Effect of Modulus of Bituminous Layers and Utilization of Capping Layer on Weak Pavement Subgrades

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Abstract

The majority of the world's highways consist of a flexible pavement commonly built of several layers (both asphaltic and granular) that have been laid over a pavement foundation known as the subgrade. A subgrade that is considered to be of a satisfying bearing capacity is expected to restrict not only the immediate distresses occurring during the construction phases, but also later deformations appearing during the service life of the pavement as it subjected to traffic loads. If the subgrade proves to be structurally weak, the highway's flexible pavement can be supported by adding such modifications as a capping layer, which serves to greatly reduce the stress being applied to the pavement. This study aims to further our knowledge about maximum pavement functionality by investigating those parameters considered crucial to pavement design: the correspondence of material properties, the number of layers, and the layer thickness. These parameters were analyzed to determine the best performing composition, while also considering the financial aspects of road construction. To achieve such an aim, we chose to use KENLAYER software to assist us in determining the design of a flexible pavement in line with a specific Equivalent Single Axle Load (ESAL). The KENLAYER configuration provided us with the required ESAL targets for specific design lives. We next calculated the relative costs of these targets and chose those that proved to be most cost-effective and economical. The results indicate that when considering feasible pavements to meet a design of high ESAL applications, those utilizing high modulus asphaltic materials are most suitable for subgrade CBR of at least 3%, while weaker subgrade constructions must be provided with a capping layer.

Keywords: Pavement Design; Weak Subgrade; Capping Layer.

1. Introduction

In the past, processes of unsystematic consensus led many highway associations to rely on standard charts when determining the superstructures to be utilized for most of the pavements they were constructing. This means that typical highway pavements were constructed of standardized thicknesses, despite the fact that they may have been used as layering on various subgrade types. However, the inevitable increase in axle loads that began to appear in the late 1950s soon demonstrated that all pavements, regardless of type (either flexible or rigid), derive their ultimate performances not only from the unique characteristics of the materials utilized and from the surroundings in which they were being used, but also from the loading capacity of the underlying subgrades. It became evident that the road designers had to have direct knowledge of the stiffness modulus and shear strength of that highway's subgrade if they were to correctly calculate the thickness of the pavement layers to be utilized. Of course there are several factors on

which these parameters depend, in particular both the soil type of the environment and effective stress caused by the overlying pavement layers. Weak subgrades may be unable to support the proper construction of the pavement layers. Poor subgrades should be avoided if possible, but when other alternatives are not available, designers can employ several techniques that allow them to build over weak soils. These subgrade remediations include soil stabilization, geosynthetic/geogrid membrane utilization, along with the removal and replacement of the subgrade material with higher quality granular fill, and the employment of a design based on thicker sections. However, recent years have also seen designers employing the addition of a broadened capping layer that serves to improve weak subgrades by using lower cost materials under the sub-base.

To date, the design of flexible pavements has most often relied on an analytical approach in which the variables related to the strain and stress response in each layer are based solely on wheel loading. In order to design a flexible pavement possessing a desired service life based on ESAL, however, the designer must also assess potential pavement failure. There are usually two critical points in flexible pavement layers where failures may occur: the first consists of that layer below the asphaltic concrete layers which undergoes tensile strain, while the second is the layer above the subgrade surface which experiences compressive strain [1]. Figure 1 highlights the tensile strain at the bottom of the asphalt layer that causes fatigue cracking and the compressive strain at the top of the subgrade that leads to rutting.
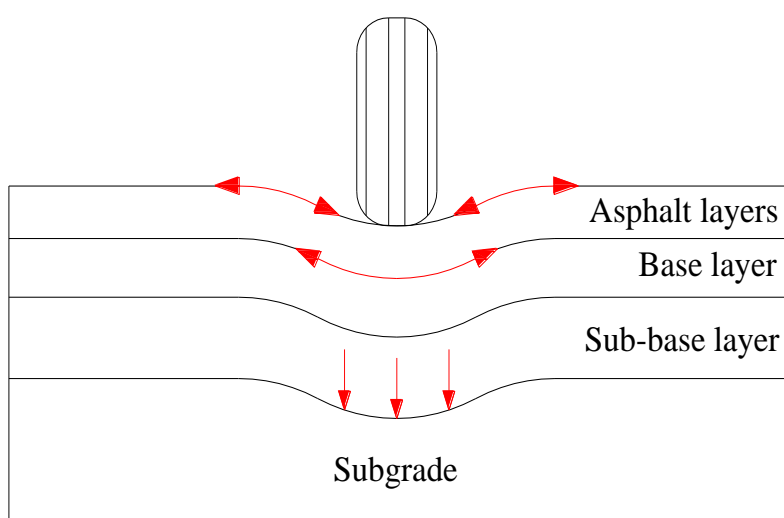

Figure 1. Bottom tension at asphaltic layer and top compression at subgrade

Rutting and fatigue failure in asphalt pavements are considered to be the detrimental distresses causing deteriorating effect on pavement performance and design life. The application of high modulus bituminous mixtures has been proposed as an alternative method that can be employed to overcome these premature failures. In addition to providing high performance, such utilization is claimed to also allow for a decrease in pavement layer thickness, thus save overall construction costs.

The aim of this study is to support the design of failure-resistant flexible pavements by investigating the effects of asphalt layer modulus and the addition of capping layers on poor subgrades. KENLAYER – a software program invented by Yang H. Huang − was utilized in this study to calculate the critical strain at each location specified under the wheel loading. After obtaining the relevant strains, allowable ESALs were computed and then the minimum was selected for pavement design. The pavement was analyzed by altering the thicknesses of the pavement layers and the capping layer and bearing capacity of subgrade. Each cross-section was also evaluated from an economical perspective by computing the overall costs of pavement construction.

