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ESTABLISHMENT OF THE UNIT PRICES FOR RIGID PAVEMENTS AND INITIAL COST COMPARISON OF FLEXIBLE AND RIGID PAVEMENTS FOR THE STATE ROADS OF TÜRKİYE

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
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BY

MUSTAFA BARIŞCAN AKBELEN

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ABSTRACT

ESTABLISHMENT OF THE UNIT PRICES FOR RIGID PAVEMENTS AND INITIAL COST COMPARISON OF FLEXIBLE AND RIGID PAVEMENTS FOR THE STATE ROADS OF TÜRKİYE

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Road pavement types are generally classified into two as flexible (asphalt) and rigid (concrete) pavements. These two are differentiated from each other depending on factors such as the binding materials used, the construction methods, and the load transfer mechanisms. The first important step in long-lasting, and economical pavement construction projects is the selection of the right type based on the technical and economic parameters. There are many studies aiming to compare the cost of flexible and rigid pavements in the world. However, in Türkiye the lack of the existence of the official unit prices for concrete roads not only limit the applicability of such comparisons but also the widespread use of concrete roads in the KGM (Turkish General Directorate of Highways) road network.

This study aims to compare the initial construction costs of jointed plain concrete pavements (JPCP) and hot mix asphalt (HMA) pavements that could be used in the state roads of the KGM road network in a systematic manner. Within the scope of the study, JPCP and HMA pavements were designed using the official KGM guidelines under the same road class, project life, traffic load, soil, and environmental/climatic conditions.

Then, unit price, analysis and descriptions of JPCP were prepared by examining two concrete road construction sites in Türkiye and abroad. Finally, the initial construction costs of JPCP and HMA pavements that will be used in the state roads of the KGM road network are compared by using the equivalent annual cost method.

As a result, it was determined that JPCP is economically efficient than HMA at about 32%, 25% and 20% for high, medium and low volume roads when the interest rate is taken as 5% as an optimistic scenario. For a possible-case scenario of 15% interest rate, JPCP seems to be feasible for high to medium volume roads, especially for low-grade subgrade strengths. The above-mentioned findings explain why concrete pavements are commonly used in the roads with high volume of traffic such as the inter-state/city roads of USA.

Keywords: Rigid Pavements, Flexible Pavements, Unit Prices for Concrete Pavements, Equivalent Annual Cost Comparison

ÖZ

RİJİT KAPLAMALARIN BİRİM FİYATLARININ OLUŞTURULMASI VE TÜRKİYE DEVLET YOLLARI AĞINDA ESNEK VE RİJİT KAPLAMALARIN İLK YAPIM MALİYETLERİNİN KARŞILAŞTIRILMASI

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Yol üstyapı tipleri genel olarak esnek (asfalt) ve rijit (beton) kaplamalar olarak ikiye ayrılır. Bu iki yol üstyapı tipi, kullanılan bağlayıcı malzemeler, yapım yöntemleri ve yük aktarım mekanizması gibi faktörlere bağlı olarak birbirinden farklılaşmaktadır. Bu nedenle uzun ömürlü ve ekonomik yol üstyapı yapım projelerinde ilk önemli adım teknik ve ekonomik parametrelere göre doğru tip seçimidir. Dünyada beton ve asfalt yolların maliyetini karşılaştırmayı amaçlayan birçok çalışma olmasına rağmen Türkiye'de beton yol uygulamalarının çok yaygın olmaması ve beton yolların resmi birim fiyatlarının eksikliği bu çalışmaların ülkemizde henüz yapılamamış olmasına neden olmaktadır.

Bu çalışma, literatürdeki eksikliği gidermek amacıyla Karayolları Genel Müdürlüğü (KGM) yol ağının devlet yollarında kullanılabilecek derzli donatısız beton yollar (JPCP) ile bitümlü sıcak karışım (BSK) yolların ilk yapım maliyetlerini sistematik bir şekilde karşılaştırmayı amaçlamaktadır. Çalışma kapsamında aynı yol sınıfı, proje ömrü, trafik yükü, zemin ve çevre/iklim koşulları altında resmi KGM rehberler kullanılarak JPCP ve BSK yollar tasarlanmıştır.

Sonrasında Türkiye'de ve yurt dışında iki adet beton yol inşaat sahası incelenerek JPCP'ye ait birim fiyat, analiz ve tarifler hazırlanmıştır. Son olarak, KGM karayolu ağının devlet yollarında kullanılacak JPCP ve BSK kaplamaların ilk yapım maliyetleri eşdeğer yıllık maliyet yöntemi kullanılarak karşılaştırılmıştır.

Sonuç olarak, iyimser bir senaryo olarak faiz oranı %5 olarak alındığında JPCP'nin yüksek, orta ve düşük hacimli yollar için HMA'ya göre yaklaşık %32, %25 ve %20 oranlarında ekonomik olarak verimli olduğu tespit edilmiştir. %15'lik olası bir faiz oranı senaryosu için, JPCP, özellikle düşük dayanımlı zeminler için yüksek ila orta trafik hacimli yollarda uygun görünmektedir. Yukarıda belirtilen bulgular, ABD'nin eyaletler arası/şehirler arası yollar gibi trafiğin yoğun olduğu yollarda neden beton yolların yaygın olarak kullanıldığını açıklamaktadır.

Anahtar Kelimeler: Beton Yollar, Asfalt Yollar, Beton Yol Birim Fiyat Analiz ve Tarifler, Yıllık Eşdeğer Maliyet Karşılaştırması

To my family,

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a	Relative strength coefficient
m	Drainage coefficient
D	Layer thickness
E_c	Modulus of elasticity
f_{ck}	Characteristic cubic strength
η	Lane distribution factor
R	Reliability
M_R	The resilience modulus
P_o	The initial serviceability
P_t	The terminal serviceability
Sc’	Average modulus of rupture
S_0	The combined standard deviation
$T_{8.2}$	Number of equivalent single axle load
k	Bearing ratio

CHAPTER 1

INTRODUCTION

1.1 General

A flexible material, when subjected to a bending load exhibits larger deformations, thus bends. Rigid materials, on the other hand, do not show such deformations and resist more to such bending loads. In pavements, these two distinct material types led to the identification of flexible and rigid pavements. In addition, there are composite pavements consisting of the combined use of flexible and rigid pavements.

Flexible pavements, generally known as asphalt pavements, are those whose main binder is bitumen, which is a by-product of crude-oil processing plant. Under the effect of traffic loading, while transferring the load to the underlaying layers, they show a rather flexible behavior, distributing the load over small areas. Asphalt pavements are built with various layers of varying thicknesses underneath due to their flexible behavior.

Rigid (concrete) pavements exhibit a more rigid behavior against traffic loading. These pavements utilize portland cement and some other supplementary cementitious materials as the main binder. Concrete pavements are built with fewer and thinner layers, as they distribute the load on a wider area owing to their rigid behavior.

Both road pavement types have different advantages and disadvantages. For this reason, it is necessary to choose the right pavement type for each pavement project by considering the project requirements, regional conditions, design parameters, and economic concerns.

For example, asphalt pavements generally come to the fore with their quieteness and comfortability during driving, while it is noteworthy that they have a relatively shorter service life and require frequent maintenance-repair requirements.

On the other hand, concrete pavements have a longer service life with low maintenance-repair requirement. Therefore, they are preferred on roads with heavy and high volumes of traffic. In addition, the inorganic constituents of concrete pavements make them preferable in tunnels due to their non-inflammable structure.

Concrete pavements can be grouped in four different categories as JPCP, JRCP; CRCP and RCC (Yoder and Witczak, 1975).

Jointed plain concrete pavements (JPCP) are the type of concrete pavements in which there is no use of transverse and longitudinal reinforcement and only dowel and tie bars are used at the joints. Although there are different examples on record, it is thought that the oldest concrete pavement in the world (because it is still usable) is the JPCP type of pavement built-in 1891 in Ohio, USA (Rao et al., 2013). For this reason, it can be said that concrete pavements have been used in the world for more than 130 years.

Jointed reinforced concrete pavements (JRCP) are the type of road pavements in which some longitudinal reinforcement is used to increase the joint spacing in addition to the dowel and tie bars.

Continuously reinforced concrete pavements (CRCP) which have been developing rapidly in recent years are the type of road pavements that do not contain transverse and longitudinal joints, and therefore there is continuous use of transverse and longitudinal reinforcement for the whole pavement section.

Besides these three basic types, other concrete pavement types also exist. For example, roller compacted concrete (RCC) pavements are the type of concrete pavements that have been frequently used around the world for the last 70 years, especially in ports, warehouse areas, military bases, and local roads.

Even though the first three pavements are manufactured with similar techniques, RCC is different. RCC pavement is a type of concrete pavements that combines the construction technique of asphalt pavements with the strength and durability of concrete. RCC pavements are distinguished from the others as they can be put in a short time.

In Türkiye, the network can be broadly grouped into two; *i)* local roads under the responsibility of municipalities and local administrations, and *ii)* national roads under the responsibility of the General Directorate of Highways (KGM).

As of 01.01.2022, KGM has a road network of 68,526 km and approximately 40% of this road network is made up of asphalt pavements, while approximately 55% is a chip-seal coating (KGM, 2022). It is known that there are a total of 8.1 km of concrete pavements in only 4 different pilot projects in the KGM road network (Komut et al., 2019). Unfortunately, concrete road applications in the KGM road network have not gone beyond those trial sections yet.

Even though, there is no officially announced data on local roads, it is estimated that there is a road network of approximately 400,000 km. On the other hand, it is estimated that there is more than 15,000 km of concrete roads in the road network of local administrations. Also, it is known that the amount of RCC pavements exceeds 1,000 km in the local road network (Abut, 2017). Although concrete pavement applications are developing rapidly, especially in the local road network, the preparation of the necessary guidelines required for road construction is continuing. Technical specifications and unit price guidelines for RCC pavements which are frequently used in the local road network have been officially published by the Ministry of Environment, Urbanisation and Climate Change in March 2020.

On the other hand, although the official publication of the technical specifications and design guidelines regarding the concrete pavement types (JPCP and CRCP) used in the KGM road network is extremely pleasing, the lack of the existence of the official unit prices for concrete roads stands out as an important shortcoming.

For this reason, it is very difficult to make a realistic analysis of the initial construction cost of a concrete pavement planned to be built on the KGM road network.

Moreover, the lack of a unit price guide for concrete pavements makes it impossible to implement the alternate bidding method which has been used for many years in some countries, especially the USA, which provides public benefit by increasing the competition between different sectors. In addition, life cycle cost analysis (LCCA) cannot be performed for concrete pavements. Therefore, it is clear that there are two main deficiencies related to the cost comparison studies. The first one is the lack of unit price analysis for concrete pavements for the state road network in Türkiye. The second one is the lack of studies focusing on the equivalent design of the both pavements for the state road network in Türkiye.

1.2 Objective

This study aims to eliminate the above-mentioned facts by proposing a model for the unit prices of concrete pavements for the KGM road network. In this context, in the first stage of the study, the unit prices of the concrete pavements (only for JPCP) to be used in the KGM road network and the descriptions of the construction stages were established. Then, concrete and asphalt pavements were designed structurally and the layer thicknesses were obtained by the method used in the official design guidelines, taking into account the same traffic load, the same environmental and climatic conditions, and the same material and soil characteristics. After that, an objective cost comparison based on initial construction cost was prepared with using equivalent annual cost method for both road pavement types designed with the same method and parameters by considering the official guidelines.

1.3 Scope

The literature review provided in Chapter 2 on the subject within the scope of the study is given under five main headings, namely, structural design of road pavement types, life cycle cost analysis, life cycle assessment and alternate bidding method for road pavements. Later, Chapter 3 presents the details of the structural design of flexible and rigid pavements for different service lifes. Chapter 4 presents the established unit price analysis and descriptions of concrete pavements for Türkiye. Chapter 5 compares the initial cost with equivalent annual cost method for flexible and rigid pavements that were previously designed using the unit price analysis established in the preceeding Chapter. Finally the last chapter lists the conclusions drawn from this study.

CHAPTER 2

LITERATURE REVIEW

The literature review part is given in 5 main topics. The first topic is about the studies that focused on design of pavements. The second one is on life cycle cost analysis for pavement projects. In the third part of the chapter the focus is on life cycle assessment for pavement projects. The focus of the fourth part is on alternate bidding/alternate design. The last part of the chapter is about the previous studies on cost comparison of pavement types in Türkiye.

2.1 Structural Design of Pavements

Several different methods have been used for many years to design both concrete and asphalt pavements. For many years, empirical approaches were used which are based on the empirically derived relationships between inputs (traffic loading, material properties, etc. in this case) and the failure of the pavement. Among these, AASHTO-93 (American Association of State Highway Transportation Officials) is the most widely used method for many years for both pavements. AASHTO-93 method uses the empirical relationships which have been derived from the road tests of a pilot project in Illinois from 1956-to 1958 conducted by AASHO.

There are some limitations of the AASHTO-93 design method since it is an empirical approach. One of the main limitations is the effect on the environment.

It is well known that environmental conditions such as temperature gradient, moisture, etc. affect the performance of pavement so it has to be taken into account during the structural design phase. However, the effect of these conditions depends on the location where the pavement is going to be constructed.

Thus, the empirical equations are limited to the environmental conditions of Illinois where the equations were derived. Also, it is known that the service life of different pavement types is more than 15-20 years generally. However, the empirical equations have been derived by two-year accelerated road tests so it forms another limitation. Moreover, soil type and the mechanical properties of subgrade are important parameters when designing a pavement but AASHTO's empirical equations were derived for a specific soil type and properties where the accelerated road tests took place. An important knowledge has been accumulated by observing the performance of the pavements designed by the AASHTO-93 method for many years.

There is another empirical design approach for concrete pavements which is called as Portland Cement Association (PCA) method. The PCA method is a type of trial-error method and it focuses on two different failure modes, namely, fatigue and erosion failures. The PCA method is based on an assumed (user-defined) slab thickness and it examines the damage factors due to the two failure modes during the service life. The assumed slab thickness is changed depending on the damage factors in every trial.

Moreover, Transportation Research Board (TRB) started a new research program which is named Long-Term Pavement Performance (LTPP) in the early 1980s in the US and Canada with the sponsorship of FHWA and AASHTO. The main goal of the LTPP program is to collect performance data and factors related to the pavement design for the in-service road network to analyze the relationship between the performance of a pavement and the road-specific (local) conditions like climate, traffic loading, etc. Hence, the big data of the program lighted the way for a new and comprehensive design approach for pavements.

In this way, a new method has been developed that exceeds the limitations of the AASHTO-93 method. The Mechanistic-Empirical Pavement Design Guide (MEPDG) method, which was first prepared in 2002, has been developed frequently over the years.

Unlike the empiric methods such as AASHTO-93, the MEPDG (M-E) method examines the relationship between the stresses, strains, and deflections that will occur in the pavement and the design inputs with mathematical models by the finite element technique. In this respect, it comes to the forefront by removing many limitations such as the effect of environmental conditions and properties of different soil types of AASHTO-93. Thanks to the M-E method, it has been possible to design road pavement types in a more reliable, realistic, and sustainable way.

As an example of assessing the environmental effects by using the M-E method, Ktari et al. (2020), have evaluated the effect of climate conditions on the structural design and performance of asphalt pavements by examining the case studies in France and Canada. It has been found that fatigue cracking is the failure criterion for the case study in France and it gets more severe with an increase in temperature. Also, it has been stated that considering moisture and freeze/thaw cycles in environmental inputs used in the M-E method results in more severe deformations as the Canada case shows. In addition, the M-E method allows the analysis of an already-in-service road pavement. Also, the M-E method provides an opportunity to optimize the structural design while protecting the same performance requirements.

The use of the M-E method, which has a more holistic approach, provides the opportunity to optimize the design of road pavements compared to the use of empirical methods. In this way, it becomes possible to design more economical road pavements only with the change in the design method.

Also, Mack and Zollinger, (2013) have developed a model for optimizing the design of concrete pavements. In the study, they have formed alternative equivalent designs for both pavement types for a real pavement project by using the AASHTO-93 method in the US. Then, the initial construction costs and life cycle costs of the alternative have been calculated.

Thus, it has been noticed that asphalt alternative provides about % 20 economical advantage in the initial cost whereas concrete pavement is more economical in the manner of LCC.

After that, they have redesigned the concrete pavement alternative by using the M-E method meeting the same performance criteria. Then, the cost calculations have been repeated. It has been found that using the M-E method has decreased the initial cost of concrete alternatives by about % 25 which makes equal costs for both alternatives almost. Also, it has been stated that the new concrete pavement designed by the M-E method has the lowest LCC among all alternatives including standard concrete pavement.

Empirical and mechanistic design studies for different pavement types under the same design inputs prove the optimization achieved in layer thicknesses.

For example, Gedafa et al., (2011), have compared the structural design of asphalt and concrete pavements by using both AASHTO-93 and MEPDG methods in Kansas. In the scope of the study, 5 different road sections built during 1990-2001 as concrete pavement have been re-designed as both concrete and asphalt pavements at a % 90 reliability level by using the M-E method. As a result of the study, it has been found that the slab thicknesses for all of the asphalt and concrete pavements have been decreased by using the M-E method except for just one road section. Also, they have found that asphalt pavements are more sensitive to changes in performance criteria than concrete pavements.

Thus, many studies show that using the M-E method instead of empirical methods like AASHTO-93 decreases the slab thickness and incorporates other design features such as joint spacing and rebar size so creating remarkable cost savings (Mack & Zollinger, 2013).

Although there are many advantages of using the M-E method, it is very critical to have national calibration data to use MEPDG more realistic.

Currently, MEPDG has local calibration data just for US and Canada but many countries have been developing a national calibration presently.

Saha, (2011) has explored the effect of Canadian climatic conditions on pavement performance by using the M-E method. In the study, data on climatic conditions for 206 different weather stations have been used in the M-E method. Also, she has compared the structural design of asphalt pavements for 3 different traffic levels (low, medium, and high based on AADT) and 2 different subgrade types (poor and good based on subgrade modulus) by using both MEPDG and Alberta Transportation Pavement Design (ATPD) methods. It has been found that Canadian climatic conditions are consonant with MEPDG data. Also, it has been noticed that rutting and longitudinal cracking of asphalt pavements are sensitive to Canadian climatic conditions.

In a similar study, Romero et al., (2015) have implemented the M-E method for an asphalt pavement project in Peru to obtain a calibration coefficient for International Roughness Index (IRI) which is used for the measurement of the driving comfort of road pavement. In the study, they have used the climate data of San Diego, the US due to the similarity with the weather condition of the location where the study took place. Also, % a 95 reliability level has been chosen for the study. As a result of the study, it has been found that there is a good correlation between the in-situ measurements and the predicted values by MEPDG for IRI.

In another study, Ameri and Khavandi, (2009), have developed a model to design asphalt pavements by using the M-E method regarding Iran's climatic conditions. They have proposed a relation for different axle loads and underlined the convenience due to the lack of using equivalent load factors in the design phase. Although MEPDG provides a calibration coefficient for US and Canada, some states have formed local calibration coefficients to improve the efficiency of reliable design obtained by the M-E method.

Slab thicknesses which are obtained from the M-E method are highly dependent on the local calibrations. Although the M-E method generally resulted in decreased slab thicknesses than the empirical method generally, local calibration may change this trend.

