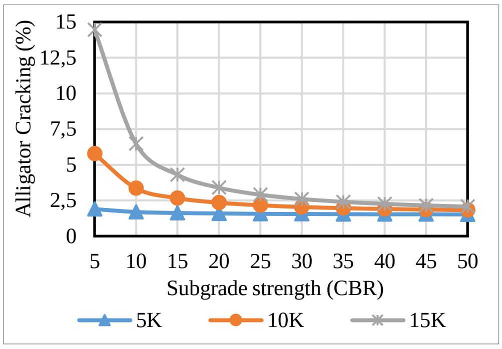

Figure 3. Effect of subgrade strength on alligator cracking

3.4. The Effect of Subgrade Strenth on Thermal Cracking

Analysis results showed that thermal cracking is not affected by variation of subgrade strength because thermal cracking is a non-load related cracking, which occurs due to repetition of cool/heat cycles in AC layers (See Figure 4).

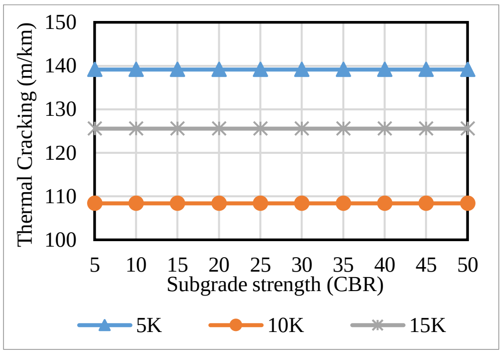

Figure 4. Effect of subgrade strength on thermal cracking

3.5. Effect of Subgrade Strenth on Longitudinal Cracking

The analysis results revealed that for all traffic levels, the variation of subgrade strength has a very high effect on longitudinal cracking magnitude. The stiffer subgrade CBR value resulted in higher top-down cracking. An increase in subgrade strength (from 5 to 50 CBR) led to a rose by 249.6 m/km (65.1 to 314.7 m/km) longitudinal cracking (See Figure 5). The existence of stiffer subgrade in a flexible pavement structure results in higher tensile shear stress on the top of topper of AC layer (wearing course) and consequently led to higher longitudinal cracking. Because the longitudinal cracking is fatigue load cracking which occurs on the topper AC layer due to repeated shear stresses[20].

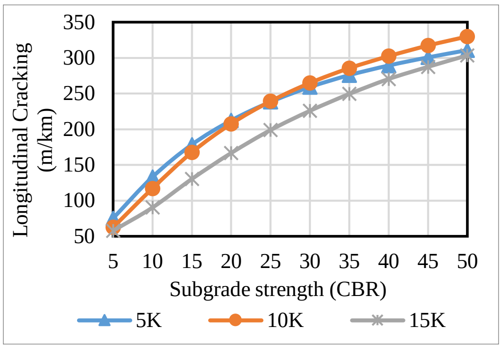

Figure 5. Effect of subgrade strength on longitudinal cracking

4. Conclusion and Recommendations

According to the objective of the study, the effect of variation of subgrade CBR values on flexible pavement distresses for Izmir, Turkey climatic condition was investigated using AASHTOWare Pavement ME Design. The conclusion of the study results is summarized as follows:

- The reduce of subgrade strength from 50 to 5 CBR resulted in an increase by 4.5 mm in total rutting depth.
- The effect of subgrade strength on rutting within asphalt concrete layers (AC rutting) is negligible.
- Thermal (transvers) cracking is not sensitive to the variation of subgrade CBR values.
- Alligator cracking is strongly affected by variation of subgrade strength. This effect is not critical for higher subgrade values (> 25 CBR). A reduction in subgrade CBR value (15 to 5) led to a 5.6 % increase in average alligator cracking magnitude. For higher traffic levels such as 10000 and 15000 AADTT, reduction in subgrade CBR value from 15 to 5 resulted in increases by 3.11 and 10.15% in alligator cracking magnitude, respectively.
- The reducing of subgrade CBR values from 50 to 5 resulted in a reduction in average longitudinal cracking magnitude from 314.7 to 65.1 m/km.
- According to the analysis results, in the presence of lower CBR value of the subgrade (<15CBR) and high traffic levels, alligator cracking would be a major distress for flexible pavements. Increasing the thickness of subbase course which is suggested by Turkish Flexible Pavement Design Guide as a solution many not be enough. Also, for subgrade CBR value lower than 10%, the total rutting and alligator cracking are increased rapidly, which confirms the using of selective materials. On the other hand, longitudinal cracking, which starts from the top of the wearing course and propagates downward is highly sensitive to the variation of subgrade strength, increasing subgrade strength results in higher longitudinal cracking. This problem can be addressed through using high quality material in wearing course.

Further studies are recommended to investigate the effect of layer thickness and environmental factors on flexible pavement distresses.

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