2. Objective

The goal of this research has been to use a mechanistic-empirical approach in an attempt to determine the required ESAL combinations that will lead to 20-year life expectancies. To this end, two different cases of pavement layers of ranging thicknesses were first examined to obtain the required ESALs and then bearing each ESAL in mind, the total costs were calculated based on the material properties and the thicknesses of the layers. Two scenarios were tested on weak subgrades of differing configurations. The first case consisted of an analysis of the impacts of bituminous layers of different Modulus of Elasticity on weak subgrades, while the second case analyzed the extent of the fortifying effects on weak subgrades of a capping layer that had been laid between the granular layers. As a final step, we next carried out a comparison/contrast of the results obtained from the two cases. A flow chart summarizing the complete research methodology is illustrated in Figure 2.
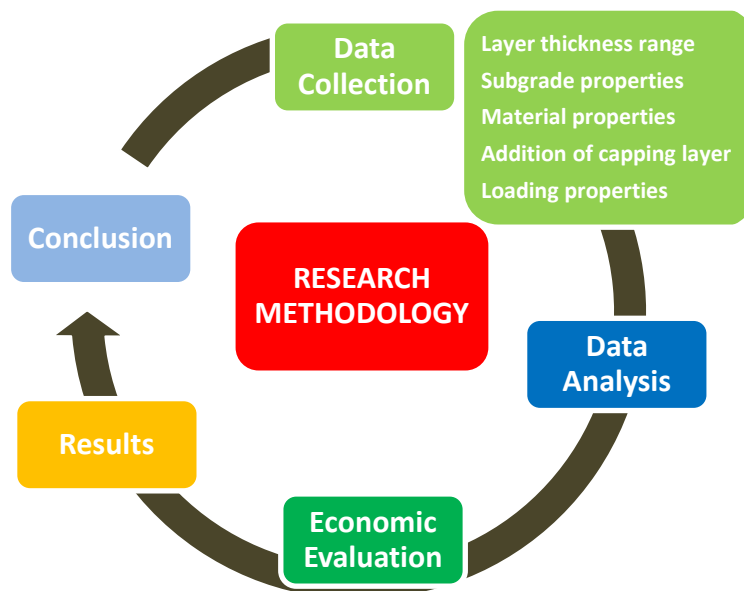
Figure 2. Flowchart of research methodology

3. Literature Review

Highway performance is mainly dependent on pavement configuration, a variable that itself depends on differing layer thicknesses and subgrade bearing capacities. Incorporating capping layers in highway infrastructures has been said to result in not only a reduction of the thickness of bituminous mixture layers, but also as a means of prolonging both the service period and the reliability of the asphaltic concrete pavements. As a transitional course, the capping layer has been primarily expected to provide resistance to frost and to contribute to drainage over the short-term, while also maintaining minimum bearing capacities in the long-term [2]. Still needing investigation are such questions as to when the construction of a capping layer is necessary, which key factors should be considered for a favorable design, and the optimal thickness of a capping layer that should be considered from both structural and economic perspectives. Even though several parameters assist pavement engineers in deciding whether or not a capping layer is essential and required, the decisive/ultimate design is largely based upon a function of the CBR value of subgrade in-situ and the eventual CBR value of the considered capping layer after compaction.

Adorjányi (2011) recommends that, in cases of weak subgrades with modulus less than 40 MPa, a capping layer should be constructed to perform as a part of the subgrade [3]. In conjunction with this approach, it was found that when a capping layer is compacted with convenient thickness over a subgrade surface, these two layers will structurally work together like a combined platform with an equivalent and effective modulus [4−5]. In order to reveal the effect of weak subgrade on pavement design and performance, Tarefder et al. (2008) developed a soil resistance R-value, a study conducted by analyzing the pavement configuration of US 550, a rural highway service in Northwest New Mexico [6]. This study concluded that while subgrade R-value has a considerable impact on permanent deformation, it has almost no effect on the cracks with top-down propagation. They determined that an increase in the R-value of a weak, treated subgrade yielded less stress and less compressive strain at the top of the subgrade.

UK requirements call for a typical capping thickness varying from 0 cm to 60 cm and a minimum capping thickness of 20 cm, which can be constructed in those cases where the CBR value of a subgrade in-situ is greater than 8% [7]. Nataatmadja (2014) stated that the presence of a capping layer with a suitable thickness is expected to improve the overall bearing capacity of pavement under traffic loads; however, it should be noted that a capping layer can only achieve adequate durability when its as-compacted CBR value is ultimately greater than 15% [7]. When considering long-term performance, it should be noted that the capping material being employed must have a minimum of 7% soaked CBR so as to have the capability of lessening the possibility of mixing between the subgrade and its overlying aggregate layers [7].

In capping layers, the utmost tensile strength indicating the fatigue criterion of hydraulically-bounded-materials is observed at the bottom of the layer under cyclic loadings [8]. In their investigation of the suitability of capping layer in railway construction, Radampola et al. (2008) conducted a large scale study on ten specimens of capping layer soil with optimum moisture content under monotonic and cyclic penetration [9]. Their experimental test results demonstrated that, although it may lower the stress formed on the surface of the weaker layers below, the construction of a thicker capping layer is associated with larger deformation. Hence, it is not always true to expect enhanced performance from a thicker capping layer in railway track structures, particularly when it consists of low quality materials. However, Preteseille and Lenoir (2016) experimentally proved that stabilized fine grained soil can be

utilized in the capping layers of high speed rail infrastructures [10]. Furthermore, miscellaneous recycled materials were investigated to confirm their suitability to serve as alternative capping materials in railway construction. Indraratna et al. (2018) demonstrated that a capping layer made up of recycled rubber tire cells could significantly decrease ballast degradation and particle movement within the track substructure [11]. Another research conducted by Naeini et al. (2019) proved that some of the common construction and demolition wastes, particularly recycled concrete aggregates (with and without recycled glass and mixed recovered plastic) and crushed brick exhibit better performance in terms of strength and stiffness compared to conventional capping materials used in railway industry [12].