Islam, Sufian, Velasquez, and Barret, (2019), have studied the local calibration of the M-E method for JPC pavements. In the scope of the study, they have examined the calibration for the distresses, join faulting, and roughness of the 22 different rigid pavement sections by using the M-E method and measurements. As a result of the study, it has been found that the empirical method resulted in higher slab thicknesses under high traffic volume whereas the M-E method resulted in higher slab thicknesses under low and medium traffic volumes. Also, it has been stated that achieving satisfactory results for the local calibration requires engineering judgment.

The use of realistic calibration data in the mechanistic design method directly affects the design results. Mu, Mack, and Rodden, (2018) have evaluated the effects of using national or local calibration coefficients on the prediction of pavement performance and structural design of concrete pavements. They have found that using local calibration has a critical impact on the predicted performance whereas it is almost insignificant for determining slab thicknesses.

In Türkiye, design guides for concrete and asphalt pavements published by KGM are based on the AASHTO-93 method. However, some studies may be milestone works for developing MEPDG in Türkiye.

As a milestone study for the M-E method, Sengun, Ozturk, and Yaman, (2020), have re-designed a concrete pavement that was designed by an empirical approach -the Belgian Catalog method- years ago by using a new M-E method in Türkiye. In the study, a jointed plain concrete pavement (JPCP) built-in 2004 in Türkiye was examined. They have designed the pavement by using the AASHTO-93 method for 2 different service life (20 and 30 years), 3 different traffic growth rates (3, 5, and 8 %), and 4 different reliability levels (85, 90, 95, and 99 %).

They have found that the results of the AASHTO-93 method are thicker than the result of the Belgian Catalog method which is 27 cm for a concrete slab. In the scope of the study, they have re-designed the same pavement by using the M-E method. In M-E, they have used the environmental inputs of a station in the US that has a very similar climate to the location of the pavement due to the lack of local data in

Türkiye. Then, they have designed the pavement by considering 2 different traffic growth rates (3 and 5 %) and 4 different reliability levels (85, 90, 95, and 99 %) by the M-E method.

Also, they have used typical AASHTO values for limits of deflections. Results of the M-E method have shown that the deflections of the related pavement will exceed the limits for roughness and faulting whereas will be within the limits for transverse cracking. Moreover, it has been found that the realized measurements for roughness are similar to the results of the M-E method with 99 % reliability. Lastly, they have underlined the need for local calibration values for improving the efficiency of the M-E method in Türkiye.

The use of the mechanistic method in different cities or geographical regions, especially in countries where different climate and weather conditions are experienced together, results in different designs as expected.

Ozturk, Tan, Sengun, and Yaman, (2019) have handled the structural design of JPC pavements for 10 different cities in Türkiye by using the M-E method. In the study, they have considered 3 different subgrade types (A-7-5, A-2-6, and A-1-b based on AASHTO), 3 different traffic volumes (low, mid, and high based on AADHT), 2 different compressive strength class (C30 and C40) and 2 different service life (20 and 40 years) to evaluate the effects of different inputs. Also, 10 different cities have been selected from different regions in Türkiye to reflect different climatic conditions. As a result of the study, it has been found that traffic volume and environmental conditions affect the slab thicknesses mainly as expected.

Also, it is possible to obtain realistic joint spacing based on climate conditions by using the M-E method. Lastly, they have stated that it is not possible to obtain applicable slab thicknesses for some cities which have a higher annual range of temperature.

The use of the mechanistic design method allows the analysis of which parameters are more effective in the performance of different pavement types.

Akpinar and Ozcanan, (2018), have studied the failure conditions of concrete pavements by considering 3 different slab thicknesses (15, 20, and 25 cm) and 3 compressive strength classes (C20, C25, and C30) with finite element analysis of the M-E method in Türkiye. As a result of the study, it has been found that concrete pavements which have slab thickness of 15 cm fail regardless of strength class whereas 20 and 25 cm of slab thickness are enough to serve.

In Türkiye, there are only pilot projects as jointed plain concrete pavements but there are many local roads that have been built as Roller Compacted Concrete (RCC) pavements. RCC pavements are preferred mainly due to the longer service life, faster opening to service, etc. Thus, there are some studies about the structural design of RCC pavements.

Abut, (2017), has developed a design chart of RCC pavements for low volume roads in Türkiye. He has designed RCC pavements for 3 different compressive strength classes (C25, C30, and C35), 4 different subbase types (varying CBR values from 20 % to 120 %), and 3 different traffic loadings with 20 years of service life. AASHTO 93 design method has been used in the study. Also, an empiric equation has been proposed for the design of slab thicknesses. Then, he has compared the results of the proposed equation and the equation given in the AASHTO 93 design guide. As a result of the study, it has been found that the proposed equation can be used to design RCC pavements with about 90 % reliability levels. Also, he has stated that implementing durability properties, temperature gradient, curling effect and heavy vehicle effect into the design phase is an important topic for future studies.

Akbelen and Yaman, (2019), have compared the initial construction costs of RCC and HMA pavements in Türkiye. In the scope of the study, they have designed RCC and HMA pavements for three different traffic volumes (high, medium, and low) and three different soil classes (high-strength, medium-strength, and weak-strength) by using the AASHTO-93 method. As a result of the study, it has been found that RCC pavements are more economical than HMA pavements for all types of traffic loadings and soil classes.

In addition, the reduction in the initial construction cost is increased for higher traffic volumes and weaker soil classes because the total layer thicknesses of RCC pavements are smaller than the total layer thicknesses of HMA pavements.

2.2 Life Cycle Cost Analysis for Pavement Projects

As stated before, Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA) are the main procedures that focus on total cost and total impact on the environment during the whole life cycle of a structure. Currently, LCCA and LCA are used as evaluation or decision-making tools for road pavement projects. One of the main reasons for this is that road pavements have longer service life than many civil engineering structures. Then, there are many types of future costs (maintenance, rehabilitation, user costs, etc.) and impacts on the environment during this longer service life. Thus, it is not a realistic approach to evaluate alternative pavement types by looking at the initial cost of construction or the impact due to the production phase only.

Lee, Kim, and Harvey, (2002), have examined the use of LCCA with the California Department of Transportation approach on a pilot project. Three different pavement alternatives have been compared in the manner of life cycle costs. As a result of the study, it has been found that the best alternative is to construct an innovative asphalt pavement that has a longer service life than the conventional asphalt pavement.

Also, it has been noticed that the use of LCCA when comparing the three alternative pavement types resulted in a cost-saving of around 24-52 % during the whole life cycle of the pilot project.

LCCA is also helpful for the prediction of the cost of future activities (maintenance and rehabilitation) for pavement projects. Wilmot and Cheng, (2003), have studied a model to predict the future construction costs for highway projects in Louisiana.

In the study, they have examined 2827 different projects of highways and bridges constructed in the past by interviewing the officials from the Louisiana Department of Transportation (LADOT) and used the data set of The Bureau of Economic Analysis (BEA) and Data Resources Incorporation (DRI) to predict the future labor and material-equipment costs respectively. It has been found that costs are going to increase quicker than the estimations based on the general inflation or extrapolation of the past trends. Also, they have noticed that the possible cause of this quick increase in construction costs is the increase in the costs of equipment and materials based on petroleum. Thus, if LADOT prefers concrete pavements, the quick increase in highway construction costs will be decreased.

LCCA can be used to choose the best alternative in the manner of costs for different bidding types. Implementing LCCA in the awarding process of biddings provides more economical solution by evaluating the whole life cycle. Gransberg and Molenaar, (2005) have evaluated awarding algorithms to determine the best offer in design/build pavement projects by using the LCCA method. In the scope of the study, two different pavement projects with design/build type of bidding have been analyzed with awarding algorithm which is based on the LCCA method. Case studies have different pavement types which are asphalt and concrete pavements. As a result of the study, it has been noticed that design/build bidding provides better solutions that have cost savings in the life cycle.

Also, using an awarding algorithm to implement LCCA on design/build biddings is very helpful to choose the best alternative. However, different awarding algorithms minimize the life cycle cost by featuring different inputs so the awarding algorithm should be carefully chosen before the bidding.

LCCA and LCA are used in the alternate bidding process by providing a holistic approach while determining the best choice among alternative pavement types. With the help of the LCCA method, it is possible to make more reliable choices in alternate biddings by analyzing all expenses coming from different steps of a road construction project.

As a milestone study, Embacher and Snyder, (2001), have investigated the comparison of life cycle costs of asphalt and concrete pavements for local roads in Minnesota. They have selected 63 different road sections in Minnesota (28 from Olmsted and 35 from Waseca County) based upon similar traffic loads, similar climatic and subgrade conditions, similar years of construction, etc. Then, they have collected the realized initial construction costs and examined the maintenance activities and their costs for each of the sections. After that, they have computed the life cycle cost of all of the road sections by using Net Present Cost-Value (NPC) and Equivalent Uniform Annual Cost (EUAC) techniques. Lastly, they have implemented the methodology for the 4 different case studies.

As a result of the study, 3 of 4 case studies have shown that concrete pavement sections have lower LCCA than asphalt pavement sections. On the other hand, they have found that the average life cycle cost of asphalt pavements is lower than the average one of concrete pavements. However, it has been noticed that comparing the average LCCs biases the results due to the variability in design parameters of different road sections which means a comparison of apples-to-oranges. Also, they have noticed that the maintenance cost of asphalt pavement sections is higher than the one of concrete pavement sections.

Since there is no single approach to LCCA, public authorities prefer to use this method with different approaches, taking into account their own legal regulations and conditions. Chan, Keoleian, and Gabler, (2008), have investigated the precision of the LCCA procedure of the Michigan Department of Transportation (DOT). In the study, 4 different case studies with at least two different pavement types have been selected by considering some parameters such as similar traffic loads and climatic conditions. Then, they have collected the initial construction costs and maintenance schedule for each of the chosen road sections. As a result of the study, it has been found that the LCCA procedure of MDOT is a useful tool to determine the pavement type which has the lowest construction cost but the predicted initial construction costs are about 10 % higher than the actual costs.

Also, they have noticed that predictions for maintenance and rehabilitation schedule were successful but the type of the activities was generally different than the actual one.

The reliability of the LCCA method is directly related to the correct selection of the inputs. The experience gained over the years that different public institutions have used the LCCA method provides an important starting point to improve the reliability of the method by enabling a more realistic selection of inputs. Guven, (2006), has examined the inputs used in the LCCA method to improve the reliability of the method. In the scope of the study, it has been investigated the approaches of different DOTs in the US and Canada based on the results of two different surveys related to the method. As a result of the study, it has been found that most states do not consider any user costs and take only the remaining service life into account while calculating the salvage value. Also, it has been noticed that there is no consensus about the discount rate value but it is an important point to improve the efficiency of the method.

Moreover, it can be seen that most of the agencies prefer service life longer than 30 years and it has an important effect on the results. Lastly, having a pavement management system to handle past data for better prediction of rehabilitation and maintenance activities is a key factor for the efficiency of the method.

At this point, it can be seen that LCCA is a developing useful tool to determine the best alternative pavement type but there is still difficulty with implementing the procedure for road pavement projects because there are many parameters affecting the results of the cost calculations and selecting an objective parameter for both of the pavements types is a big challenge.

Mack et al., (2014), have studied 7 different parameters which are used in LCCA calculations to improve Alabama Department of Transportation’s (ALDOT) LCCA procedure. Trigger value for LCCA, analysis period, performance period, discount rate, price adjustment clauses, inflation rate, and salvage value were examined in the study.

They have found that using a threshold for construction cost is useful in the LCCA procedure. Also, a minimum of 50 years of analysis period should be taken in the calculations of LCCA.

Moreover, including a price adjustment clause affects the efficiency of LCCA. In addition to that, remaining service life (RSL) can be used to represent salvage value in the calculations. Also, a material-specific inflation rate should be taken into account in the calculations to improve the ALDOT's LCCA procedure. Thus, it can be said that considering more parameters in the calculations logically increases the efficiency of LCCA.

In the LCCA procedure, selecting an inflation rate is generally a bit problematic because there is a long period to analyze and prediction for an economic value is very hard in many countries. Also, it has been known that the selection of inflation rate is a sensitive parameter which means it affects the results of LCCA calculation significantly.

Mack, (2012), has investigated the validity of the assumption that using the real inflation rate as the discount rate in LCCA calculations is logical. In the study, the Producer Price Index (PPI), Consumer Price Index (CPI), and the compound annual growth rate (CAGR) which are published by the Bureau of Labor Statistics (BLS) have been examined for each paving materials such as cement, aggregate, and asphalt.

As a result of this study, it has been found that the CAGR for cement, aggregate, and ready-mix concrete is coherent with PPI and CPI but CAGR for asphalt differentiates from the others. Also, the volatility of asphalt is higher than that of other paving materials. Therefore, he has proposed using the escalation rate which is the difference between the materials' specific inflation rate and the general inflation rate for each of the paving materials in LCCA calculations to deal with the future costs more accurately. Also, he has noticed that the economic advantage of the lowest bid which is the concrete alternative in this case increases by about 5 % with the implementation of the escalation rates.

Although the results of the studies related to the LCCA procedure for road pavement projects have shown that it is a logical tool for determining the best option, there are some limitations too. Limitations in the LCCA procedure are mainly due to the uncertainty in future costs which are composed of varying items. There is no common maintenance and rehabilitation schedule generally. Thus, defining future activities creates a problem.

Even though, most of the agencies focus on the agency costs for future activities (maintenance and rehabilitation), there is another important cost items named user costs, such as delay costs due to maintenance activities or accident costs due to the deformation of the pavement. Babashamsi, Yusoff, Ceylan, Nor, and Jenatabadi, (2016), have shown that most of the agencies in the US consider only delay costs as user costs in future activities. Also, preventive maintenance activities are not included in the calculations generally.

Moreover, computing the salvage value of road pavement is another challenge because it is very sensitive to the approach such as remaining service life or recycling of the pavement at the end of the analysis period. Thus, there is no consensus about it generally.

LCCA is used for road pavement projects for many years in the US and Europe. However, only the initial construction cost is taken into account in Türkiye for road pavement projects due to the legal regulations which have been formed many years ago. Thus, there are a limited number of studies related to LCCA for pavement projects. The lack of an LCC approach in Türkiye prevents using the alternate bidding process and determining the most economical alternative for road projects.

As a basis for LCCA in Türkiye, Bagdatli and Yildirim, (2017), have studied the cost analysis of maintenance and rehabilitation activities for asphalt pavements in Türkiye. Firstly, they have defined the types of deterioration for asphalt pavements and then grouped them into 3 main categories, namely distortions, disintegration, and cracking.

Then, they have determined the type of maintenance and rehabilitation activities for each type of deterioration based on the guide of the General Directorate of Highways (KGM) and the costs for each activity by using the official unit prices which are published by KGM annually. As a result of the study, it has been found that repairing of heaving which is a deterioration type occurred due to freeze-thaw action has the highest cost. Also, they have found that the lowest cost belongs to repairing of polished aggregate and thermal cracking types of deteriorations. Lastly, they have proposed that implementing a maintenance and rehabilitations schedule by considering the degree of deterioration parameters which are defined by KGM may be useful for future researches.

As another study Karahacıoğlu and Corum, (2019), have examined the life cycle cost analysis (LCCA) of asphalt pavements. In that study, they have calculated the LCC of an asphalt pavement project in Türkiye and, they have covered the initial construction cost, future cost (maintenance and rehabilitation costs), and salvage value in the calculations.

Using the data obtained from the İstanbul Municipality to calculate construction costs and maintenance costs, they have calculated the rehabilitation costs of similar roads. Then, they have dealt with the salvage value by considering different recycling ratios for each layer of the asphalt pavement (15 % for the wearing course, 20 % for the binder course, 30 % for the base layer, and 40 % for the subbase layer).

They have determined the discount rate by using the exchange rate of the dollar. As a result of the study, they have found that the net present value (NPV) of the road is 1252386 $/km. Also, they have noticed that about two-thirds of the total life cycle cost is the initial construction cost (64 %). Moreover, about one-third of the total life cycle cost is future costs and salvage value which corresponds to a very low portion (5 %) of the total LCC. In addition to that, they have keynoted that it is very important to have a proper maintenance and rehabilitation schedule because an improper schedule increases the LCC and decreases the service life of the pavement.

In Türkiye, there are other studies that compare the life cycle costs of asphalt and concrete pavements. Past experience and literature studies in the USA and Canada prove the importance of considering the life cycle cost rather than the initial construction cost in the selection of the pavement type.

Abut, (2020), has compared roller compacted concrete (RCC) pavements and asphalt pavements in Kocaeli, Türkiye in the context of life cycle costs. In the scope of the study, real case pavement projects and past data about rehabilitation and maintenance activities have been taken into account. As a result of the study, it has been found that RCC pavements are % 39.4 more economical than asphalt pavements when only initial construction costs are considered.

Also, it has been stated that RCC pavements are 46 % more economical than asphalt pavements when the whole life cycle costs with a 30-year analysis period are considered too.

Ucar, Akakin, and Engin, (2007), have compared concrete and asphalt pavements for both initial construction and life cycle costs. In the scope of the study, Jointed Plain Concrete Pavements (JPCP), Continuously Reinforced Concrete Pavements (CRCP), and Hot-Mix Asphalt (HMA) pavements have been designed for 11 different traffic categories by using the AASHTO-93 method. As a result, it has been found that JPCP is more economical than asphalt pavements for all traffic categories when only the initial construction costs are considered. Also, CRCP is more economical than asphalt pavements for only a low volume of traffic when only the initial construction costs are considered. Moreover, the life cycle cost of CRCP is lower than that of asphalt pavements and JPCP.

2.3 Life Cycle Assessment for Pavement Projects

Besides the economic evaluation of the whole life span of road pavement, it is very critical to evaluate the pavement type in the scope of environmental aspects.

From extraction of raw materials to disposal or recycling phase, considerable amount of energy and water are used for a pavement project. Also, a high amount of greenhouse gases (GHG) such as carbon are emitted due to the high energy usage for different stages of the project. Thus, it is clear that a comparison between different pavement types (asphalt and concrete) or different structural designs should include the environmental impacts. Life cycle assessment (LCA) is a popular method to analyze these environmental (carbon emissions, etc.) and social (effect on human health, etc.) impacts of an activity or product generally.

LCA has been used for many years worldwide for pavement projects too. Similar to LCCA, LCA has been used as a decision-making tool because the environmental impacts of a pavement project highly depend on the pavement type. Thus, evaluating the impacts of a pavement type provides an objective comparison between different alternatives.

Like the LCCA method, the LCA method also plays an important role in the selection of pavement type. The use of the LCCA method in pavement construction projects provides a more realistic economic analysis, while the LCA method allows the environmental effects of pavement construction projects to be evaluated with a realistic approach.

Blaauw and Maina, (2021), have studied on developing an LCA model for road construction projects by reporting Life Cycle Inventory (LCI) for all phases of a pavement project in South Africa. In the study, authors focused on the emissions of greenhouse gases, use of energy and use of water by an approach of cradle-to-grave which includes 6 different system boundaries from raw material extraction to recycling. They have calculated the indicator factors for different phases and implemented the LCA model to a case study project in South Africa. As a result of the case study, it has been found that it is possible to decrease the GHG emissions by about 40 %, use of energy by 56 % and use of water 58 % by implementing the LCA model proposed.