Valle and Thom (2018) investigated the effect of variability of pavement layer thickness due to construction process on pavement performance [13]. Their study revealed that variations in bituminous material layers (even at tolerable levels according to construction specifications) influence the ultimate pavement performance, especially its fatigue life, while allowable thickness variations in granular sub-base do not have a significant impact on pavement performance. Geng et al. (2013) studied the role of high modulus asphalt binders (HMABs) on the fundamental characterization of asphalt pavement structures [14]. According to their findings, HMABs were found to be promising in reducing bituminous materials layer thickness by 9.6 – 30.2% without an increase in total permanent deformation. Additionally, pavements consisting of HMABs were observed to have fewer cracks with bottom-up propagation compared to those consisting of neat binders. Consistent with these findings, Lee et al. (2007) showed that tensile strain values at the bottom of asphalt layers including HMABs were lower than those of conventional mix sections even though bituminous material layers thicknesses of the HMAB sections were thinner than those of conventional sections [15]. Furthermore, HMAB sections were observed to be more durable against rutting compared to conventional sections (i.e., two times smaller rut depth was detected). With its better water stability and fatigue resistance, the mixtures with HMAB are recommended as applications in the base course or middle course of surface layer; however their utilization should be limited in cold regions due to controversial low temperature cracking resistance [16].

4. Research Methodology

Several aspects must be considered in the process of designing flexible pavements. The analysis of flexible pavement in this study is based on Burmister's theory of stress-strain response of the elastic layers [17]. This theory has been adapted into KENLAYER software in order to carry out an in-depth analysis of the stress-strain response [18]. The Modulus of Elasticity and Poisson's ratio values of which are determined by assuming average temperature – are the only linear material properties considered in KENLAYER. Stress and strain due to the wheel loading are evaluated by employing structural models; only linear and non-linear elastic behaviors are considered in these models. The linear elastic model adapts the Modulus of Elasticity theory, while the non-linear elastic model endorses the resilient modulus theory. Equation 1 demonstrates the relationship between the resilient modulus and stress invariant for non-linear analysis.

$$M_R = k_1 \theta^{k2} \tag{1}$$

Where, M_R is the resilient modulus of granular material; θ is the stress invariant; and k_1 and k_2 are experimental constants.

Both CBR and resilient modulus can refer to the mechanical properties of the subgrade. Dating back to the earlier years of the 20th century, CBR has still been a key input for the empirical flexible pavement design method. Through the transition from the empirical to the mechanistic method, the resilient modulus – described as the ratio of the cyclic deviator stress to recoverable strain – is acknowledged as one of today's pivotal design parameters to characterize pavement materials. Equation 2 demonstrates the relationship between resilient modulus (MPa) and CBR (%) [19].

$$M_R = 10*(CBR) \tag{2}$$

Considering a single axle with dual tires (80 kN), the load is accepted to be uniformly distributed at the top of the pavement surface. As previously indicated by Huang (2004), the contact area of pressure chosen for each wheel in KENLAYER is a circle [18]. Although the shape of the contact area is actually elliptical, preferring a circular area sounds more reliable due to lower error rate and further simplicity in the analysis. The relationship between contact pressure and contact radius is shown in Equation 3.

$$C_p = L/A \tag{3}$$

Where, C_p is the contact pressure of tire; L is the load; and A is the contact area.

The horizontal points of stress and strain to be computed in this study are the center of the circle, the tangent point, and the center spacing between the two circles as shown in Figure 3 [18].
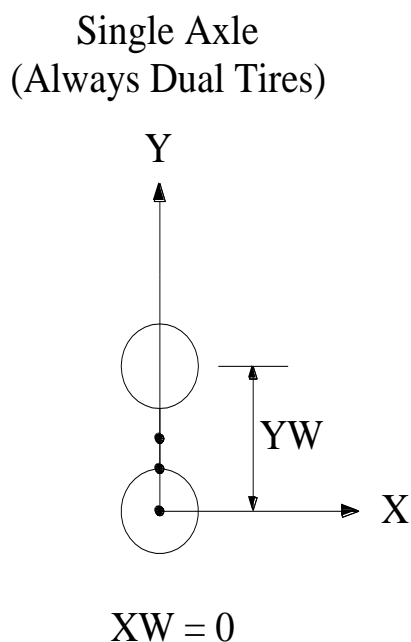
Single Axle
(Always Dual Tires)

Figure 3. Points for calculating stress and strain

KENLAYER employs distress models that are used to calculate the allowable ESAL at each layer where critical strains may lead to pavement failure. Huang (2004) describes the failure criteria for fatigue cracking and permanent deformation (rutting) as expressed in Equation 4 and Equation 5, respectively [18].

$$N_f = f_1(1/\varepsilon_t)^{f2}(1/E_{ac})^{f3} \tag{4}$$

Where, N_f is the allowable number of load repetition to prevent fatigue cracking reaching 20% of the asphalt surface; f_1, f_2, and f_3 are regression coefficients; ε_t is the tensile strain at the bottom of the asphalt layer; and E_{ac} is the Modulus of Elasticity for the asphalt layer.

$$N_r = f_4(1/\varepsilon_c)^{f5} \tag{5}$$

Where, N_r is the allowable number of load repetition to cause rutting; f_4 and f_5 are regression coefficients; and ε_c is the compressive strain at the top of the subgrade.

4.1. Pavement Design Layers and Thickness Range

Communication with the General Directorate of Highways (KGM) in Istanbul, Turkey, has indicated the most applied flexible pavement configurations and thickness ranges. These were thus considered as the basis for the analysis in this study and are shown in Table 1.

Table 1. Pavement thickness range

Layer	Thickness Range (cm)
AWC	4-6
ABC	8-12
HBBC	10-14
PMSC	20-30
Subgrade	Semi-Infinite

The report of relative to Part 3 of the Keşan-Mecidiye Highway (2018) has suggested minimum thickness values for a capping layer depending on the subgrade CBR range; Table 2 demonstrates the CBR subgrade configurations and the capping layer thickness based on the subgrade strength [20]. It should be emphasized that this table was constituted on the assumption that after compacted properly, a capping layer with as-compacted CBR value of at least 15% would serve as a satisfying platform for the construction of the upper pavement layers.

Table 2. Capping layer thickness

Subgrade CBR (%)	Capping Layer Thickness (cm)
1	80
2	55
3	40
4	35
5	25
6	20
7	20

4.2. Loading Properties and Determination of Regression Coefficients

A single axle with dual wheels was accepted as 80 kN in this study. A tire pressure of 700 kPa was assigned for the pavement design; the contact radius was calculated as 9.54 cm according to Equation 3. Dual wheels spacing was assumed as 33 cm. The regression coefficients for fatigue cracking and rutting models are in accordance with those provided by the Asphalt Institute (1981) and are summarized in Table 3 [21].

Table 3. Regression coefficients used by asphalt institute

Distress Model	f_1	f_2	f_3	f_4	f_5
Asphalt Institute	0.414	3.291	0.854	1.365E-09	4.477

Note: the value of f_1 is in metric units.

4.3. Material Properties for Non-linear Layers

The unit weights of the asphaltic layer, the granular layer, and the subgrade were proposed as 22.8, 21.2, and 19.6 kN/m^3, respectively and were inserted into KENLAYER for further analyses. The parameters considered for the non-linear materials consist of the experimentally derived constants (k_1 and k_2). The subbase and the capping layer are the only non-linear layers included in this study. Another determinant associated with the non-linear layers is the coefficient of earth pressure at rest (k_0). A default value for k_0 is proposed as 0.6 for granular material by the KENLAYER software. For PMSC, Rada and Witczak (1981) recommended that a crushed stone granular material is expected to have a mean value for k_1 and k_2 as 50000 kPa and 0.45, respectively [22]. For the linear analytic part of the PMSC, Newcomb et al. (2002) assumed that a granular subbase may have an average resilient modulus of 250 MPa [23]. Hicks (1970) proposed range values for k_1 (11040-34500 kPa) and k_2 (0.57-0.73) for a partially crushed gravel or crushed rock to be used as a capping layer [24]. A greywacke material is used for the capping layer which corresponds to the material of partial gravel or crushed rock. The resilient modulus was determined by the trial and error method. First, the capping layer is assumed to be linear with a modulus value of 150 MPa and the horizontal and vertical stresses for the capping layer are averaged by a dozen samples obtained from KENLAYER as outputs. The average horizontal and vertical stresses are summed according to Equation 6 as follows:

$$\theta = \alpha_1 + \alpha_2 + \alpha_3 \tag{6}$$

Where, α_1 and α_2 are the horizontal stresses; α_3 is the vertical stress; and θ is the stress invariant.

An average value of θ is calculated as 57.76 MPa and then Equation 1 is used for calculating k_1 and k_2. If k_1 is assumed to be 11040 kPa, then k_2 is calculated as 0.643.

4.4. Material Properties for Linear Layers

Mathew (2009) addressed the fact that a surface or wearing course must have the highest strength among all layers in terms of the Modulus of Elasticity, but that this property may decrease gradually for the inferior layers [25]. The Federal Aviation Administration (2011) has suggested that an asphaltic concrete and asphalt treated base may have a modulus range between almost 500 and 140000 MPa [26]. Therefore, four combinations of HMA layers with differing Modulus of Elasticity (from lowest to highest) have been assumed for this study and are shown in Table 4.

Table 4. Asphalt Layers' modulus of elasticity configurations used in the analyses

Layer	Modulus of Elasticity (MPa)			
	Configuration 1	**Configuration 2**	**Configuration 3**	**Configuration 4**
AWC	3000	5000	8000	12000
ABC	2500	4000	6000	10000
HBBC	1500	2000	3000	4000

As for the subgrade, Equation 2 is used to convert the CBR to resilient modulus that is used in KENLAYER. The calculated values are shown in Table 5.

Table 5. Subgrade CBR configurations to be used in the analyses

Configuration	1	2	3	4	5	6	7
CBR (%)	1	2	3	4	5	6	7
M_R (MPa)	10	20	30	40	50	60	70

Newcomb et al. (2002) recommended that the bituminous layers utilized in hot and cold climates conditions should have a Poisson's ratio value ranging 0.25 and 0.45 [23]. However, an average temperature was assumed in this study and therefore a value of 0.35 was assigned for the bituminous layers. For granular layers, Newcomb et al. (2002) proposed that a granular material has a Poisson's ratio of 0.4; therefore, this value was appointed for granular layers [23]. The natural subgrade having a CBR value range from 1% to 7% is assumed to have an average Poisson's ratio of 0.4.

4.5. Determination of ESAL Range

The selection of ESAL for each configuration is based on the minimum strain either at the maximum bottom tension of bituminous layers or at the top compression of the subgrade. According to Specification, Ontario Provincial Standard (2006), ESAL planning is divided into many categories ranging from local roads to highways with a design life of 20 years [27]. Table 6 demonstrates the traffic category, the ESAL range, and the application to be taken into consideration.