Also, they have noticed that reactive approach for maintenance and rehabilitation results in approximately 2 times more emissions than the proactive approach. In addition to that, it has been found that the environmental effects of the maintenance and rehabilitation activities much more than the construction activities.

Heidari et al., (2019), have proposed a life cycle assessment model to select the best sustainable pavement type for road projects in a case study in Iran. They have assessed alternative pavement types (41 different asphalt pavement designs and 32 different concrete pavement designs) by using LCA and LCCA. Then applied stochastic analysis and implemented the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to select the best alternative. As a result of the study it has been found that the best alternative highly depends on the main criteria between emissions, energy usage, or cost comparisons. Also, they have found that the variability in LCCA cost and energy usage for asphalt pavements is less than the variability in concrete pavements. However, the variability in emissions for asphalt pavements is more than the variability in concrete pavements. Moreover, the best asphalt pavement design has lower LCCA costs but has higher carbon emissions and energy usage. Thus, it can be said that determining the main criteria to select the pavement type is very critical.

It is known that some agencies specify the primary criteria while comparing the alternative by using LCA but there is no consensus about it. Moreover, it is not enough to consider only the impacts of the construction and recycling because there are noticeable impacts that arise during the usage phase of a road pavement. LCA can be used to evaluate the effects of using additives or different materials in the production of the pavement mixture as well as to evaluate the alternative pavement types.

Shi et al., (2019), have compared the sustainability of concrete pavements constructed with or without reclaimed concrete aggregates (RCA) by using the economic input-output (EIO) LCA method.

In the study, 3 main phases which are production & construction, use, and end-of-life phases have been covered in EIO LCA calculations. However, they have excluded the maintenance phase because there is not enough data about it. The Vehicle Operating Costs (VOC) model of NCHRP 720 has been considered in the use phase only. Then, they have computed an inventory of stressors to assess the impacts by using the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI). As a result of the study, it has been found that RCA concrete pavement is more sustainable than plain concrete pavement in the context of material production and construction phase whereas plain concrete pavement is more sustainable than RCA concrete pavement for only the usage phase. Also, they have compared the overall results but the more sustainable alternative depends on the impact category such as ecotoxicity, fuel consumption, etc.

2.4 Alternate Bidding/Alternate Design

Alternate bidding/design (ADAB) is a procedure that lets contractors submit alternative designs or materials to the tender. It has been used for many years in the United States and Canada successfully (Gransberg et al., 2018). ADAB procedure is used in different areas like roads, bridges, etc. but ADAB for road pavements projects is going to be the focusing area due to the scope of this study. There are some advantages of using ADAB for road pavement projects. The main advantage of using the ADAB procedure is that it increases the number of bidders and allows inter-industry competition because both asphalt and concrete contractors are allowed to bid for road pavement projects.

Also, it creates a potential cost savings for agencies due to the increased competition (Mack et al.,2012). In addition to that, ADAB procedure provides more objective cost comparison for alternative pavement types because the winner of the bids has the lowest life cycle cost which considers future costs as well as the initial construction cost.

Buss et al., (2017), have studied the process that agencies use for implementing ADAB for road pavement projects. They have examined the results of a questionnaire which is sent to the Department of Transportation agencies (DOTs) in 2016 in US and Canada (Ontario). Then, they have found that many of the DOTs mostly use deterministic type of Life Cycle Cost Analysis (LCCA) in ADAB to decide the pavement type. Moreover, it has been found that the majority of the DOTs use a bid adjustment factor to take into account the difference between the future costs such as maintenance and rehabilitation of the two alternative pavement types.

There are different ways of using ADAB procedure because there are different approaches to handle future costs, threshold in LCC and etc. For example, while some agencies only consider maintenance and rehabilitation costs in their future costs, some agencies include user costs too.

Temple et al., (2004), have examined the ADAB process of Louisiana Department of Transportation (LADOT) which uses the procedure since 1998 for pavement projects. It has been found that LADOT uses ADAB successfully by improving the efficiency of the procedure with contributions of alternative pavement industries.

One of the main points of the success has been found as creating a reasonable maintenance and rehabilitation schedule which increases the reliability of future cost calculations. Also, LADOT uses a 20 % threshold for LCC calculations.

Some of the agencies in US use a bid adjustment factor to handle the price changes for different paving materials. However, there are different algorithms to calculate the bid adjustment factors. Buss et al., (2018), have examined the effect of bid adjustment factors on the winner of the ADAB for pavement projects. In the study, they have studied the results of the survey which was responded by % 80 of the DOTs. Also, they have implemented different bid adjustment factors which are obtained by different formulas suggested by FHWA in an ADAB road project in Kentucky. Then, they have considered the results of 187 case study ADAB projects in Missouri. As a result of the study, they have found that bid adjustment factors hardly change the winner of the ADAB for pavement projects.

On the other hand, there are some drawbacks of using ADAB in road pavement projects. One of the main drawbacks of using it is that it is very compelling process to design structurally equivalent rigid and flexible pavements. There are many differences in the design of rigid and flexible pavements such as load carrying mechanisms and etc. Another drawback is that it is very well-known that the service life of both pavements is different from each other so there is a challenge to determine a reasonable analysis period.

Also, future activities (maintenance and rehabilitation) depend on many factors such as climate conditions, location and etc. Thus, determining a realistic schedule for maintenance and rehabilitation activities creates another challenge. In addition to that, specifying a realistic discount rate for a long analysis period (20-30 years generally) is another question to answer.

Mack and Reece, (2012), have examined some factors which can contribute to the development of the efficiency of ADAB procedure for pavement projects by a case study in North Carolina. They have found that the inflation rate is taken into account in LCCA as a real discount rate which is 4 %. However, it has been found that the inflation rate for asphalt which is nearly 7 % is higher than the rate for cement and ready-mixed concrete which are 4.3 % and 4.6 % respectively. Also, the inflation rate for asphalt is higher than the real discount rate. Moreover, they have discovered that the asphalt prices are more volatile than cement and concrete. Also, they have noticed that some of the DOTs consider different analysis period for the two types of pavements but it may bias the results of the comparison of alternatives.

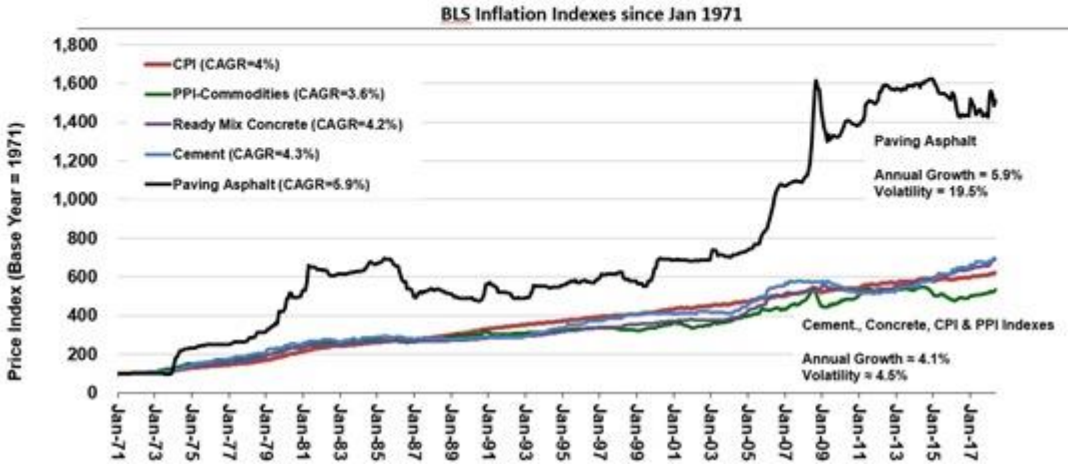

Figure 2.1. Inflation Indexes for Paving Materials Since January 1971

In a similar study that focuses on the inflation rate, Lindsey, Sechmalensee, and Sacher, (2011) have examined the effects of inflation and volatility on the performance of LCCA calculations.

Firstly, they have conducted a traditional LCCA process that considers a constant price change for every material for a pilot project. Then, they have examined the realized price changes for four different materials (asphalt, concrete, and steel) to obtain material-specific inflation rates by evaluating historical data published by BLS. As a result of the study, it has been found that realized asphalt prices increase annually for the analysis period whereas other materials decrease. Also, they have found that concrete has the lowest volatility among other materials.

2.5 Previous Studies in Türkiye

A meticulously calculated and reliable cost comparison is the basis for the choice of road pavement type to be built to provide public benefit.

In this context, the comparison of the costs of flexible and rigid pavements, which are used as alternatives to each other all over the world, emerges as an important research topic.

Anlar, (2019), has compared the construction cost of rigid and flexible pavements in Türkiye. In the scope of the study, rigid and flexible pavements have been designed for 3 different traffic volumes (low, medium, and high) according to the design guides of KGM. In addition, the initial construction costs were calculated for both pavements according to the determined slab thicknesses. Similarly, possible maintenance costs are taken into account concerning the initial construction costs (specific ratios of the initial cost). As a result, it has been shown that flexible pavements are more economical than rigid pavements at low traffic volumes, while rigid pavements become more economical as the traffic volume increases. In addition, rigid pavements are more economical than flexible pavements when maintenance costs are considered.

Akpinar and Dengiz, (2019), have compared the initial construction costs of Roller Compacted Concrete (RCC) and Hot-Mix Asphalt (HMA) pavements in the Eastern Anatolia region in Türkiye.

They have examined the costs of RCC and HMA pavements which are built in 2018 and 2019 in a Turkish city, Igdir. As a result of the study, they have stated that RCC pavements are 20 % more economical than HMA pavements. Also, they have underlined that the economic advantage of RCC pavements over HMA pavement becomes higher when the life cycle costs are taken into account.

As stated before, it is seen that there are very few studies aiming to compare the cost of rigid and flexible pavements in Türkiye. Considering that there are many factors affecting the layer thickness of road pavements, it can be said that the priority for a realistic cost comparison is that both pavement types should be designed under the same parameters (traffic, soil, etc.).

Within the scope of this study, in the next chapter, both road pavement types were designed under the same parameters according to the official design guides and the initial construction costs of both pavements were compared using official unit prices to fill the gap in the literature.

When the studies on concrete roads in Türkiye are examined, it can be seen that a total of 53 thesis studies have been conducted. The first thesis study was done in 1991 and the studies continue today. Most of the thesis studies (around 80%) are at the master's thesis level.

Also, the most commonly researched subjects in the thesis studies on concrete pavements are the use of substitute materials and fibers in concrete pavement mixtures and the structural design of concrete pavements.

In addition, the main focus of the thesis studies on concrete pavements was the structural design in the first years. It is noticeable that the focus is on the use of substitute materials and fibers in concrete pavement mixtures in recent years.

For this reason, it can be said that there is an important deficiency/insufficiency in the literature regarding the design of concrete and asphalt pavements under the same parameters with the same method and comparing their costs.

In the next chapter, this study aims to contribute to the elimination of the deficiency in the literature.

CHAPTER 3

STRUCTURAL DESIGN OF FLEXIBLE AND RIGID PAVEMENTS

In this chapter, asphalt and concrete pavements are designed using the same design parameters according to the official guidelines of General Directorate of Highways (KGM).

3.1 Road Classification in Türkiye

As stated earlier, the Turkish road network can be grouped into two. The first group is the road network that is under the responsibility of General Directorate of Highways (KGM) with a total road network of 68,526 km (KGM, 2022). The second group is the road network that is under the responsibility of municipalities and local administrations. It is estimated that the road network length in the second group exceeds 400,000 km.

KGM classifies the roads as highways, state roads and provincial roads. Highways can be defined as the wide roads for fast-moving traffic where pedestrians, animals, and non-motorized vehicles cannot enter and only permitted motor vehicles can use with a limited number of places at which drivers can enter and leave them. State roads can be defined as the roads that connect provinces. Lastly, provincial roads can be defined as the roads that connect towns to provinces. Within the scope of the study, only a part of KGM road network (state roads) has been considered.

3.2 Design Parameters

In the scope of the study, all of the design parameters have been chosen in accordance with the official guidelines of KGM (KGM, 2008, 2019).

3.2.1 Reliability

Reliability level is basically the safety coefficient which is a criterion for maintaining the validity of the accepted design criteria of the designed pavement, under the prevailing traffic and environmental conditions, throughout the life of the project. Reliability Coefficients (R) related to road classes are given in Table 3.1. Reliability levels have been selected in accordance with the Rigid Pavements Design Guide (2019) and Flexible Pavements Design Guide (2008) by KGM.

Table 3.1 Road Classes and Reliability Coefficients (R)

Road classes	Reliability level in Rigid Pavements Design Guide (%)	Reliability level in Flexible Pavements Design Guide (%)
Highways	95	95
State roads	95	85
Provincial roads	85	70

3.2.2 Service Life

Service life is the time (year) that elapses from the opening of the road to traffic until it reaches its final serviceability value. The service life values have been determined by using the official design guidelines of KGM as twenty years for asphalt pavements and thirty years for concrete pavements.

3.2.3 Traffic

In designing the asphalt and concrete pavements, there are different inputs used to implement the effect of traffic loading. All of the inputs used in the traffic loading calculations are given in detail below.

Traffic Growth Factor is the coefficient determined differently for each vehicle group, used to determine the number of equivalent single axle load that the pavement will be exposed to during the life of the project, using the first year traffic volume. The traffic growth factor (r) used in the calculations for vehicle groups are given in Table 3.2.

Table 3.2 Traffic Growth Factor

Type of Vehicle	**Growth Factor (%)**
Trailer	4
Truck	4
Bus	4
Medium-load commercial vehicle	5
Car	5

The Load Equivalency Factor [LEF] is the ratio of equivalent single axle load of each passing of a vehicle, such as a car, medium-load commercial vehicle, bus, truck or trailer that has an effect equal to the damage to the pavement. LEF values for both pavement designs were taken as given in Table 3.3 in accordance with the guidelines.

Table 3.3 Load Equivalency Factors (LEF)

Type of Vehicle	LEF
Trailer	4.10
Truck	2.90
Bus	3.20
Medium-load commercial vehicle	0.60
Car	0.0006

The directional distribution factor is an indicator of the lane-based distribution of traffic passing in both directions. Since only state roads are analyzed in the calculations made within the scope of this study, it is assumed that the traffic value is equal for each traffic direction.

Direction Distribution Factor has been taken as 50 % for rigid and flexible pavements. The traffic lane used by heavy vehicles should be taken as a basis in the design of the pavements. Lane Distribution Factor is the parameter that is used to represent the effect of heavy vehicles and it is based on the number of lanes in one direction that have been used by heavy vehicles.

Lane distribution factors based on the number of lanes on the basis of road classes are given in Table 3.4.

Table 3.4 Lane Distribution Factors

Road Class	Number of Lanes in Two Directions	Lane Distribution Factors (η)
State roads	4	0.90

3.2.4 Subgrade

In this study, subgrade classes are divided into three groups in terms of bearing capacity as high, medium and weak strength, and the specified subgrade classes are given in Table 3.5.

Table 3.5 Subgrade Classes

Subgrade Class	CBR Value
High-strength	CBR% >50
Medium-strength	$8 \leq$ CBR% ≤ 50
Weak-strength	CBR% <8

Weak-strength subgrades are defined as the soil types that have a CBR value smaller than eight in the guidelines of KGM. Weak-strength soils were evaluated separately and examined in five groups according to their CBR values, as shown in Table 3.6.

Table 3.6 CBR % Values of Different Soil Classes

Subgrade Class	CBR Values (%)	Representative CBR Values (%)
Weak-strength soils 1	1	1
Weak-strength soils 2	2	2
Weak-strength soils 3	4	4
Weak-strength soils 4	6	6
Weak-strength soils 5	7-8	8
Medium-strength soils	8-50	15
High-strength soils	>50	50

Also, the Bearing Coefficient of the Soil (k) value which is defined as the ratio between the load on a unit area under a load and the deformation at that point has been used as an engineering parameter to classify the integrated base/subbase/subgrade layers. Using the correlation curve between "CBR" and soil bearing coefficient (base reaction modulus), "k", soil bearing coefficient, "k" values for seven different soil classes were determined using Figure 3.1.

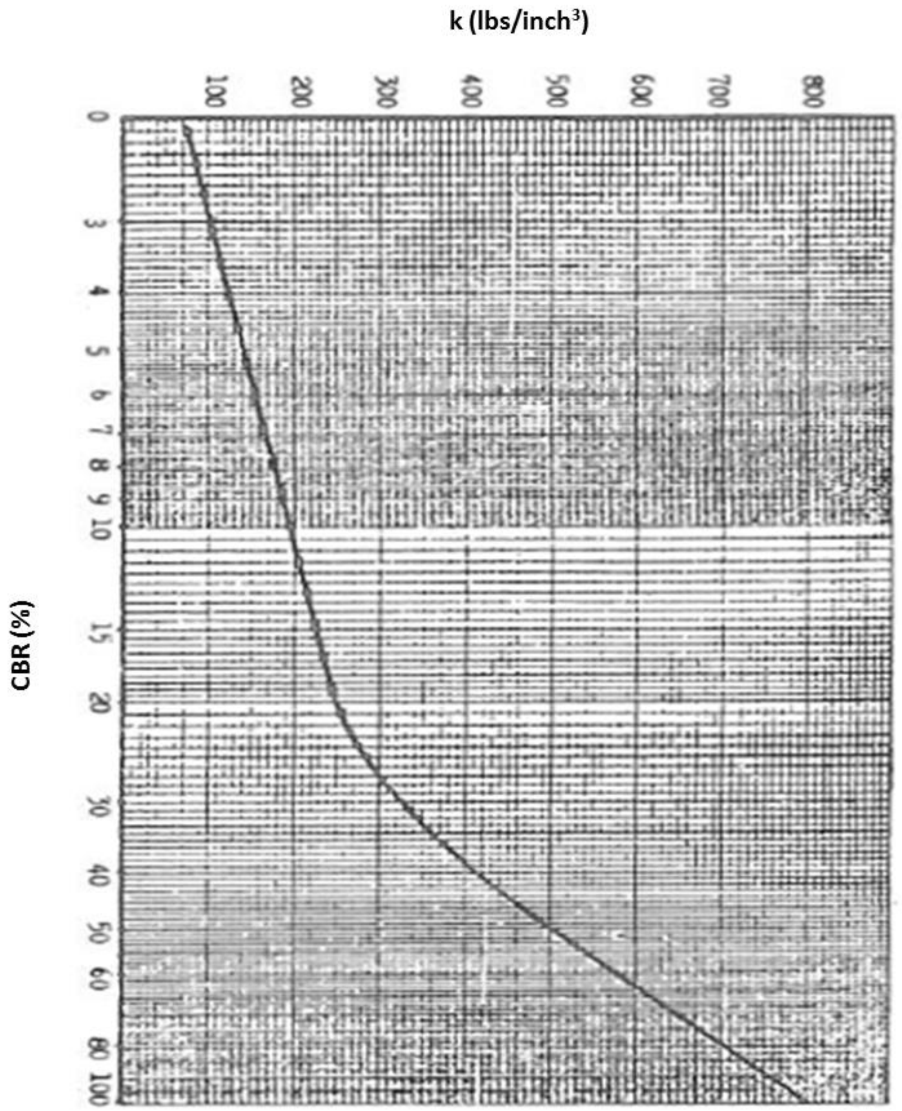

Figure 3.1. Correlation Curve between California Bearing Ratio (CBR) and Soil Bed Coefficient (k) (KGM, 2019)

On the other hand, in the flexible pavement design (Figure 3.2), calculations need the resilient modulus (MR) parameter (Figure 3.3), which is an engineering parameter that defines the behavior of the mixtures that make up the subgrade and pavement layers under cyclic loads.