Table 6. ESAL ranges according to SUPERPAVE

Traffic Category	ESAL (1000)	Application
A	100-300	Residential and low volume roads
B	300-3000	Minor collector roads
C	3000-10000	Major collector and minor arterial roads
D	10000-30000	Major arterial roads
E	30000-100000	Freeways and major arterial roads

As shown in Table 7, in this research, four traffic categories (i.e., major collectors, minor arterial, major arterial, and freeway/highway) were taken into consideration. Rather than obtaining the ESAL targets at their exact numbers (e.g., 3 million), we considered the determination of values lying between the above-mentioned ranges to be suitable for this study.

Table 7. ESAL range for each target

ESAL (1000)	Application	ESAL Range
3000	Major collectors	2.5 to 3.5 million
10000	Minor arterial	9 to 10 million
30000	Major arterial	27 to 33 million
100000	Freeway or highway	95 to 105 million

4.6. Economical Selection of Pavement Composition

KGM annually publishes the unit price of each material along with their engineering properties to be used for all flexible pavement layers. The 2018 Superstructure Unit Price handbook is used to determine the cost of each layer [28]. We based the cost of each layer as specified in Table 1 and Table 2 (including the specification of material properties as previously described) on our direct communications with the KGM. Table 8 demonstrates the unit price of each material (per 1 ton) which is considered to have a construction area of 1 m^2 for a thickness of 1 m in depth.

Table 8. Unit price of each material

Layer	Modulus of Elasticity (MPa)	UP for 1 ton ($)
AWC	3000	78.57
	5000	100.83
	8000	134.21
	12000	178.71
ABC	2500	72.76
	4000	90.00
	6000	112.25
	10000	156.76
HBBC	1500	62.07
	2000	67.64
	3000	78.76
	4000	89.89
PMSC		12.39
GCL		3.52

5. Data Analysis

Layer configurations, layer thickness, material properties, and loading were all run on KENLAYER and the minimum allowable ESAL results were tabulated. The ESAL targets of 3, 10, 30, and 100 million have been estimated from the pavement thickness range for each layer provided that other layers have a fixed value which could be equal to only the minimum or the maximum according to the specified range. For example, an ESAL of 30 million is calculated when the binder course layer thickness is estimated to be 10 cm from the given range (8 to 12 cm) and other layers have a constant thickness which may be only maximum or minimum according to their specified range. The estimation is linearly completed between two ESALs in which a small variation or deviation from the actual number will not have a questionable impact on the required ESAL targets, since there is a range for each one. The estimations do not have to meet 100% of the ESAL targets because they are conducted in a range as described in Table 7. This process has been repeated for each subgrade CBR configuration, Modulus of Elasticity configuration of bituminous layers, and the inclusion of capping layer.

The total cost of pavement structure configuration estimated from the ESAL targets has been calculated according to the unit prices of materials specified in Table 8. A similar philosophy for the calculation process has been adapted for each subgrade CBR configuration, Modulus of Elasticity configuration of bituminous layers, and the inclusion of capping layer.

6. Results

In accordance with the two objectives determined in this study, this section provides the analyses results for the configurations given for the flexible pavement design. First, the minimum ESAL selections for flexible pavement design configurations according to the layer thickness, subgrade CBR, and Modulus of Elasticity are discussed. Second, the effect of Modulus of Elasticity for the bituminous layers for each subgrade CBR identified is discussed and the most economical configurations are selected for pavement design. Finally, the effect of the capping layer on the flexible pavement design is compared to the same pavement design without a capping layer which has the same material characteristics and thickness configurations, and then the selection of pavement design configurations is discussed with recommendations from an economical point of view.

6.1. Analysis of Minimum ESAL

The minimum ESAL configurations for each flexible pavement layer thickness are obtained from the strains calculated by KENLAYER. These strains are observed at the top compression of subgrade and at the maximum bottom tension of bituminous layers, which result in rutting and fatigue cracking, respectively. When the thicknesses are minimal, the lowest strain is detected mostly at the top compression of subgrade, which indicates the minimum ESAL configuration. When the thicknesses increase, particularly that of the subbase layer, the minimum strains occur rather at the bottom tension of the asphaltic layers. According to the CBR of subgrade ranging from 1% to 7%, the low CBR values have prompted a minimum strain to occur at the top compression of the subgrade. Increases in CBR cause the minimum strains to be more pronounced at the bottom tension of the asphaltic layers. In our considerations of the asphaltic layer strength, we determined that low modulus configurations induced minimum strains to mostly occur at the top compression of the subgrade and when the modulus configurations are increased, the minimum strains also appear more often at the bottom tension of the asphaltic layers. On the other hand, the addition of a capping layer causes the minimum strain to develop totally at the bottom tension of the asphalt layers for all CBR subgrade values and elastic modulus configurations for asphalt layers because it lessens the stress on the top of subgrade and, hence, supports it in a reasonable way.

6.2. Findings of Asphaltic Layers Pursuant to Modulus of Elasticity

The most economical configurations for flexible pavement layer thicknesses according to the Modulus of Elasticity configurations of the bituminous layers and subgrade with CBR values having a range from 1% to 7% are summarized in Table 9.