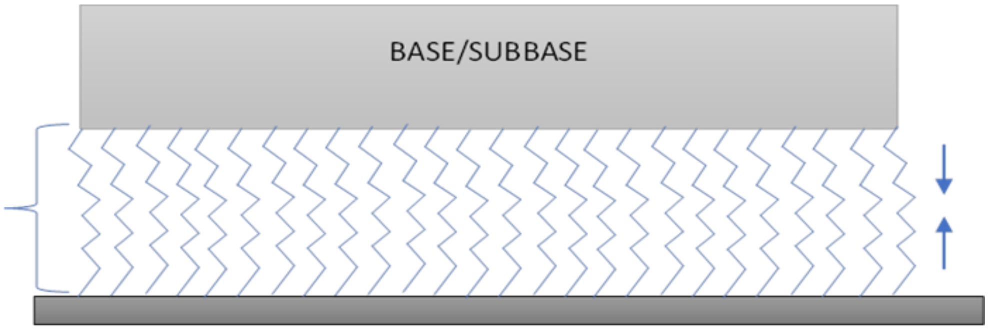

Figure 3.2. Soil Bearing Coefficient Model

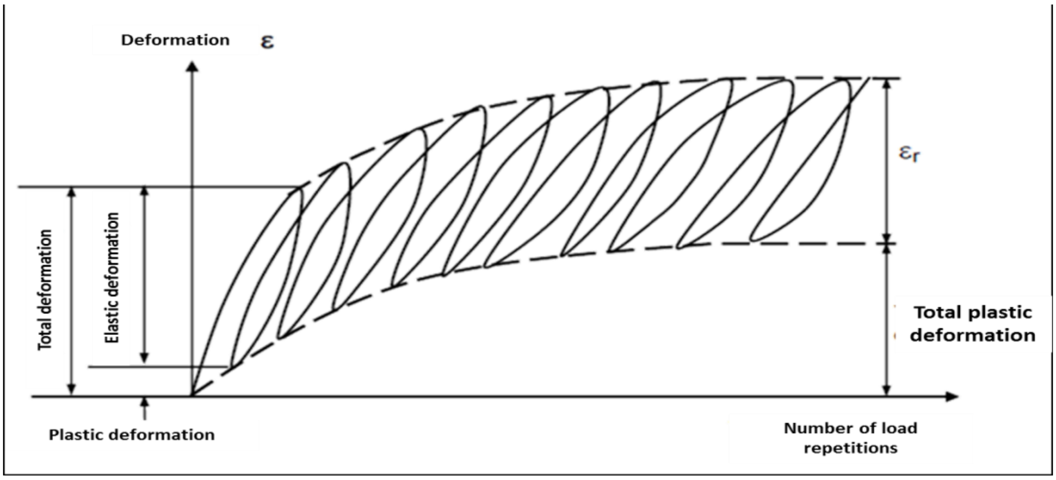

Figure 3.3. Behavior of Pavement Materials Under Repetitive Loads (KGM, 2008)

The resilience modulus (M_R) values of the subgrade according to the CBR (%) values determined for the soil classes specified before. It has been calculated for seven different soil classes by evaluating according to the methods suggested in ACPA, AASHTO and KGM guidelines.

The MR and k values of the soils related to the soil classes, used within the scope of pavement thickness designs, are given in Table 3.7.

Table 3.7 “k” and “MR” Values of Different Soil Classes

Soil Class	**Representative CBR Values (%)**	**MR Values (psi)**	**Bearing ratio (k) (psi)**
Weak-strength soils 1	1	1800	48
Weak-strength soils 2	2	3100	76
Weak-strength soils 3	4	4750	120
Weak-strength soils 4	6	6750	154
Weak-strength soils 5	8	8300	180
Medium-strength soils	15	12600	234
High-strength soils	50	28000	501

3.2.5 Reliability (R-%), Standard Normal Deviate (Z_R) and Combined Standard Deviation (S_0) Values

Reliability, (R) coefficient is the safety factor that indicates the probability of the pavement design to meet the project design conditions during the project period under traffic and environmental conditions.

The level of reliability and the standard normal deviation (Z_R) of reliability have been chosen depending on the class of the road.

The Combined Standard Deviation (S_0) value varies between 0.40-0.50 for flexible pavements, depending on the reliability of the anticipated traffic, and S_0=0.45 is taken as the average. For concrete pavements, S_0=0.35 is taken from the KGM guidelines.

When the pavement is newly constructed, the initial serviceability (P_o) value of the road is generally taken as 4.2 in flexible pavement projects and 4.5 in rigid pavement projects. The terminal serviceability (P_t) is chosen based on the lowest allowable serviceability of the road pavement before repair or reinforcement.

The parameters used in the calculations depending on the pavement type are given in Table 3.8.

Table 3.8 Parameters Used in Rigid and Flexible Design Calculations

Parameters	Rigid Pavements	Flexible Pavements
Reliability, R %	95	85
Standard normal deviation, Z_R	-1.645	-1.037
Combined standard deviation S_o	0.35	0.45
Initial serviceability P_o	4.5	4.2
Terminal serviceability P_t	2.5	2.5

3.2.6 Material Properties

In rigid pavement structural design calculations, the following (Table 3.9) material properties of concrete were utilized (KGM, 2019).

Table 3.9 Rigid Pavement Material Properties

Parameter Name	Unit	Value
Compressive strength class	-	C 35/45
Characteristic cylinder strength (f_{ck})	MPa	35
Characteristic cubic strength (f_{ck})	MPa	45
Avg. flexural strength according to TS 500	MPa	4.2
Avg. modulus of rupture according to TS 500 Sc’	psi	610
Avg. modulus of rupture according to AASHTO Sc’	psi	709
Avg. modulus of rupture Sc’	psi	660
Modulus of elasticity E_c	MPa	33,000
Modulus of elasticity E_c	psi	4,783,244

Similarly, the material properties used in flexible pavement structural design calculations have been taken in accordance with the Flexible Pavements Design Guide of KGM. The material properties used are given in Table 3.10.

The coefficient ‘a’ is the relative strength coefficient, which expresses the empirical relationship between SN and the thickness and is defined as a measure of the bearing capacity of the material as a composition of the pavement.

Table 3.10 Material Properties of Flexible Pavement Layers

Layer Type	**M.S.(kg)**	**CBR (%)**	**SBD (kg/cm^2)**	**A coefficient**
Stone mastic asphalt (SMA)	-	-	-	0.44
Asphalt concrete wearing course	≥ 900	-	-	0.42
Asphalt concrete binder course	≥ 750	-	-	0.40
Bituminous treated base	≥ 600	-	-	0.36
Base Layers				
Cement bounded granular base	-	-	35-55	0.23
Plant-Mixed base	-	≥ 120	-	0.15
Granular base	-	≥ 100	-	0.14
Subbase Layers				
Crushed stone subbase	-	≥ 50	-	0.13
Sand-gravel subbase	-	≥ 30	-	0.11

3.3 Structural Design of Protective Layers

Soils with CBR value smaller than 8 % are defined as weak soils and should not be used on the pavement base according to the Rigid Pavements Design Guide and Flexible Pavements Design Guide by KGM. In such cases, it was stated that the base of the pavement should be reformed by using selected materials. This layer is called the protective layer.

The protective layer thicknesses vary according to the number of equivalent single axle load. Protective layer thicknesses were determined for two different traffic volumes according to the Concrete Pavements Design Guide, and for three different traffic volumes in the Flexible Pavements Design Guide. Protective layer thicknesses related to traffic volumes and CBR% values are given in Table 3.11.

Table 3.11 Protective Layer Thicknesses

a) Rigid Pavement

Number of equivalent single axle load ($T_{8.2}$)	**Protective Layer Thicknesses for Weak Soils in Rigid Pavements Design Guide (cm)**			
Wet CBR %	CBR% <2	2 ≤ CBR% < 4	4 ≤ CBR% < 6	6 ≤ CBR% < 8
< 80 million	55	35	25	20
> 80 million	60	40	30	20

b) Flexible Pavement

Number of equivalent single axle load ($T_{8.2}$)	**Protective Layer Thicknesses for Weak Soils in Flexible Pavements Design Guide (cm)**					
Wet CBR %	1	2	3	4	5	6	7-8
< 40 million	75	50	40	35	25	20	20
40-80 million	80	55	40	35	25	20	20
> 80 million	85	60	45	40	30	25	20

It is stated that the selected material to be used in the construction of the protective layer should meet the characteristics given in Table 3.12 for both guides.

Table 3.12 Protective Layer Properties

Experiment Name	Limit Value	Relevant Standard
Material passing through 0.075mm (No:200) sieve	< 50 %	TS 1900 AASHTO T-11
Liquid Limit (LL)	< 40	TS 1900 AASHTO T-89
Plasticity Index (PI)	< 15	TS 1900 AASHTO T-90
Wet CBR	≥ 10 %	TS 1900 AASHTO T-193

In the structural design phase of flexible pavements, the protective layer thicknesses were used in the structural designs according to the values given in above and were also checked with the SN calculation method. Then, it was determined that the thicknesses from the tables and the thicknesses of the calculations were compatible. Required protective layer thickness calculations have been made based on the related section in Flexible Pavements Design Guide of KGM.

While calculating the required protective layer thickness, D, the following formula is used, taking into account the required SN.

$$D = \frac{Required\ SN - Pavement\ SN}{a \times m} \quad \textit{(Equation 1)}$$

where “a” is the relative strength coefficient and “m” is the drainage coefficient.

In the calculations, the wet CBR% value of the selected material to be used in the construction of the protective layer is taken as 10 %. The resilience modulus (M_R) values of the soil according to the determined CBR% values are evaluated according to the methods recommended in ACPA, AASHTO and KGM guidelines, MR = 9,389 psi.

Accordingly, the relative strength coefficient of the selected material was calculated according to the formula specified in the "11.2.2 Layer Coefficients" section in the Flexible Pavements Design Guide of KGM.

$$a = 0.0045 \times \sqrt[3]{M_R} = 0.0045 \times \sqrt[3]{9389} = 0.095 \quad \textit{(Equation 2)}$$

After that, material drainage coefficient was selected as m=0.95 from Table 3.13 to represent a general soil type in Türkiye. The required selected material thicknesses related to the soil drainage coefficient and the calculated relative strength coefficient have been calculated and are given in the following section.

Table 3.13 Drainage Coefficients

Soil Type	**Symbol for the related soil type**	**Percentage of materials smaller than 0.075 mm %**	**N Drainage coefficient (m_i)**
Gravel	GW, GP, GW-GM, GW-GC, GP-GM, GP-GC	<12	1.0
	GM, GC	12-20	0.95
		>20	0.90
Sand	SW, SP, SW-SM, SW-GC, SP-SM, SP-SC	<12	0.95
	SM, SC	12-20	0.90
		>20	0.85
Silt	ML, MH	>50	0.75
Clay	CL, CH	>50	0.50

3.4 Structural Design of Rigid Pavements

In rigid pavement structural design calculations, the layer thicknesses were calculated based on the equations for Jointed Plain Concrete Pavement (JPCP) specified in the relevant guide in relation to load transfer coefficient, drainage coefficient and base reaction modulus values.

The equation used in the calculation of JPCP layer thicknesses in the Rigid Pavements Design Guide is as follows.

$$log_{10}(T_{8.2}) = Z_R \, x \, S_0 + 7.35 \, x \, log_{10}(d+1) - 0.06 + \frac{log_{10}\left(\frac{\Delta PSI}{4.5-1.5}\right)}{1+\frac{1.624x10^7}{(d+1)^{8.46}}} +$$

$$(4.22 - 0.32 \, x \, p_t) \, x \, log_{10}\left[\frac{S_c' \, x \, C_d \, x \, (d^{0.75}-1.132)}{215.63 \, x \, J \, x \left[d^{0.75} - \frac{18.42}{((\frac{E_c}{k})^{0.25})}\right]}\right] \textit{(Equation 3)}$$

Layer thicknesses were calculated for different traffic volumes and 7 different soil classes for JPCP based on the scope of the study and the results are given in Table 3.14.

Table 3.14 Layer Thicknesses of JPCP in State Roads for 30 Years of Service Life

Number of equivalent single axle load ($T_{8.2}$)	CBR %	k-coefficient (pci)	Thicknesses of JPCP (cm)	Thicknesses of PMB(cm)	Thicknesses of Protective Layer(cm)
468,631,612	1	48	43	20	60
	2	76	42	20	40
	4	120	42	20	30
	6	154	42	20	20
	8	180	42	20	0
	15	234	41	20	-
	50	501	40	20	-
129,789,263	1	48	36	20	60
	2	76	35	20	40
	4	120	35	20	30
	6	154	35	20	20
	8	180	34	20	0
	15	234	34	20	-
	50	501	33	20	-
11,736,392	1	48	25	20	55
	2	76	25	20	35
	4	120	24	20	25
	6	154	24	20	20
	8	180	24	20	0
	15	234	23	20	-
	50	501	22	20	-

3.5 Structural Design of Flexible Pavements

In flexible pavement structural design process, pavement layer thicknesses are calculated by determining the pavement number (SN) as a result of the formula developed by AASHTO road tests based on the serviceability-pavement behavior relationship.

The determined layer thicknesses must provide the required SN value on the base and subbase. The calculated layer thicknesses were checked with the calculation method specified in the Flexible Pavements Design Guide by KGM. The equations given for the control of layer thicknesses in the Flexible Pavement Design Guide are given in Figure 3.4.

$$log(T_{8.2}) = Z_R \; x \; S_0 + 9.36 \; x \; log(SN+1) - 0.20 + \frac{log\left(\frac{\Delta PSI}{4.2-1.5}\right)}{0.40+\frac{1094}{(SN+1)^{5.19}}} + 2.32 \; x \; logM_R - 8.07 \textit{ (Equation 4)}$$

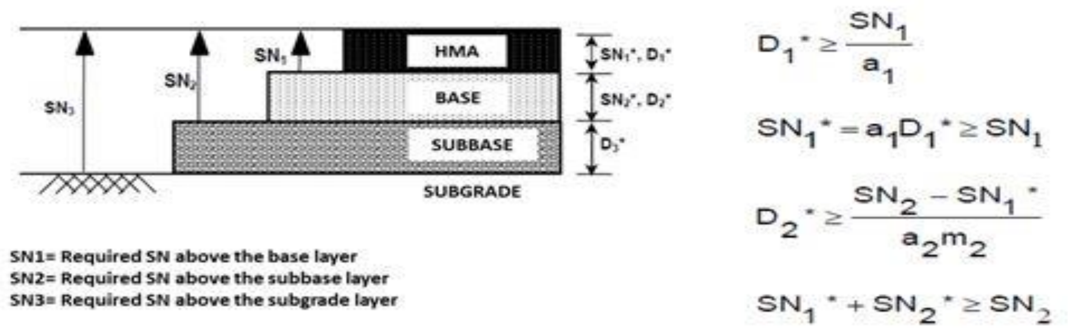

Figure 3.4. SN Value for Flexible Pavements (KGM, 2008)

Layer thicknesses were calculated separately for three different traffic volumes and seven different soil classes for HMA pavements and the results are given in Table 3.15.

Table 3.15 Layer Thicknesses of HMA Pavements in State Roads for 20 Years of Service Life

Number of equiv. single axle load ($T_{8.2}$)	CBR %	MR (psi)	Thickness of Asphalt Courses (cm)					
			SMA Wearing	Binder	B.Base	PMB	Subbase	Protective Layer
245,000,004	1	1,800	4	14	18	20	20	85
	2	3,100	4	14	17	20	15	60
	4	4,750	4	13	16	20	15	40
	6	6,750	4	11	16	20	15	25
	8	8,300	4	10	16	20	15	20
	15	12,600	4	11	14	20	15	-
	50	28,000	4	10	14	20	15	-
67,500,000	1	1,800	4	12	14	20	15	80
	2	3,100	4	10	13	20	15	55
	4	4,750	4	8	14	20	15	35
	6	6,750	4	8	13	20	15	20
	8	8,300	4	7	12	20	15	20
	15	12,600	4	7	12	20	15	-
	50	28,000	4	7	12	20	15	-
6,000,000	1	1,800	4	12	0	15	15	75
	2	3,100	4	11	0	15	15	50
	4	4,750	4	10	0	15	15	35
	6	6,750	4	10	0	15	15	20
	8	8,300	4	10	0	15	15	20
	15	12,600	4	10	0	15	15	-
	50	28,000	4	10	0	15	0	-

CHAPTER 4

ESTABLISHMENT OF UNIT PRICE ANALYSIS AND DESCRIPTIONS OF CONCRETE PAVEMENTS FOR TÜRKİYE

In Türkiye, official unit prices and descriptions for asphalt pavements are legally available. However, there is a lack of official unit price analysis and descriptions for concrete pavements. Thus, it is needed to establish unit prices and descriptions for concrete pavements to compare the initial construction costs of both pavement types.

Then, this study aims to establish the unit prices only for Jointed Plain Concrete Pavements on state roads of KGM in the scope of the study. For this purpose, all steps have been examined to determine the needs for materials, types of equipment, and crew for JPCP construction. Then, the quantities of usage for these needs have been determined and unit prices have been examined for availablility to use in the unit price analyses.

The first step of the construction is the supply and transportation of materials, equipment, and crew to the construction site. After that, reinforcements (dowel bars and tie bars) are prepared and placed. Then, concrete is produced, transported to the construction site, and laid. The next steps are surface finishing and curing activities of the pavement. The final step is joint cutting for the construction of JPCP. Thus, all related cost items should be legally available for cost comparison studies. In the scope of the study, all official unit prices are examined for each step of construction. There are available official unit cost items for many construction steps but there are two important missing items. The first one is the market price of slip-form paver which is used in the step of laying concrete.

The second one is the market price of hot-applied sealant material which is used in the joint sealing construction step. Therefore, it is necessary to determine the missing market prices before to form the unit price analyses for concrete pavements.

It should be noted that especially slipform pavers come with a wide variety of features that will affect its cost. For example, its capacity in terms of paving width and thickness; availability of an automatic dowel bar insertion system, a stringless control system and the use of a spreader at front can significantly change the cost of the slipform paver.

To determine the market prices, price offers were collected from the companies producing the relevant equipment or materials. As for the paver, a slipform paver that does not have any automatic dowel bar insertion and stringless control system is considered and its market prices are collected. Then, offers are examined and by considering an average value, prices have been estimated for each item. Thus, as shown in Table 4.1, two different market prices have been formed to use in the unit price analysis.

Table 4.1 Newly Formed Market Prices

Estimated Item Number	**Description**	**Market Price**
10.120.(…)	Slip-form concrete paver for road or field concrete applications	15,000,000 TL
10.300.(…)	Hot-applied joint sealant	13.94 TL/kg

Then, six different unit price analyses (Table 4.2 to Table 4.7) have been formed by using newly formed and official market prices to calculate the initial construction cost for JPCP in state roads. Formed unit price analyses that corrrespond to each step of construction are given below. Table 4.2 and Table 4.3 present the hourly price of a slipform paver. Before establishing these two items, a worksite visit at Belgium and Türkiye was conducted and video recordings were made which were later used to determine the hourly rates of the machine and the operators.

For Item 10.160.1026, the quantity of usage has been obtained from the companies as 41.6 l/h and it has been converted to kg/h in the analysis.

Also, the quantity has been taken as 1.3 for the items 10.100.1055 and 10.100.1059 because operators are responsible for the installation and cleaning of the machines in addition to the laying work so it corresponds to a 30 % increase in these specified work items. Lastly, 2 assistant operators have been taken into account for the calculation of quantity for item 10.100.1057.

Table 4.2 Hourly Price of Slip-form Paver (for Concrete Pavements) (KGM/BY-1)

Item No.	**Descriptions**	**Unit of Measurement (UoM)**	**Quantity**
10.120.(1)	Depreciation 0.000114 Spare 0.000061 Repair/Maintenance 0.000015 Insurance 0.000037 Transportation, installation, disassembly 0.000016 Slip-form paver	h	0.000243
10.160.1026	Diesel fuel (grease gasoline and etc. are included)	kg	35.36
10.100.1055	Machine operator	h	1.30
10.100.1057	Assistant operator	h	2.60
10.100.1059	Greaser	h	1.30

Table 4.3 Laying Concrete with Slip-form Paver (KGM/BY-2)

Item No.	**Descriptions**	**UoM**	**Quantity**
KGM/BY-1	Hourly price of slip-form paver (for concrete pavements)	h	0.0143
19.100.1001	Hourly price of excavator (100 HP)	h	0.0092
10.100.1061	Surveyor	h	1.364
10.100.1015	Concrete master	h	1.364
10.100.1060	Foreman	h	0.341
10.100.1062	Unskilled worker	h	1.364

For Item KGM/BY-1, production capacity has been taken as 70 m^3/h which is a general capacity in similar works. Also, the working duration of the excavator has been estimated as 30-35 seconds for 1 m3 of concrete for the item 19.100.1001, after viewing and counting from the video recordings of an actual site. Lastly, it is assumed that four surveyors, four concrete masters, four unskilled workers and one foreman work in the laying step of the construction.

As it has been given in Table 4.4, it is estimated that six concrete masters, four unskilled workers and one foreman work in the surface finishing and texturing step of the construction.

Table 4.4 Surface Finishing and Texturing of Concrete Pavement (KGM/BY-3)

Item No.	Descriptions	UoM	Quantity
10.100.1015	Concrete master	h	0.09
10.100.1060	Foreman	h	0.015
10.100.1062	Unskilled worker	h	0.060

For the curing step of the construction, it is assumed that 0.35 kg/m^2 curing compound is enough to prevent the water loss limit which is specified as 0.55 kg/m^2 per 72 hours in TS 10967 standard and a concrete master work for curing as it has been given in Table 4.5 and Table 4.6.

Table 4.5 Curing Concrete Pavement with Paraffin Based Curing Compound (KGM/BY-4)

Item No.	Descriptions	UoM	Quantity
10.300.2063	Paraffin based curing compound	kg	0.35
10.100.1015	Concrete master	h	0.08

Table 4.6 Curing Concrete Pavement with Acrylic Based Curing Compound (KGM/BY-5)

Item No.	Descriptions	UoM	Quantity
10.300.2062	Acrylic based curing compound	kg	0.35
10.100.1015	Concrete master	h	0.08

In the calculations for item 10.120.1203, the duration for joint cutting has been taken as 1.8 minutes because it generally takes 1.5-2.0 min/m for concrete pavements. Also, it is estimated that the duration for the usage of the compressor is around 36 seconds to clean the joint before sealing.

Lastly, it is assumed that two first-class masters, two unskilled workers, and a surveyor work for the joint cutting and sealing step of the construction so the unit price analysis for joint construction has been given in Table 4.7.

Table 4.7 Joint Cutting and Sealing for Concrete Pavements (KGM/BY-6)

Item No.	Descriptions	UoM	Quantity
10.120.1203	Joint cutting machine (including knife, water tank and etc.)	h	0.030
10.120.1025	Compressor (250 HP)	h	0.010
10.300.2158	Polyethylene cylinders (diameter= 6 mm)	m	1.000
10.100.1068	First class master	h	0.100
10.100.1062	Unskilled worker	h	0.100
10.100.1061	Surveyor	h	0.040

All in all, six different unit price analyses have been formed for JPCP in state roads by considering official and two newly formed market prices. In the following chapter the initial construction costs of asphalt and concrete pavements have been compared by using unit price analyses for state roads in Türkiye.

CHAPTER 5

THE INITIAL COST COMPARISON OF FLEXIBLE AND RIGID PAVEMENTS IN TÜRKİYE

In the scope of the study, initial construction costs for both pavement types have been calculated by using the official unit price analyses for asphalt pavements and the ones for concrete pavements which have been obtained in the last chapter. Official unit prices published by public authorities and market prices in 2021 were used in all of the cost calculations.

The pavement geometric properties used in the study were determined by considering the geometric standards of the state roads in the Highway Design Handbook. The relevant properties are given in Table 5.1.

Table 5.1 Geometric Properties of State Roads

Property	**State Roads**
Number of directions	2
Number of lanes in the same direction	2
Lane width (m)	3.5
Inner safety strip width (m)	1
Outer safety strip width (m)	2.5
Platform width (m)	21
Length (m)	1,000
Total square area (m^2)	21,000

5.1 Construction Cost of Base, Subbase and Protective Layers

In the scope of the study, costs of base, subbase and protective layer have been calculated by using the official unit prices which are given in Table 5.2.

Table 5.2 Unit Costs for the Construction of Plant Mix Base and Subbase Layers

Item No.	Description	UoM	Unit Price (TL)
6100/3	Construction of Plant Mix Base Layer (with crushed and sifted hearthstone)	t	61.78
01.03.6100	Construction of Plant Mix Subbase Layer (with crushed and sifted hearthstone)	t	54.31

While calculating the costs for base and subbase layers all expenses which are not included in the unit prices were considered separately. The parameters were selected by considering the KGM Unit Price Analysis Book and the Ministry of Environment, Urbanization and Climate Change Unit Price Book. Selected parameters are given in Table 5.3.

Table 5.3 Selected Parameters to Calculate Other Expenses

Parameter	Selected Value
Transport Coefficient	427
Difficulty Coefficient	1
Transportation distance of aggregates from the crusher to the plant area	10 km
Transportation distance of mixing water to the plant area	1 km
Transportation distance of base/subbase materials from the plant area to the workplace	10 km
Transportation distance of irrigation water to the workplace	10 km
Water Content of Base/Subbase mixes	4.5 %
Dry aggregate ratio	0.957 %
Water ratio	0.043 %

As it has been given in Table 5.4, total costs of constructing the plant mix base and subbase layers should be formed by considering the costs which are not included in the unit prices.

Table 5.4 Total Costs for the Construction of Plant Mix Base and Subbase Layers

Item No.	**Description**	**UoM**	**Unit Price (TL)**	**Expenses Not Included in the Unit Prices (TL)**	**Total Unit Price (TL)**
6100/3	Construction of Plant Mix Base Layer (with crushed and sifted hearthstone)	t	61.78	17.98	79.76
01.03.6100	Construction of Plant Mix Subbase Layer (with crushed and sifted hearthstone)	t	54.31	17.98	72.29

While calculating the protective layer construction costs, the costs of scraping and transporting the weak soil layer, bringing material from the borrow pit, laying/compaction the material and supplying the water required for the compaction process to the workplace have been taken into account.

Table 5.5 Cost of the Construction of Protective Layers

Item No.	Description	UoM	Quantity	Unit Price (TL)	Cost (TL)
15.005	Excavation and use of weak ground (Vegetal earth etc.) (including transport to 100 m)	m^3	1.000	3.21	3.21
15.006/B	Excavation and use of all types of loose rock with an excavator (Excavations to be brought from the borrowed pit or to the quarry/warehouse) (including transportation to 100 m)	m^3	0.500	6.66	3.33
15.010/B	Excavation and use of soft rock with excavator (Excavations to be brought from the borrowed pit or to the quarry/warehouse)	m^3	0.500	14.61	7.31
15.047	Irrigation with sprinkler	t	0.100	15.25	1.53
15.052/4	Compacting with a vibrating roller (including 9-11 tons -11 tons - static weight) and 18-22 tons of dynamic force vibratory roller + crawler tractor (approximately 66-86 HP)	h	0.010	305.53	3.06
07.005/K-1	Transporting of weak soil material	m^3	1.000	9.07	9.07
07.005/K-1	Transportation of the selected material required for the protective layer to the workplace	m^3	1.000	13.99	13.99
07.005/K	Transporting the irrigation water required for the protective layer to the workplace (10 km, A=1)	t	0.066	9.07	0.60
Total Cost (TL/m^3)					42.08

Also, grading costs have been determined according to the situation where the grader blade width is 3.70 m and unit prices for grading step of the construction are given in Table 5.6.

Table 5.6 Unit Prices for Grading

Item No.	Description	UoM	Unit Price (TL)
15.044	Grading on all types of soil with the machine	km	4,353.75
15.044_Special	1 m^2 grading on all types of soil with the machine	m^2	1.18

5.2 Construction Cost of Rigid Pavements

Within the scope of the study, unit prices and related market prices were determined for each stage of concrete pavement construction. The official market prices published by KGM and Ministry of Environment, Urbanization and Climate Change were primarily used in the formation of unit price analysis for concrete pavements. However, for the slip-form paver used in concrete pavement construction, there is no existing official market price in Türkiye. Thus, market price has been established as stated before. The unit price determined and established by the market prices and market price researches is marked as bold and italic. All unit prices related to concrete pavement costs are given below.

Table 5.7 Material Price for Production of Concrete

Item No.	Description	UoM	Unit Price (TL)
10.130.1507	C 35/45 Concrete grout (including transportation)	m^3	228.00

Table 5.8 Cost of Slip-form Paver (for Concrete Pavements) (KGM/BY-1)

Item No.	Descriptions	UoM	Quantity	Unit Price (TL)	Cost (TL)
10.120.(1)	Depreciation 0.000114 Spare 0.000061 Repair/Maintenance 0.000015 Insurance 0.000037 Transportation, installation, disassembly 0.000016 Slip-form paver	h	0.000243	15,000,000.00	3,645.00
10.160.1026	Diesel fuel (grease gasoline and etc. are included)	kg	35.36	6.54	231.25
10.100.1055	Machine operator	h	1.30	26.40	34.32
10.100.1057	Assistant operator	h	2.60	21.65	56.29
10.100.1059	Greaser	h	1.30	16.80	21.84
Total Cost (TL/h)					3,988.70

Table 5.9 Cost of Laying Concrete with Slip-form Paver (KGM/BY-2)

Item No.	Descriptions	UoM	Quantity	Unit Price (TL)	Cost (TL)
KGM/BY-1	Hourly price of slip-form paver (for concrete pavements)	h	0.0143	3,988.70	57.04
19.100.1001	Hourly price of excavator (100 HP)	h	0.0092	200.23	1.84
10.100.1061	Surveyor	h	1.364	24.60	33.55
10.100.1015	Concrete master	h	1.364	22.50	30.69
10.100.1060	Foreman	h	0.341	33.00	11.25
10.100.1062	Unskilled worker	h	1.364	16.45	22.44
Total Cost (TL/m^3)					156.82

Table 5.10 Cost of Surface Finishing and Texturing of Concrete Pavement (KGM/BY-3)

Item No.	Descriptions	UoM	Quantity	Unit Price (TL)	Cost (TL)
10.100.1015	Concrete master	h	0.090	22.50	2.03
10.100.1060	Foreman	h	0.015	33.00	0.50
10.100.1062	Unskilled worker	h	0.060	16.45	0.99
Total Cost (TL/m^2)					3.51

Some work items related to concrete pavement construction are not included in the official unit prices. For this reason, the costs not included in the unit prices for the construction of 1 m^2 concrete pavement and their required quantities were determined separately for each unit price and the costs were calculated by multiplying the quantities with the relevant unit price.

The first of the costs that are not included in the unit prices is the curing required for the protection of the concrete pavement surface. Within the scope of the study, while calculating the costs of curing, the criterion of not exceeding 0.55 kg/m2 of water loss in 72 hours as a result of the water holding property test performed in accordance with the TS 10967 standard and criteria stated in the "Concrete Chemical Curing Agents" section of the Technical Specification for Concrete Pavements by KGM have been considered.

As a result, the use of paraffinic curing material with a consumption of 0.35 kg/m2 has been taken as basis in the calculations and the detailed costs are given in Table 5.11.

Table 5.11 Cost of Curing Concrete Pavement with Paraffin Based Curing Compound (KGM/BY-4)

Item No.	**Descriptions**	**UoM**	**Quantity**	**Unit Price (TL)**	**Cost (TL)**
10.300.2063	Paraffin based curing compound	kg	0.35	5.80	2.03
10.100.1015	Concrete master	h	0.08	22.50	1.80
Total Cost (TL/m^2)					3.83

Also, the costs of joints have been determined by considering the locating the joints and directions, making the markings, cutting the joints at the depth specified in the project, forming the reservoirs in accordance with the drawings, cleaning the cut joints and filling them with hot-applied joint sealants in the calculations. Also, cold-applied sealants may be used but the general practice is to use hot-applied sealants in Türkiye.

In the calculations, the density of the hot-applied sealant has been taken as 1.20 g/cm3. Cost calculations were made by taking the appropriate joint dimensions in the section given in Figure 5.1.

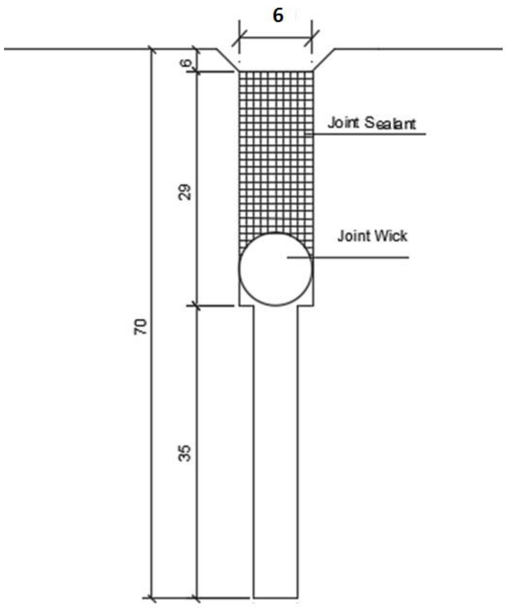

Figure 5.1. Joint Details

In the analysis of "Joint Cutting on Concrete Road Surface and Filling with Hot-Applied Joint Sealant", the current price of hot-applied joint sealing material is not included in the Unit Price Book of KGM and the Ministry of Environment, Urbanization and Climate Change.

The price of hot-applied joint sealing material has been determined as a result of detailed market price research. The item numbers of the result of price research are given in bold and italic.

Table 5.12 Cost of Joint Cutting and Sealing for Concrete Pavements (KGM/BY-6)

Item No.	Descriptions	UoM	Quantity	Unit Price (TL)	Cost (TL)
19.100.1093	Joint cutting machine (including knife, water tank and etc.)	h	0.030	40.28	1.21
KGM/03.589	Compressor (250 HP)	h	0.010	202.25	2.02
10.300.2158	Polyethylene cylinders (diameter= 6 mm)	m	1.000	0.22	0.22
10.300.(…)	Hot-applied joint sealant (TS EN 14188-1)	kg	0.216	13.94	3.01
10.100.1068	First class master	h	0.100	22.50	2.25
10.100.1062	Unskilled worker	h	0.100	16.45	1.65
10.100.1061	Surveyor	h	0.040	24.60	2.46
Total Cost (TL/m)					12.82

The cost of plain and ribbed reinforcements, their transportation to the workplace, cutting, bending and placing the reinforcements according to their drawings after transportation, loss of reinforcement, and connecting wire costs are not included in the unit price when determining the unit prices for construction of concrete pavements. These costs are considered as expenses that are not included in the unit price and are added to the costs separately.

Reinforcement densities and dimensions have been determined in accordance with the Concrete Pavements Design Guide by KGM, and their amounts have been calculated separately for varying concrete slab thicknesses. Reinforcement costs have been determined in accordance with the calculated quantities. Recommended reinforcement diameters in the Concrete Pavements Design Guide by KGM are given in Table 5.13.

Table 5.13 Recommended Dowel Bar Diameters

Slab Thickness (d)	Recommended Diameter (Ø)
d ≤ 28 cm	32 mm
28 cm < d ≤ 34 cm	38 mm
35 cm ≤ d ≤ 40 cm	44 mm

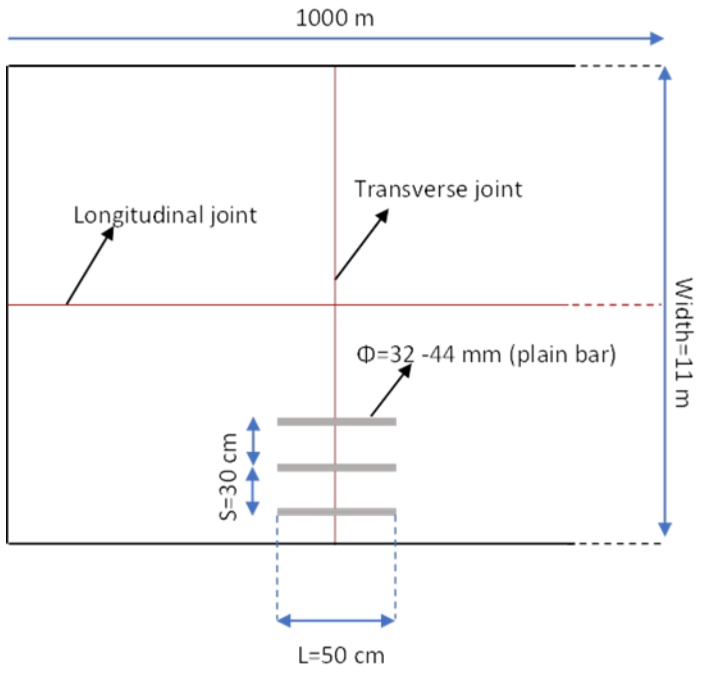

Figure 5.2. Layout of Dowel Bars According to Concrete Pavements Design Guide of KGM

Table 5.14 Recommended Tie Bar Diameters

Slab Thickness (d)	**Recommended Diameter (Ø)**
d ≤ 30 cm	12-14 mm
30 cm < d	16-20 mm

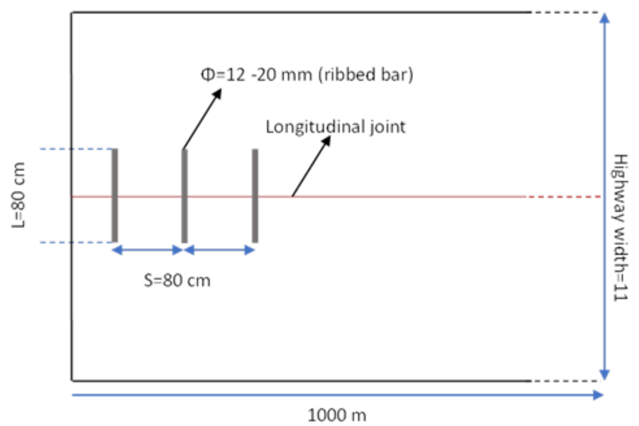

Figure 5.3. Layout of Tie Bars

Hence, the initial construction costs for JPCP in state roads are given in Table 5.15 by considering three different traffic loadings, thirty years of service life and seven different soil classes.