Table 9. The most economical pavement design considerations according to ESAL targets and subgrade CBR configurations

ESAL Target (1000)	Subgrade CBR (%)	E Configurations (MPa)	Thickness (cm)				TP ($)
			AWC	ABC	HBBC	PMSC	
3000	1	AWC = 3000, ABC = 2500, HBBC = 1500	6	12	14	30	25.85
	2	AWC = 3000, ABC = 2500, HBBC = 1500	4	8.4	14	30	21.66
	3	AWC = 3000, ABC = 2500, HBBC = 1500	4	8	10.4	30	19.13
	4	AWC = 3000, ABC = 2500, HBBC = 1500	4	8	10	26	18.39
	5	AWC = 3000, ABC = 2500, HBBC = 1500	4	8	10	21	17.77
	6	AWC = 3000, ABC = 2500, HBBC = 1500	4	8	10	20	17.64
	7	-	-	-	-	-	-
10000	1	AWC = 8000, ABC = 6000, HBBC = 3000	5	12	14	30	34.92
	2	AWC = 5000, ABC = 4000, HBBC = 2000	6	9.7	14	30	27.96
	3	AWC = 3000, ABC = 2500, HBBC = 1500	6	9.2	14	30	23.81
	4	AWC = 3000, ABC = 2500, HBBC = 1500	4.5	8	14	30	21.76
	5	AWC = 3000, ABC = 2500, HBBC = 1500	4	8	12	30	20.13
	6	AWC = 3000, ABC = 2500, HBBC = 1500	4	8	10	30	18.88
	7	AWC = 3000, ABC = 2500, HBBC = 1500	4	8	10	30	18.88
30000	1	AWC = 12000, ABC = 10000, HBBC = 4000	6	12	14	30	45.83
	2	AWC = 8000, ABC = 6000, HBBC = 3000	6	11	14	30	35.14
	3	AWC = 5000, ABC = 4000, HBBC = 2000	6	12	14	30	30.03
	4	AWC = 5000, ABC = 4000, HBBC = 2000	6	9.5	14	30	27.78
	5	AWC = 3000, ABC = 2500, HBBC = 1500	4.8	12	14	30	24.91
	6	AWC = 3000, ABC = 2500, HBBC = 1500	4	12	14	30	24.29
	7	AWC = 3000, ABC = 2500, HBBC = 1500	6	9.4	14	30	23.96
100000	1	-	-	-	-	-	-
	2	-	-	-	-	-	-
	3	AWC = 12000, ABC = 10000, HBBC = 4000	6	12	14	30	45.83
	4	AWC = 12000, ABC = 10000, HBBC = 4000	6	11	14	30	44.27
	5	AWC = 12000, ABC = 10000, HBBC = 4000	6	10.3	14	30	43.17
	6	AWC = 12000, ABC = 10000, HBBC = 4000	6	9.7	14	30	42.23
	7	AWC = 12000, ABC = 10000, HBBC = 4000	6	12	10.7	20	41.64

Bituminous layers with low Modulus of Elasticity configurations resulted in the lowest total cost of unit prices for all layers compared to higher modulus of elasticity configurations for the ESAL target of 3 million considering all CBR values for subgrades. Low Modulus of Elasticity configurations for the ESAL target of 10 million are applicable for a minimum subgrade CBR of 3%; CBR of 1% and 2% are only applicable for midrange values of Modulus of Elasticity in asphalt layers. As for the ESAL target of 30 million, low to moderate values of Modulus of Elasticity of bituminous layers are applicable depending on the subgrade CBR; CBR of 1% requires a very high asphalt modulus (Configuration 4). We have noted that increases in CBR tend to also increase the cost-saving aspects of lower asphalt modulus. High Modulus of Elasticity configurations of bituminous layers are only applicable for the ESAL target of 100 million for a corresponding subgrade CBR of at least 3%.

We thus recommend the choice of the lowest Modulus of Elasticity configurations for bituminous layers since it provides better cost-saving solutions when compared to those with a very narrow thickness difference. Unit prices according to low elastic solutions in asphalt layers are close; whereas higher elastic solutions result in much higher costs. The minimum total prices of Modulus of Elasticity configurations in every ESAL target are close to each other when their CBR values are high, with these differences decreasing as the CBR values lower.

6.3. Findings Pursuant to the Capping Layer Effect

Table 10 summarizes the minimum cost of flexible pavement design thickness with the addition of a capping layer according to the Modulus of Elasticity configurations of bituminous layers on subgrade having a CBR range from 1% to 7%. The incorporation of the capping layer into the desired flexible pavement has provided at least 10 million ESAL targets for a CBR subgrade of 1% having the minimum Modulus of Elasticity configuration in asphaltic layers. Therefore, designing a flexible pavement having an ESAL target of 3 million does not require a capping layer. An ESAL target of 30 million is also applicable for low modulus values in bituminous layers and a minimum CBR subgrade of 1%, which also provides the best cost-saving solutions. However, for an ESAL target of 100 million, only high modulus values of bituminous layers are applicable on the total subgrade CBR ranges. The most economical selections for each ESAL configuration do not rely on subgrade CBR since each one has its own capping thickness and therefore, total cost does not elevate with variation in subgrade CBR value. A capping thickness for a subgrade CBR of 7% resulted in the minimum cost compared to other configurations in all ESAL targets.

Finally, the inclusion of a capping layer may reduce the total cost of pavement layers compared to a capping layer-free pavement having the same layers for all CBR subgrade cases and considering all asphalt modulus configurations. Moreover, we saw in our study that the addition of a capping layer decreased the required elastic modulus of bituminous layers to the lowest for any ESAL less than or equal to 30 million. For a-100-million ESAL design having a subgrade CBR of 1% and 2%, the addition of capping layer is necessary since it can support the weak subgrade compared to the same pavement without a capping layer. These findings are also in agreement with previously published works. Jones and Dawson (2016) suggested that the thickness of the capping layer depends on the CBR of the subgrade. A capping layer of 60 cm thickness is prescribed for CBR less than 2%; while a CBR ranging between 2%-5% requires a capping layer thickness of 35 cm. A capping layer is not required for CBR greater than 5% [29]. Similarly Rao (2015) stated that if the subgrade CBR is less than 2%, a capping layer of 15cm thickness of material with a minimum CBR of 10% should be constructed in addition to the sub-base [30].