Table 5.15 Initial Construction Costs for JPCP in State Roads

Reliability (%)	**T (8.2)**	**CBR (%)**	**Total Cost (TL/km)**
95	468,631,612 (High Volume Traffic)	1	6,732,634
		2	6,507,023
		4	6,371,739
		6	6,253,458
		8	6,054,772
		15	6,023,458
		50	5,914,362
	129,789,263 (Medium Volume Traffic)	1	6,002,302
		2	5,776,690
		4	5,641,407
		6	5,523,126
		8	5,324,440
		15	5,293,125
		50	5,040,523
	11,736,382 (Low Volume Traffic)	1	4,629,052
		2	4,405,291
		4	4,269,417
		6	4,196,240
		8	3,996,543
		15	3,963,209
		50	3,838,961

When the values presented in Table 5.15 is presented in a graph, Figure 5.4 is obtained. As it is clearly seen from this graph the soil condition clearly affects the initial construction costs of concrete pavements. Moreover, the slope of the lines does not change much and this indicates that the effect of the soil strength is limited in the construction costs of concrete pavements.

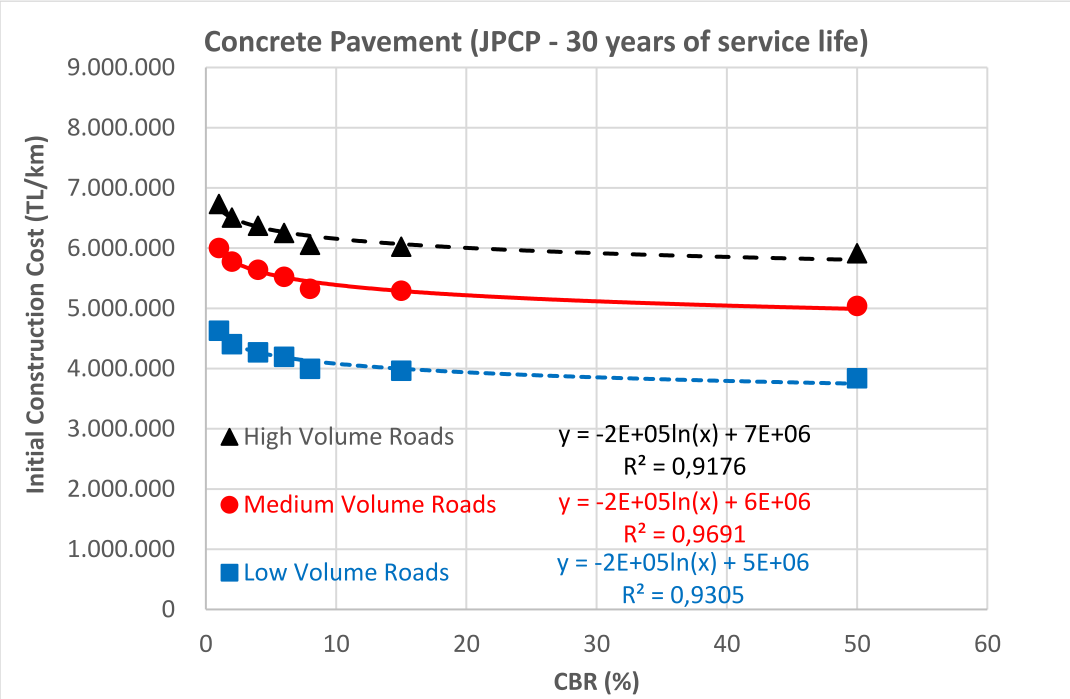

Figure 5.4. Construction Cost of JPCP for Different Soil Classes

5.3 Construction Cost of Flexible Pavements

Within the scope of the study, the unit prices which are used to calculate the total initial construction cost of flexible pavements are given in Table 5.16, Table 5.17 and Table 5.18 based on the layer types and layer thicknesses. These unit prices are already being established and announced by KGM.

Table 5.16 Construction Cost of Bituminous Base Layer

Item No.	Descriptions	UoM	Unit Price (TL)
KGM/6214	Constructing bituminous base layer of 1 m^2 with a compacted thickness of 14 cm (with crushed and sifted hearthstone) (TYPE-A)	m^2	34.29
KGM/6213	Constructing bituminous base layer of 1 m^2 with a compacted thickness of 13 cm (with crushed and sifted hearthstone) (TYPE-A)	m^2	31.89
KGM/6212	Constructing bituminous base layer of 1 m^2 with a compacted thickness of 12 cm (with crushed and sifted hearthstone) (TYPE-A)	m^2	29.49
KGM/6211	Constructing bituminous base layer of 1 m^2 with a compacted thickness of 11 cm (with crushed and sifted hearthstone) (TYPE-A)	m^2	27.09
KGM/6210	Constructing bituminous base layer of 1 m^2 with a compacted thickness of 10 cm (with crushed and sifted hearthstone) (TYPE-A)	m^2	24.69
KGM/6209	Constructing bituminous base layer of 1 m^2 with a compacted thickness of 9 cm (with crushed and sifted hearthstone) (TYPE-A)	m^2	22.29
KGM/6208	Constructing bituminous base layer of 1 m^2 with a compacted thickness of 8 cm (with crushed and sifted hearthstone) (TYPE-A)	m^2	19.89

Table 5.17 Construction Cost of Binder Layer

Item No.	Descriptions	UoM	Unit Price (TL)
KGM/6308	Construction of 1 m² asphalt concrete binder layer with 8 cm compacted thickness (with crushed and sifted hearthstone)	m²	20.86
KGM/6308/S	Construction of 1 m² asphalt concrete binder layer with 8 cm compacted thickness (with crushed and sifted hard stone)	m²	22.79
KGM/6307	Construction of 1 m² asphalt concrete binder layer with 7 cm compacted thickness (with crushed and sifted hearthstone)	m²	18.34
KGM/6307/S	Construction of 1 m² asphalt concrete binder layer with 7 cm compacted thickness (with crushed and sifted hard stone)	m²	20.03
KGM/6306	Construction of 1 m² asphalt concrete binder layer with 6 cm compacted thickness (with crushed and sifted hearthstone)	m²	15.82
KGM/6306/S	Construction of 1 m² asphalt concrete binder layer with 6 cm compacted thickness (with crushed and sifted hard stone)	m²	17.27
KGM/6305	Construction of 1 m² asphalt concrete binder layer with 5 cm compacted thickness (with crushed and sifted hearthstone)	m²	13.29
KGM/6305/S	Construction of 1 m² asphalt concrete binder layer with 5 cm compacted thickness (with crushed and sifted hard stone)	m²	14.50

Table 5.18 Construction Cost of Wearing Layer

Item No.	Descriptions	UoM	Unit Price (TL)
KGM/6454/S-M	Construction of 1 m² SMA wearing course with 4 cm compacted thickness (with crushed and sifted hard stone and modified bitumen) (TYPE-1)	m²	14.99
KGM/6405/S-M	Construction of 1 m² wearing course with 5 cm compacted thickness (with crushed and sifted hard stone and modified bitumen) (TYPE-1)	m²	17.33

When calculating the unit prices of the flexible pavement layers, some of the costs (transportation of materials, heating the bitumen and etc.) are not included in the unit price analyses so they must also be added to the calculations. Thus, the costs of other expenses which are not included in the unit price analysis have been calculated. The parameters were selected by considering the Unit Price Analysis Books of KGM and the Ministry of Environment, Urbanization and Climate Change. Selected parameters are given below with details.

In the unit price analysis of the construction of bituminous base, binder and wearing layers, costs of transporting aggregates to a distance of more than 150 m between the quarry and the crusher, transporting the aggregates to the plant site, supplying bitumen, transporting the bitumen adhesive to the workplace, transporting the bituminous material to the storage tank, heating the solid bituminous material and transporting the mixture to the workplace are not included in the unit price analysis. Thus, they have been calculated for each layer and added to the unit price analysis. Detailed expenses which are not included in the unit price analyses are given in Table 5.19, Table 5.20 and Table 5.21.

Table 5.19 Expenses not Included in Unit Price Analysis for Construction of Bituminous Base Layer

Item No.	Descriptions	UoM	Quantity	Unit Price (TL)	Cost (TL)
07.005/K	Transporting aggregates to an average distance of more than 150 m between the quarry and crusher	t	0.962	1.28	1.23
07.005/K	Transport of the aggregate required for the binder to the plant area (up to M=10 km.)	t	0.962	9.07	8.73
10.330.5422	Asphalt Cement (Penetration Asphalt) (Kırıkkale)	kg	38	3.64	138.23
07.005/K	Transportation of bituminous adhesive from supply place to workplace	t	0.0002	9.07	0.00
07.005/K	Transportation of bituminous material from supply place to storage tank M= 300 km	t	0.038	117.43	4.46
KGM/4358	Heating of solid bituminous material in cisterns or tanks up to the degree of suction (by machine)	t	0.038	65.75	2.50
07.005/K	Transportation of Bituminous Hot Mixture (Binder) to workplace	t	1.000	9.07	9.07
Total Cost (TL/t)					164.22

Table 5.20 Expenses not Included in Unit Price Analysis for Construction of Binder Layer

Item No.	Descriptions	UoM	Quantity	Unit Price (TL)	Cost (TL)
07.005/K	Transporting aggregates to an average distance of more than 150 m between the quarry and crusher	t	0.952	24.02	22.87
07.005/K	Transport of the aggregate required for the binder to the plant area (up to M=10 km.)	t	0.952	9.07	8.64
10.330.5422	Asphalt Cement (Penetration Asphalt) (Kırıkkale)	kg	48	3.64	174.72
07.005/K	Transportation of bituminous adhesive from supply place to workplace	t	0.0002	9.07	0.002
07.005/K	Transportation of bituminous material from supply place to storage tank M= 300 km	t	0.048	117.43	5.64
KGM/4358	Heating of solid bituminous material in cisterns or tanks up to the degree of suction (by machine)	t	0.048	65.75	3.16
07.005/K	Transportation of Bituminous Hot Mixture (Binder) to workplace	t	1.000	9.07	9.07
Total Cost (TL/t)					224.10

Table 5.21 Expenses not Included in Unit Price Analysis for Construction of SMA Wearing Layer (Type-1)

Item No.	Descriptions	UoM	Quantity	Unit Price (TL)	Cost (TL)
07.005/K	Transporting aggregates to an average distance of more than 150 m between the quarry and crusher	t	0.939	24.02	22.55
07.005/K	Transport of the aggregate required for the wearing course to the plant area (up to M=10 km.)	t	0.939	9.07	8.52
10.330.5422	Asphalt Cement (Penetration Asphalt) (Kırıkkale)	kg	61	3.64	221.89
Market Research	Supply of modifying additive material to the workplace	t	0.003	24,000.00	65.88
Market Research	The supply cost of fiber which is used as an additive in wearing course	t	0.0035	7,125.00	24.94
07.005/K	Transportation of bituminous adhesive from supply place to workplace	t	0.0002	9.07	0.0018
07.005/K	Transportation of bituminous material from supply place to storage tank M=300 km	t	0.061	117.43	7.16
KGM/4358	Heating of solid bituminous material in cisterns or tanks up to the degree of suction (by machine)	t	0.061	65.75	4.01
07.005/K	Transportation of Bituminous Hot Mixture (Wearing) to workplace	t	1.000	9.07	9.07
Total Cost (TL/t)					364.03

In addition, the bitumen ratios and mixture densities to be used in the mixtures have been determined in accordance with the KGM Unit Prices Analysis Book. The parameters used to determine the costs that are not included in the unit prices are given in Table 5.22, Table 5.23 and Table 5.24.

Table 5.22 Bituminous Binder Ratios

Parameter Name	**Selected Value (%)**
Bitumen rate for Wearing Course (WC) Layers (Hard Stone)	5.2
Bitumen rate for Stone Mastic Asphalt (SMA) Layers (Hard Stone)	6.1
Bitumen rate for Binder Layers (Hard Stone)	4.8
Bitumen rate for Binder Layers (Hearthstone)	4.3
Bitumen rate for Bituminous Base Layers (Hearthstone)	3.8

Table 5.23 Mixture Densities

Parameter Name	**Selected Value (t/m^3)**
Density for Wearing Course (WC) Layers (Hard Stone)	2.45
Density for Stone Mastic Asphalt (SMA) Layers (Hard Stone)	2.45
Density for Binder Layers (Hard Stone)	2.45
Density for Binder Layers (Hearthstone)	2.40
Density for Bituminous Base Layers (Hearthstone)	2.30

Table 5.24 Transportation Parameters

Parameter Name	Selected Value
Transport Coefficient	427
Difficulty Coefficient	1
Transportation distance of HMA aggregate from the crusher to the plant area (Hard Stone)	50 km
Transportation distance of HMA aggregate from the crusher to the plant area (Hearthstone)	10 km
HMA Quarry Crusher Interval Avg. Transport Distance (Hard Stone)	10 km
HMA Quarry Crusher Interval Avg. Transport Distance (Hearthstone)	0.2 km
Bitumen Transportation Distance	300 km
HMA transportation distance to workplace (site)	10 km
Transportation distance of bitumen adhesive to workplace (site)	10 km

Moreover, the usage amount of bituminous adhesive is recommended as 0.15-0.50 l/m2 in the KGM Technical Specification of Highways. Within the scope of the study, calculations were made according to the use of 0.20 l/m^2 bitumen adhesive. Also, it has been assumed that 4.5 % of the bitumen amount of the modifying additive is used, and the cost of 1 ton of modifying additive material has been taken as 24,000 TL (equivalent to 3,000 $).

In addition to that, it has been estimated that 0.35 % of the fiber additive mixture amount is used and the cost of 1-ton fiber additive material has been taken as 7.125 TL (equivalent to 750 €). In the scope of the study, unit price analyses have been prepared for flexible pavements by considering all of the costs for each layer. Total costs and analyses for flexible pavement layers are given Table 5.25, Table 5.26 and Table 5.27.

Table 5.25 Cost of the Construction of Bituminous Base Layer

Item No.	Descriptions	UoM	Unit Price (TL)	Other Expenses (TL)	Cost (TL)
KGM/6214	Constructing bituminous base layer of 1 m² with a compacted thickness of 14 cm (with crushed and sifted hearthstone) (TYPE-A)	m²	34.29	52.88	87.17
KGM/6213	Constructing bituminous base layer of 1 m² with a compacted thickness of 13 cm (with crushed and sifted hearthstone) (TYPE-A)	m²	31.89	49.10	80.99
KGM/6212	Constructing bituminous base layer of 1 m² with a compacted thickness of 12 cm (with crushed and sifted hearthstone) (TYPE-A)	m²	29.49	45.33	74.82
KGM/6211	Constructing bituminous base layer of 1 m² with a compacted thickness of 11 cm (with crushed and sifted hearthstone) (TYPE-A)	m²	27.09	41.55	68.64
KGM/6210	Constructing bituminous base layer of 1 m² with a compacted thickness of 10 cm (with crushed and sifted hearthstone) (TYPE-A)	m²	24.69	37.77	62.46
KGM/6209	Constructing bituminous base layer of 1 m² with a compacted thickness of 9 cm (with crushed and sifted hearthstone) (TYPE-A)	m²	22.29	34.00	56.29
KGM/6208	Constructing bituminous base layer of 1 m² with a compacted thickness of 8 cm (with crushed and sifted hearthstone) (TYPE-A)	m²	19.89	30.22	50.11

Table 5.26 Cost of the Construction of Binder Layer

Item No.	Descriptions	UoM	Unit Price (TL)	Other Expenses (TL)	Cost (TL)
KGM/6308	Construction of 1 m² asphalt concrete binder layer with 8 cm compacted thickness (with crushed and sifted hearthstone)	m²	20.86	35.19	56.05
KGM/6308/S	Construction of 1 m² asphalt concrete binder layer with 8 cm compacted thickness (with crushed and sifted hard stone)	m²	22.79	43.90	66.69
KGM/6307	Construction of 1 m² asphalt concrete binder layer with 7 cm compacted thickness (with crushed and sifted hearthstone)	m²	18.34	30.79	49.13
KGM/6307/S	Construction of 1 m² asphalt concrete binder layer with 7 cm compacted thickness (with crushed and sifted hard stone)	m²	20.03	38.41	58.44
KGM/6306	Construction of 1 m² asphalt concrete binder layer with 6 cm compacted thickness (with crushed and sifted hearthstone)	m²	15.82	26.39	42.21
KGM/6306/S	Construction of 1 m² asphalt concrete binder layer with 6 cm compacted thickness (with crushed and sifted hard stone)	m²	17.27	32.93	50.20
KGM/6305	Construction of 1 m² asphalt concrete binder layer with 5 cm compacted thickness (with crushed and sifted hearthstone)	m²	13.29	21.99	35.28
KGM/6305/S	Construction of 1 m² asphalt concrete binder layer with 5 cm compacted thickness (with crushed and sifted hard stone)	m²	14.50	27.44	41.94

Table 5.27 Cost of the Construction of Wearing Layer

Item No.	Descriptions	UoM	Unit Price (TL)	Other Expenses (TL)	Cost (TL)
KGM/6454/S-M	Construction of 1 m² SMA wearing course with 4 cm compacted thickness (with crushed and sifted hard stone and modified bitumen)(TYPE-1)	m²	14.99	35.68	50.67
KGM/6405/S-M	Construction of 1 m² wearing course with 5 cm compacted thickness (with crushed and sifted hard stone and modified bitumen)(TYPE-1)	m²	17.33	36.17	53.50

Hence, the initial construction costs for HMA pavements in state roads are given in Table 5.28 for three different traffic categories, twenty years of service life and seven different soil classes.

Table 5.28 Initial Construction Costs for HMA Pavements in State Roads

Reliability (%)	**T (8.2)**	**CBR (%)**	**Total Cost (TL/km)**
85	245,000,004 (High Volume Traffic)	1	7,832,320
		2	7,459,426
		4	6,965,757
		6	6,506,201
		8	6,314,167
		15	5,977,022
		50	5,831,521
	67,500,000 (Medium Volume Traffic)	1	6,763,751
		2	6,100,907
		4	5,735,811
		6	5,465,860
		8	5,190,850
		15	4,982,171
		50	4,982,171
	6,000,000 (Low Volume Traffic)	1	4,850,457
		2	4,604,656
		4	4,010,317
		6	3,870,715
		8	3,870,715
		15	3,662,877
		50	3,662,877

When the values presented in Table 5.28 is presented in a graph, Figure 5.5 is obtained. As it is clearly seen from this graph the soil condition clearly affects the initial construction costs of asphalt pavements. In addition, the change in the slope of the lines for different volume roads indicate that this effect is dependent on the volume of traffic that the road is carrying.

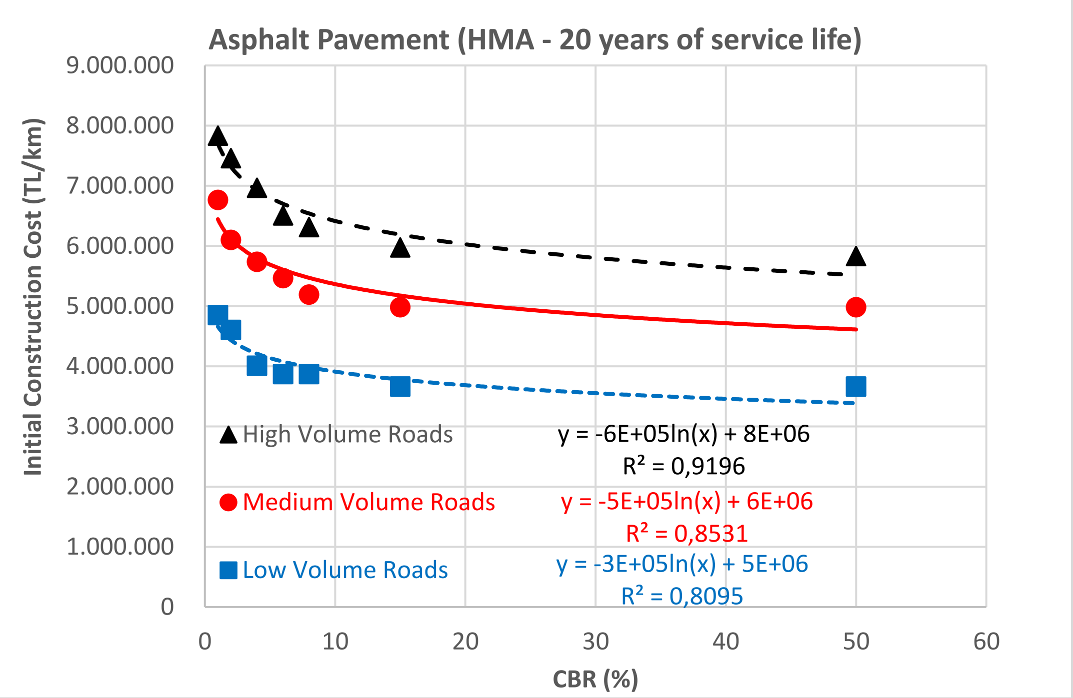

Figure 5.5. Construction Costs of HMAP for Different Soil Classes

5.4 Comparison of Initial Construction Costs for Both Pavement Types

In the above sections, the parameters used in cost calculations within the scope of the study are explained in detail. In this section, cost comparisons are made according to these parameters and reductions in the costs are given with tables and graphs. The initial construction costs of both pavements having different service lives are compared for roads having different traffic volumes in Figure 5.6, Figure 5.7 and Figure 5.8. As seen from all these curves both soil type and traffic volume affects the initial construction cost of pavements. Even though they are designed for different service lives JPCP is cheaper for soils having a low bearing capacity, regardless of the volume of traffic. On the other hand, for stronger soils this cost difference drops down.

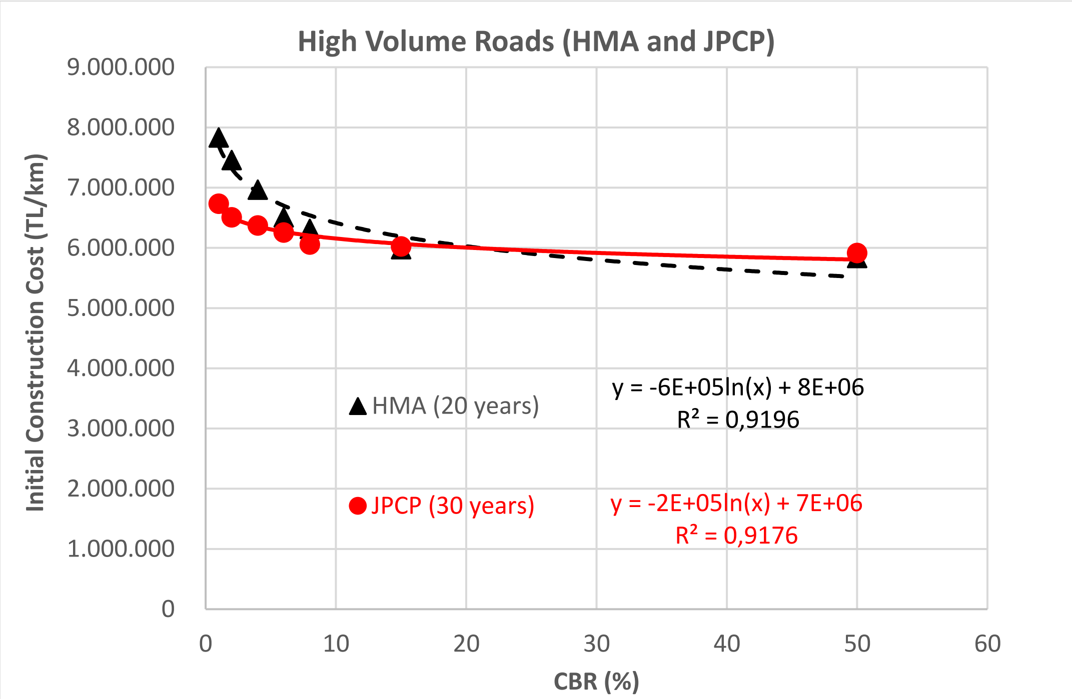

Figure 5.6. Cost Comparison of Both Pavements for High Traffic Volume

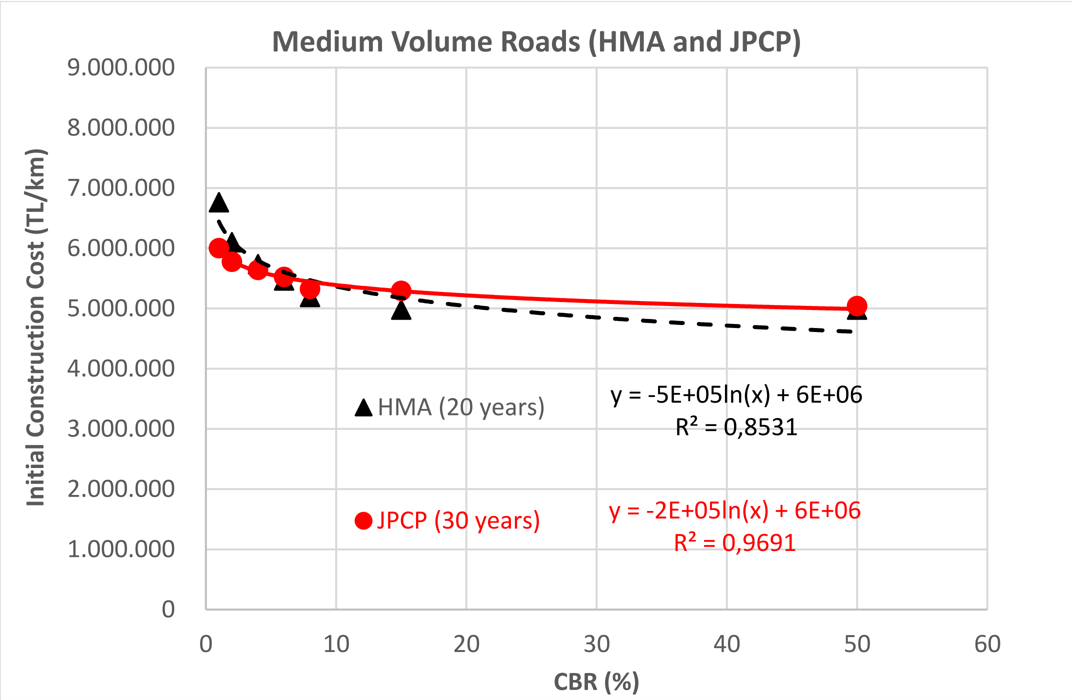

Figure 5.7. Cost Comparison of Both Pavements for Medium Traffic Volume

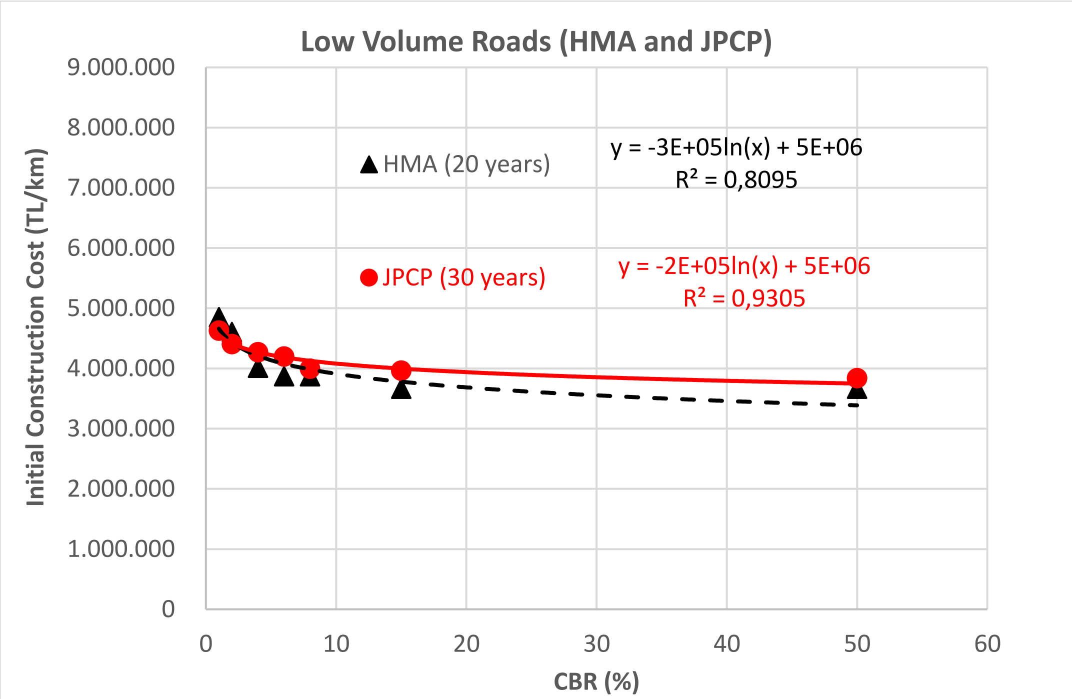

Figure 5.8. Cost Comparison of Both Pavements for Low Traffic Volume

In order to compare the initial construction costs of different alternatives having different lifespans, equivalent annual cost of alternatives for their least common multiple can to be computed. In this case, since JPCP and HMA pavements are designed for 30 and 20 years, respectively, economic analysis can be performed for their least common multiple, i.e. 60 years.

In order to make such analysis one needs to calculate the net present value (NPV) and equivalent annual cost (EAC) for HMA and JPCP type of pavements. The NPV calculations are especially suitable for road pavement projects because there are many future costs during the life cycle and salvage value at the end of life cycle of a pavement. For example, the delay costs for the users due to a maintenance and rehabilitation activity can be considered by using NPV. Similarly, costs for all of the maintenance and rehabilitation activities can be defined as future agency costs and are taken into account in NPV calculations. Thus, comparing costs for different pavement types with different service life values is possible by implementing the NPV method. Because of this advantage, NPV method is commonly used in the LCCA calculations of pavements. In this thesis, however only the initial construction costs will be considered as other cost items are not readily available in Türkiye.

The net present values can be calculated for HMA and JPCP using Equation 5, and equivalent annual cost can be calculated using Equation 6 as shown below.

$$NPV_{HMA} = ICC_{HMA}\left(1 + \frac{1}{(1+i)^{20}} + \frac{1}{(1+i)^{40}}\right)$$
$$NPV_{JPCP} = ICC_{JPCP}\left(1 + \frac{1}{(1+i)^{30}}\right) \quad \textit{(Equation 5)}$$

$$EAC_{HMA/JPCP} = NPV_{HMA/JPCP}\,\frac{i(1+i)^{60}}{(1+i)^{60-1}} \quad \textit{(Equation 6)}$$

where NPV_{HMA} and NPV_{JPCP} are the net present values and ICC_{HMA} and ICC_{JPCP} are the initial construction cost of HMA and JPCP pavements, respectively. $EAC_{HMA/JPCP}$ is the equivalent annual cost of either HMA or JPCP.

In these equations *i* represent the interest rate, which needs to be identified. Determining a specific interest rate may be difficult, because there are lots of parameters affecting the interest rate such as economic and social conditions, pandemic and etc. In order to obtain a comprehensive result, three different scenarios as optimistic, possible and worst-case have been formed to represent different conditions. For the optimistic scenario, an interest rate of 5 % have been determined by considering the previous studies about choosing an interest rate for alternate bidding and LCCA for pavement projects as stated in the literature review chapter. For the possible scenario, an interest rate of 15 % has been chosen by considering the average Producer Price Index (PPI) for the last sixteen years (2005-2021, data processing method has been changed in 2005). Lastly, an interest rate of 40 % has been determined as for the worst-case scenario by considering the average PPI for the last three years (2018-2021) to include the pandemic effect.

After that, common service life has been determined as sixty years to cover twenty years of service life for asphalt pavements and thirty years of service life for concrete pavements.

Then, EAC values for both pavement types have been computed for three different traffic volumes and seven different soil conditions with three different interest rates. The EAC values are given below.

Table 5.29 Equivalent Annual Costs for Interest Rate (i)= 5 %

Traffic Volume	**CBR (%)**	**EAC of JPCP (TL/km)**	**EAC of HMAP (TL/km)**
High traffic volume	1	437,968	628,486
	2	423,291	598,564
	4	414,491	558,950
	6	406,796	522,074
	8	393,872	506,665
	15	391,835	479,612
	50	384,738	467,936
Medium traffic volume	1	390,458	542,741
	2	375,782	489,553
	4	366,982	460,256
	6	359,287	438,595
	8	346,362	416,527
	15	344,325	399,782
	50	327,893	399,782
Low traffic volume	1	301,126	389,213
	2	286,570	369,489
	4	277,732	321,798
	6	272,971	310,596
	8	259,981	310,596
	15	257,812	293,919
	50	249,730	293,919

Table 5.30 Equivalent Annual Costs for Interest Rate (i)= 15 %

Traffic Volume	**CBR (%)**	**EAC of JPCP (TL/km)**	**EAC of HMAP (TL/km)**
High traffic volume	1	1,025,382	1,251,303
	2	991,021	1,191,729
	4	970,417	1,112,860
	6	952,403	1,039,440
	8	922,143	1,008,761
	15	917,374	954,898
	50	900,759	931,652
Medium traffic volume	1	914,152	1,080,587
	2	879,791	974,690
	4	859,187	916,362
	6	841,173	873,234
	8	810,913	829,298
	15	806,144	795,959
	50	767,673	795,959
Low traffic volume	1	705,005	774,916
	2	670,927	735,647
	4	650,233	640,694
	6	639,088	618,391
	8	608,674	618,391
	15	603,597	585,187
	50	584,675	585,187

Table 5.31 Equivalent Annual Costs for Interest Rate (i)= 40 %

Traffic Volume	CBR (%)	EAC of JPCP (TL/km)	EAC of HMAP (TL/km)
High traffic volume	1	2,693,165	3,136,677
	2	2,602,917	2,987,341
	4	2,548,801	2,789,637
	6	2,501,487	2,605,595
	8	2,422,009	2,528,689
	15	2,409,483	2,393,670
	50	2,365,843	2,335,400
Medium traffic volume	1	2,401,020	2,708,738
	2	2,310,772	2,443,283
	4	2,256,656	2,297,070
	6	2,209,342	2,188,960
	8	2,129,864	2,078,825
	15	2,117,338	1,995,253
	50	2,016,293	1,995,253
Low traffic volume	1	1,851,697	1,942,504
	2	1,762,189	1,844,066
	4	1,707,837	1,606,046
	6	1,678,565	1,550,139
	8	1,598,683	1,550,139
	15	1,585,349	1,466,904
	50	1,535,648	1,466,904

Figure 5.9, Figure 5.10 and Figure 5.11 show the EAC comparison for concrete and asphalt pavements under high volume of traffic with interest rates of 5 %, 15 % and 40 %. As it can be seen from the figures, concrete pavements are more economical than asphalt pavements for most of the conditions. Asphalt pavements only become more economical option for the worst-case scenario with stronger soils.

Also, the economic efficiency decreases with higher strength of soil classes. Lastly, the economic efficiency increases with decreasing interest rate.

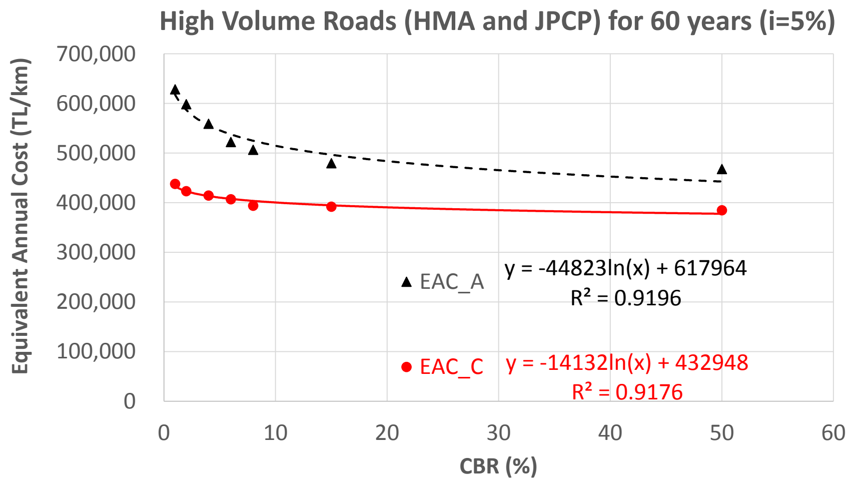

Figure 5.9. EAC Comparisons Under High Volume Traffic with an Interest Rate of 5 %

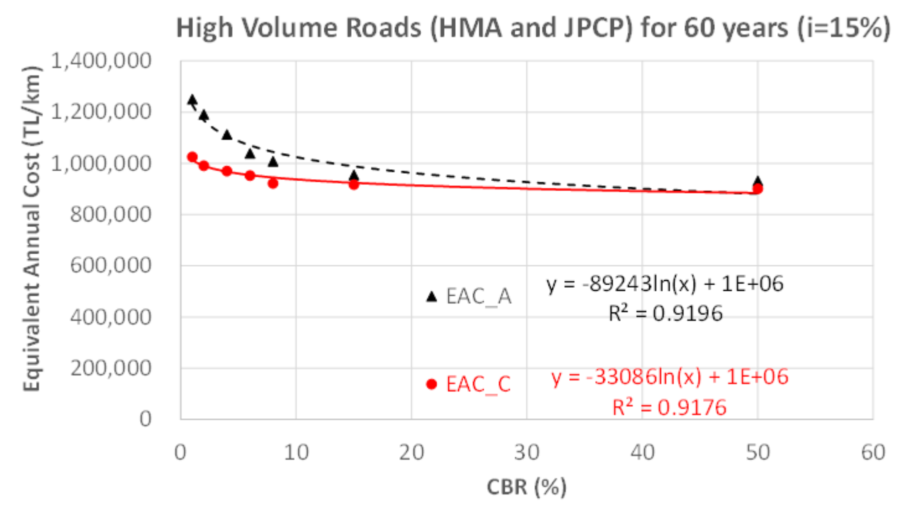

Figure 5.10. EAC Comparisons Under High Volume Traffic with an Interest Rate of 15 %

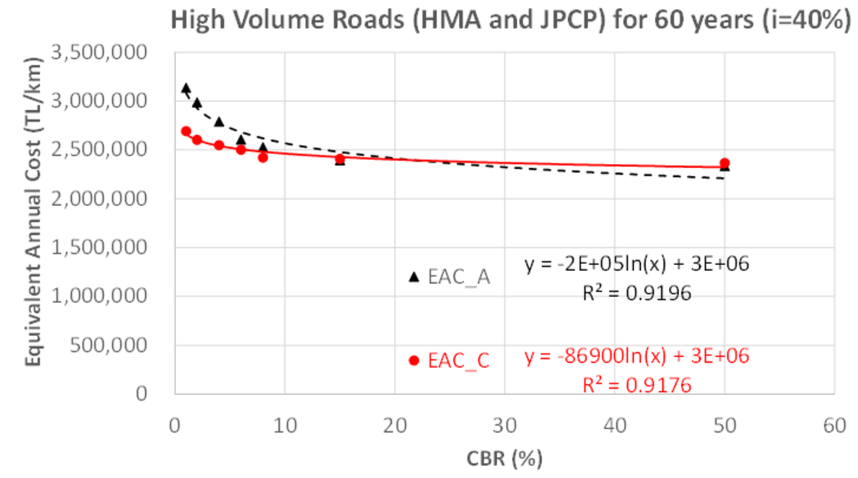

Figure 5.11. EAC Comparisons Under High Volume Traffic with an Interest Rate of 40 %

Similarly, Figure 5.12, Figure 5.13 and Figure 5.14 present the EAC comparison of concrete and asphalt pavements under different soil conditions for medium traffic volume with an interest rates of 5 %, 15 % and 40 %. Similar to the high traffic volume, concrete pavements are more economical than asphalt pavements for most of the cases. Asphalt pavements become more economical than concrete for only the stronger soils with highest interest rate. Also, the economic efficiency values decrease with decreasing traffic volume as the results for medium and high traffic volumes compared. Moreover, the economic efficiency decreases with higher strength of soils as expected.