Table 10. The most economical pavement design considerations including capping layer according to ESAL targets and subgrade CBR configurations.

ESAL Target (1000)	Subgrade CBR (%)	E Configurations (MPa)	Thickness (cm)				TP ($)
			AWC	ABC	HBBC	PMSC	
3000	1	-	-	-	-	-	-
	2	-	-	-	-	-	-
	3	-	-	-	-	-	-
	4	-	-	-	-	-	-
	5	-	-	-	-	-	-
	6	-	-	-	-	-	-
	7	-	-	-	-	-	-
10000	1	WC = 3000, BC = 2500, HBBC = 1500	4	8	10	20	20.47
	2	WC = 3000, BC = 2500, HBBC = 1500	4	12	14	20	24.97
	3	WC = 3000, BC = 2500, HBBC = 1500	4	8	10	20	19.06
	4	WC = 3000, BC = 2500, HBBC = 1500	4	8	10	20	18.88
	5	WC = 3000, BC = 2500, HBBC = 1500	4	8	10	20	18.53
	6	WC = 3000, BC = 2500, HBBC = 1500	4	8	10	20	18.35
	7	WC = 3000, BC = 2500, HBBC = 1500	4	8	10	20	18.35

	1	WC = 3000, BC = 2500, HBBC = 1500	4	12	14	20	25.85
	2	WC = 3000, BC = 2500, HBBC = 1500	6	12	12.8	20	25.81
	3	WC = 3000, BC = 2500, HBBC = 1500	6	9.5	14	30	25.45
30000	4	WC = 3000, BC = 2500, HBBC = 1500	4.8	12	14	20	24.91
	5	WC = 3000, BC = 2500, HBBC = 1500	4.8	12	14	20	24.55
	6	WC = 3000, BC = 2500, HBBC = 1500	6	12	12.2	20	24.21
	7	WC = 3000, BC = 2500, HBBC = 1500	4	12	13	30	23.13
	1	WC = 12000, BC = 10000, HBBC = 4000	6	10.5	14	20	45.08
	2	WC = 12000, BC = 10000, HBBC = 4000	6	10	14	30	44.64
	3	WC = 12000, BC = 10000, HBBC = 4000	6	10	14	30	44.10
100000	4	WC = 12000, BC = 10000, HBBC = 4000	6	10.5	14	20	43.48
	5	WC = 12000, BC = 10000, HBBC = 4000	6	9.5	14	30	42.80
	6	WC = 12000, BC = 10000, HBBC = 4000	6	10	14	20	42.16
	7	WC = 5000, BC = 4000, HBBC = 2000	6	12	14	30	36.97

Figures 4 to 7 summarize the minimum total cost for each ESAL target according to their CBR of subgrade range and the inclusion of capping layer.
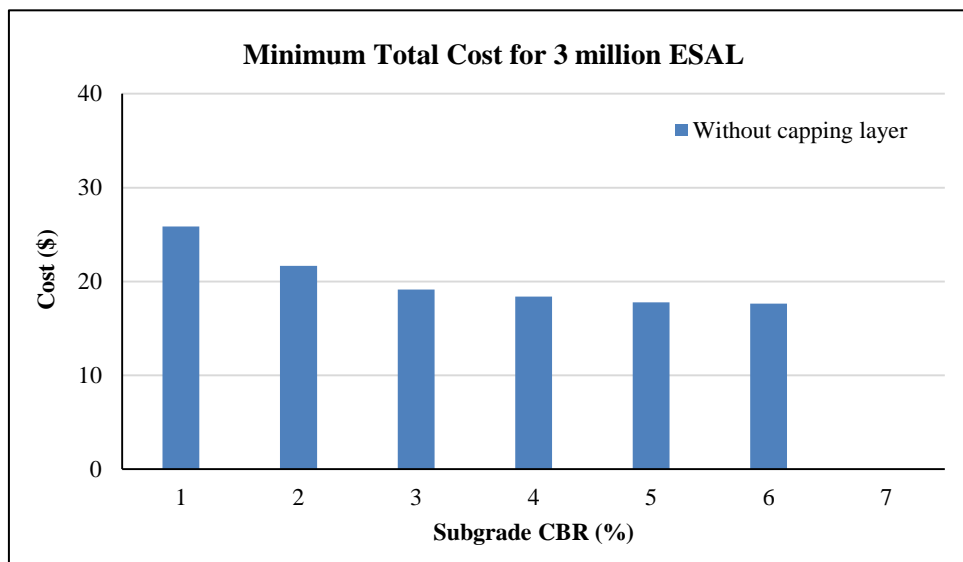