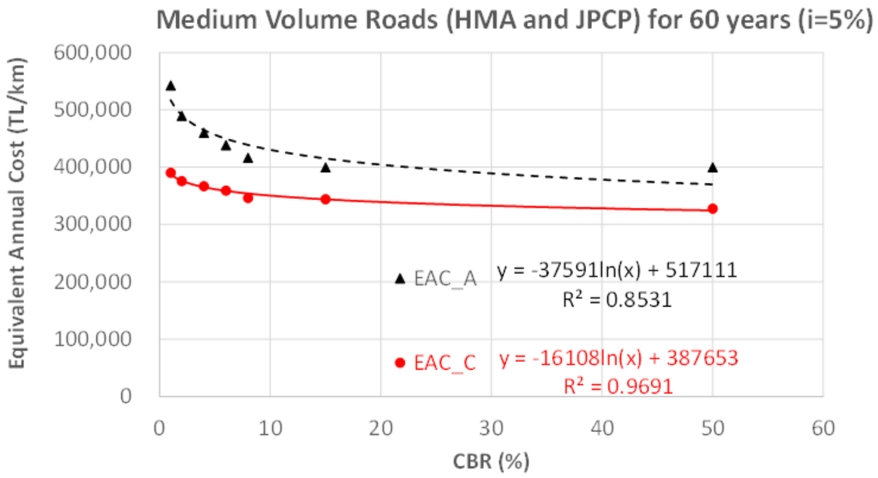

Figure 5.12. EAC Comparisons Under Medium Volume Traffic with an Interest Rate of 5 %

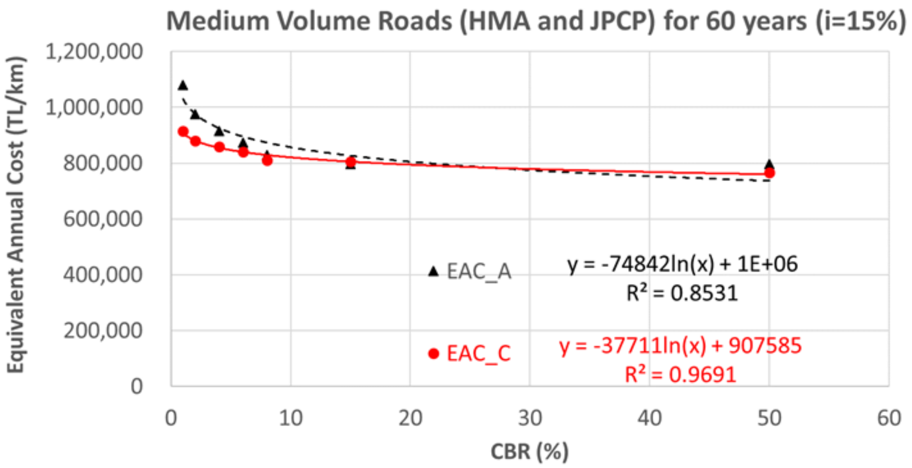

Figure 5.13. EAC Comparisons Under Medium Volume Traffic with an Interest Rate of 15 %

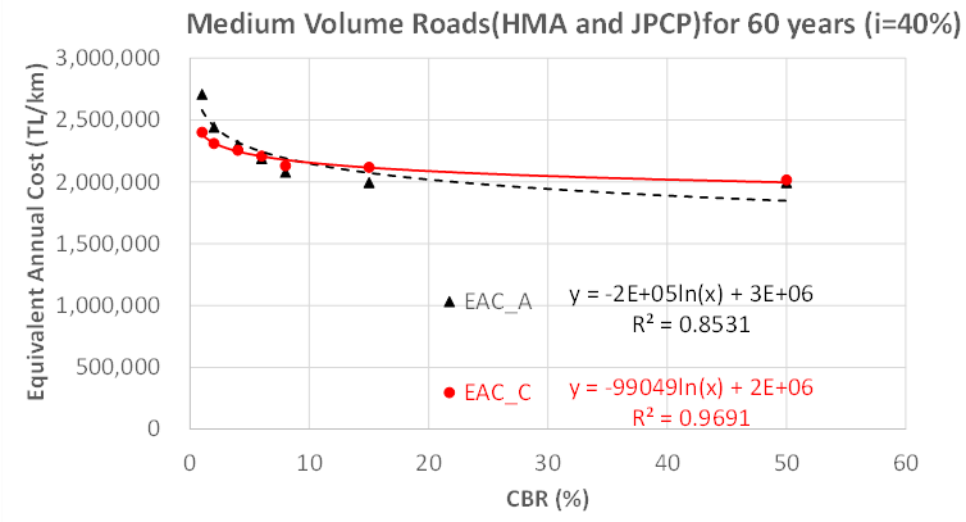

Figure 5.14. EAC Comparisons Under Medium Volume Traffic with an Interest Rate of 40 %

Figure 5.15, Figure 5.16 and Figure 5.17 show the ECA comparison for concrete and asphalt pavements for low volume of traffic. As it can be seen from the figures, concrete pavements are more economical than asphalt pavements for the optimistic interest rate scenario and asphalt pavements become more economical than concrete pavements for stronger soils (CBR $\geq$ 6 %) with higher interest rates. Also, the economic efficiency values decrease with increasing strength of soils and decreasing traffic volume similar to the other traffic volumes.

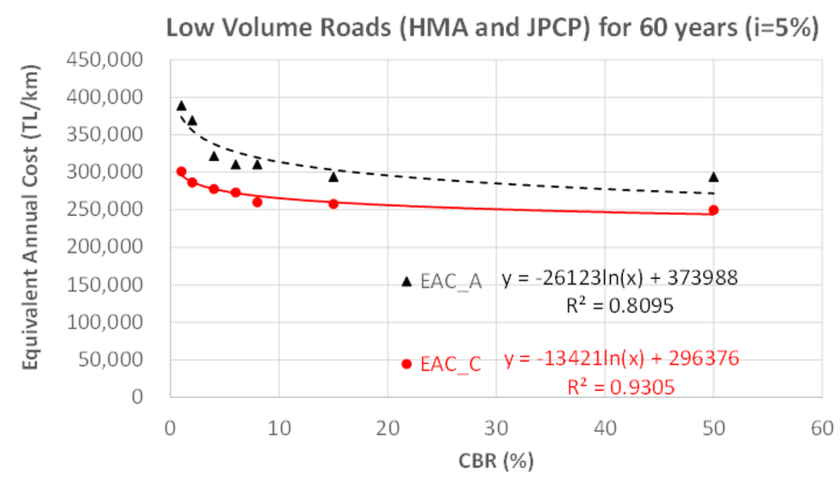

Figure 5.15. EAC Comparisons Under Low Volume Traffic with an Interest Rate of 5 %

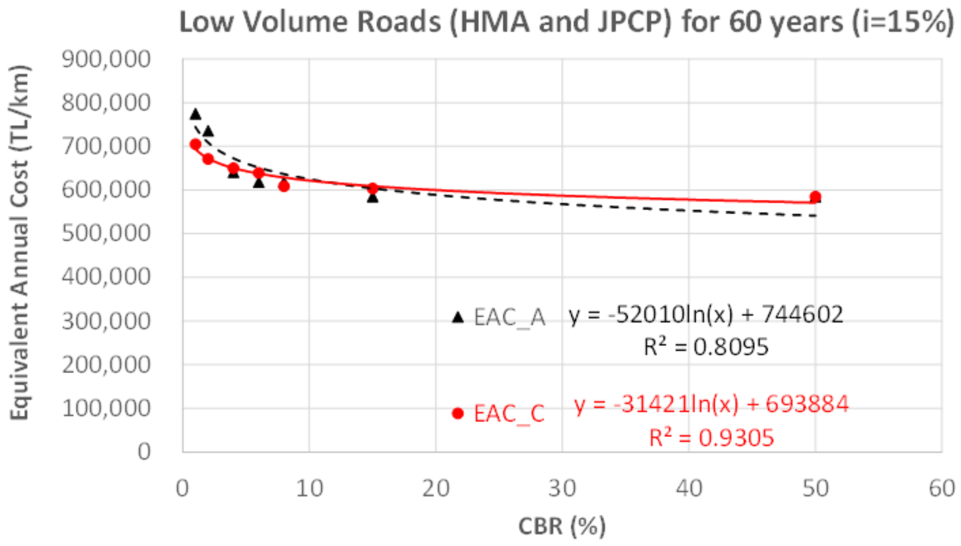

Figure 5.16. EAC Comparisons Under Low Volume Traffic with an Interest Rate of 15 %

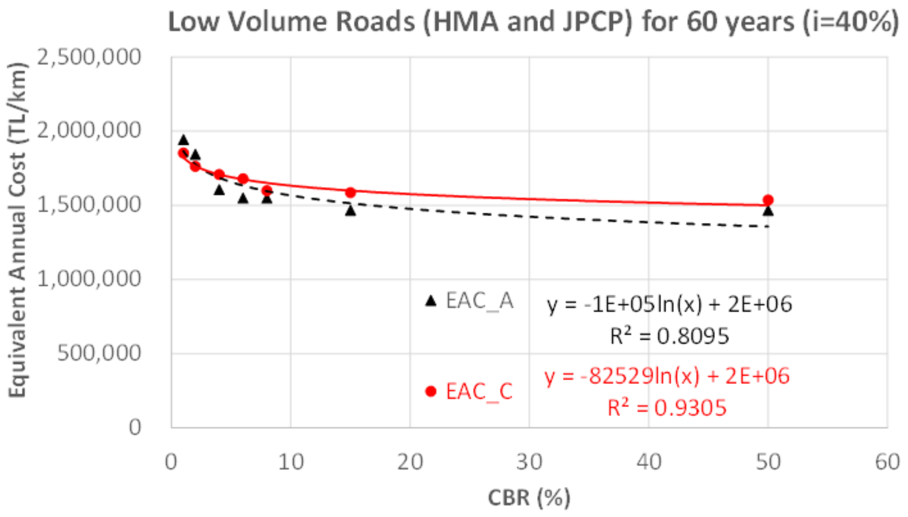

Figure 5.17. EAC Comparisons Under Low Volume Traffic with an Interest Rate of 40 %

After obtaining the EAC values for both pavements, a parameter called economic efficiency is used to compare how feasible is the rigid pavement when compared to the flexible pavement for the same design factors as shown below.

$$\%\ Economic\ Efficiency = \frac{EAC_{JPCP} - EAC_{HMA}}{EAC_{HMA}} \times 100 \quad (Equation\ 7)$$

Table 5.32 Economic Efficiency Values for Different Interest Rates

Traffic Cat.	CBR %	Economic Efficiency (%) Interest Rate (i)= 5 %	Average	Interest Rate (i)= 15 %	Average	Interest Rate (i)= 40 %	Average
High Volume	1	44	**32**	22	**12**	16	**7**
	2	41		20		15	
	4	35		15		9	
	6	28		9		4	
	8	29		9		4	
	15	22		4		-1	
	50	22		3		-1	
Medium Volume	1	39	**25**	18	**6**	13	**1**
	2	30		11		6	
	4	25		7		2	
	6	22		4		-1	
	8	20		2		-2	
	15	16		-1		-6	
	50	22		4		-1	
Low Volume	1	29	**20**	10	**2**	5	**-3**
	2	29		10		5	
	4	16		-1		-6	
	6	14		-3		-8	
	8	19		2		-3	
	15	14		-3		-7	
	50	18		0		-4	

As seen in Table 5.32 JPCP is economically more feasible for most cases. The economic efficiency can go as high as 44% for high volume roads constructed on weak soils having a CBR of 1% and when the interest rate is taken as 5%. This efficiency can go as low as 14% for all conditions of the optimistic scenario, i.e. interest rate is taken as 5%. JPCP becomes only inefficient for high interest rates and when the roads have stronger subgrades.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Rigid (concrete) and flexible (asphalt) pavements have various advantages and disadvantages over each other and hence they are interchangeably used in the construction of pavement superstructures. Specific project requirements, regional conditions, different design parameters and economic concerns are effective in the selection process. When the Turkish road network is considered, it is clearly seen that there is an increasing trend in the use of concrete pavements especially for the local roads, which are under the responsibility of municipalities and local administrations. Even though, concrete pavements are not used in the national roads that are under the responsibility of KGM, there is an increasing awareness on concrete pavements. The official technical specification documents and the design guidelines regarding the concrete pavement types (JPCP and CRCP) to be used in the KGM road network is prepared within the last five years. However, the lack of the existence of the official unit prices for concrete roads stands out as an important shortcoming.

In this regard one of the aims of this study is to propose a model for the unit prices of concrete pavements for KGM. In this context, in the first stage of the study, the unit prices of the concrete pavements (only for JPCP) to be used in the KGM road network and the descriptions of the construction stages were established. Then, concrete and asphalt pavements were designed structurally and the layer thicknesses were obtained by the methods used in the official design guidelines, taking into account the same traffic load, the same environmental and climatic conditions, and the same material and soil characteristics.

After that, an objective cost comparison based on initial construction costs was prepared using the equivalent annual cost method for both road pavement types designed with the same method and parameters, and by considering the official guidelines. The following conclusions can be drawn as a result of this study.

- When the unit prices of all governing institutions in Türkiye are considered, two new market prices are needed; one for the slipform paver and the other one for the hot-applied joint sealant. Moreover, when the construction steps of JPCP is considered, six different unit price analyses needs to be formed by using the two-newly formed market prices together with the available official market prices.
- Besides the volume of traffic, the subgrade strength has a remarkable affect on the initial cost of pavement structures. As compared to JPCP, this effect is more pronounced for HMA pavements.
- When the design of pavement superstructures using the official guidelines of KGM is considered, it can be revealed that the two pavement types use different service lifes. Therefore, when comparing the initial construction costs of two pavement types having two different serfice lifes (20 years for flexible and 30 years for rigid pavements), equivalent annual cost for their least common multiple, i.e. 60 years, can be utilized. On the other hand, for such long-term analysis, one needs to identify the interest rate. For that, three different interest rates could be chosen as to represent optimistic, possible and worst-case scenarios. By considering the previous studies about choosing an interest rate for alternate bidding and LCCA for pavement projects a 5% interest rate was selectes as an optimistic scenario. For a possible scenario, an interest rate of 15 % has been chosen by considering the average Producer Price Index (PPI) for the last sixteen years (2005-2021). Lastly, an interest rate of 40 % has been determined as for the worst-case scenario by considering the average PPI for the last three years (2018-2021).

- When such comparisons are made using those interest rates, the following observations are made. For the optimistic scenario, JPCP is always cheaper than the HMA pavements, regardless of the traffic volume and subgrade type. For the possible and worst-case scenarios JPCP is always cheaper than the HMA pavements for high volume roads. When it comes to medium or low volume roads JPCP is only cheaper for lower strength subgrades.
- An average economic efficiency (%) of JPCP over HMA can be calculated based on the EAC values for three different traffic volumes and seven different soil strength classes. For the optimistic scenario, it was observed that, JPCP is economically efficient than HMA about 32%, 25% and 20% for high, medium and low volume roads respectively. For a possible scenario economic efficiency drops down to 12%, 6% and 2% for high, medium and low volume roads respectively. For the worst-case scenario, economic efficiency further drops down to 8% and 1% for high and medium volume roads, and JPCP is no longer feasible for low traffic volume roads as the economic efficiency is calculated as -3%.
- The above-mentioned findings may explain why concrete pavements are commonly used in the roads with high volume of traffic such as inter-state/city roads of USA. Also, the countries which have lower interest rates may obtain more cost savings by preferring concrete pavements.

6.2 Recommendations

In addition to the findings, it should also be mentioned that this study has some limitations and shows further areas of research. These could be summarized as follows.

- The unit price analysis and the unit prices of the JPCP type of concrete pavements were established by monitoring the construction activities in only two constructions sites, one in Belgium and the other in İstanbul. In order to increase the accuracy of those more site visits with other geographic differences should be made.
- In all of the cost comparisons made within the scope of the study, only the initial construction costs were considered. However, road pavements are designed and built for long service life generally more than 20 years. Therefore, some maintenance and repair activities are required for rigid and flexible pavements throughout their service life. These maintenance and repair activities vary in terms of type and quantity according to the pavement type. Therefore, the costs of maintenance and repair activities to be carried out during the service life should be evaluated separately. This concept is called Life Cycle Cost Analysis (LCCA) as stated in the literature review part. The lack of concrete pavements in Türkiye make it difficult to estimate the maintenance and repair activities that would incur in the Turkish road network. However, these activities and their frequency can be identified from the literature and the associated costs can be estimated using the unit prices of KGM. It is presumed that, the fact that rigid pavements require less maintenance and repair activities during their service life compared to flexible pavements, will make rigid pavements advantageous in life cycle costs.

- Moreover, it may be possible to develop an alternate bidding model for road pavement projects in Türkiye by implementing the LCCA method in the cost comparison calculations. As it is stated in the literature review part, the public benefit can be accomplished by using alternate bidding for road pavement projects because it increases the number of bidders and creates an inter-industry competition between asphalt and concrete industries.
- Thus, it is very important to consider and compare different pavement types by looking at the costs and environmental effects in the long term or the whole service life.

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