Figure 4. Minimum total cost for 3 million ESAL on each CBR of subgrade configuration
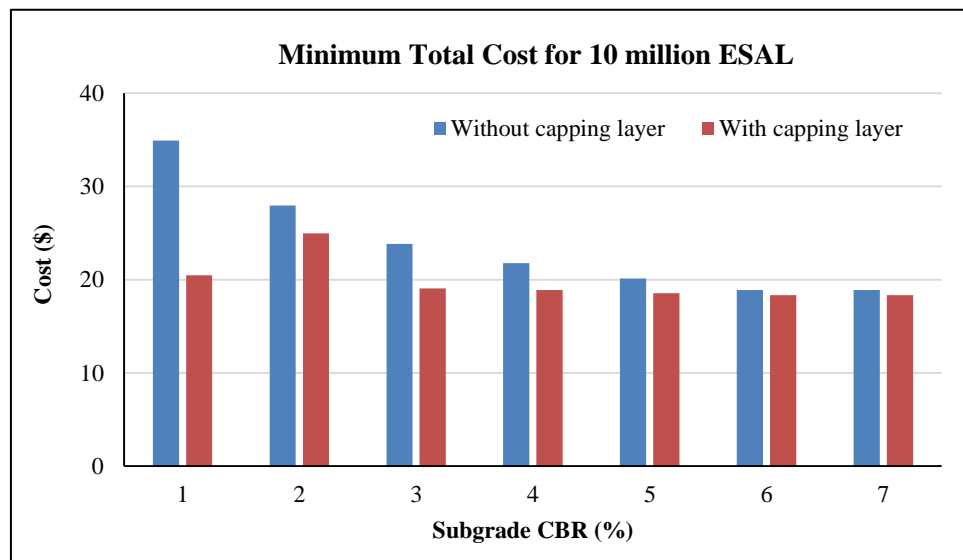

Figure 5. Minimum total cost for 10 million ESAL on each CBR of subgrade configuration and the inclusion of capping layer
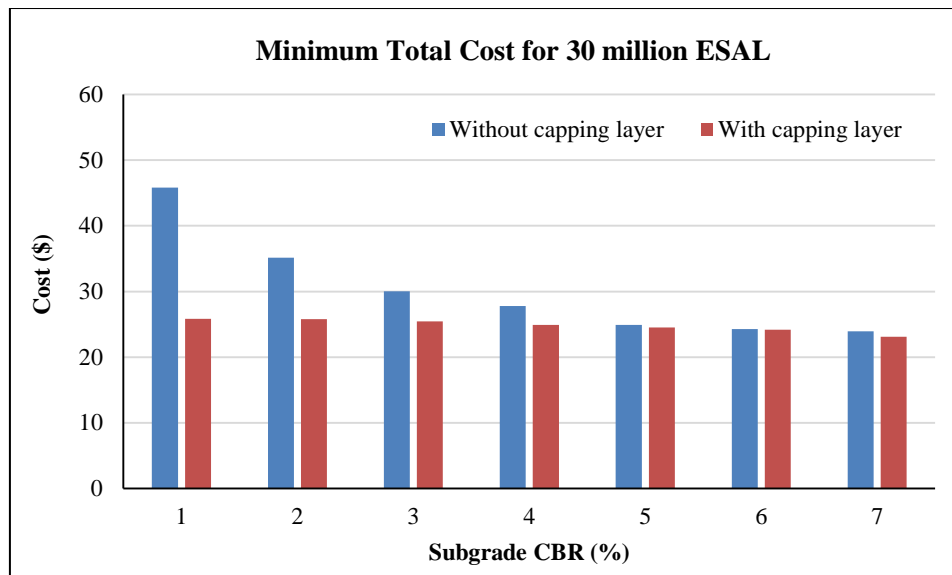
Figure 6. Minimum total cost for 30 million ESAL on each CBR of subgrade configuration and the inclusion of capping layer
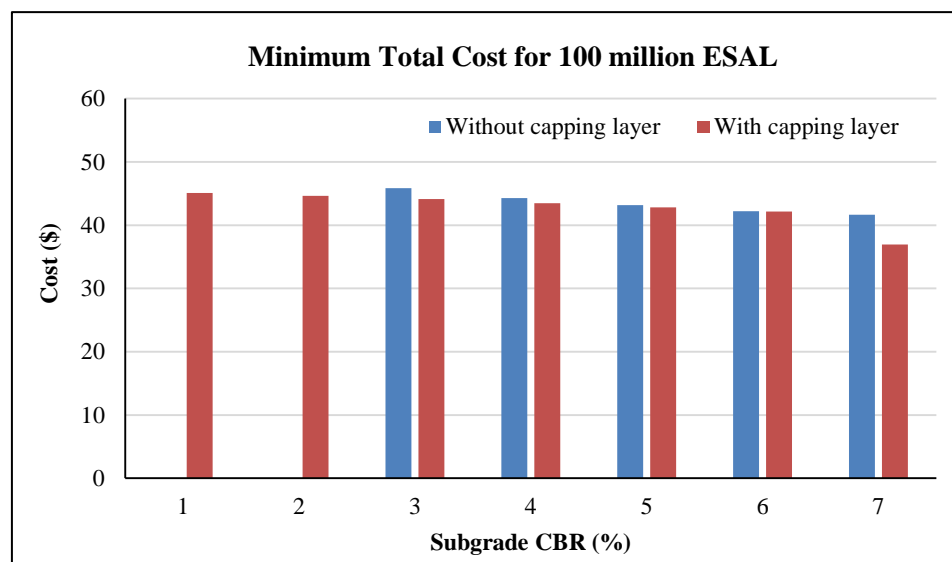

Figure 7. Minimum total cost for 100 million ESAL on each CBR of subgrade configuration and the inclusion of capping layer

7. Conclusions

Because they are of significant effect to the cost considerations of highway construction, the Modulus of Elasticity of bituminous layers and the addition of a capping layer play essential roles in the design and construction of a flexible pavement design. In this research, the impacts of asphaltic materials of distinctive engineering properties and the incorporation of a capping layer into the process have been evaluated on their utilizations with weak subgrades of wide variations in strength and stiffness so as determine their utilization in a feasible and affordable pavement design. Based on the preliminary findings from this study, the following statements can be reported:

- The minimum strain either at the bottom tension of bituminous layers or at the top compression of subgrade will result in the minimum allowable ESAL. Minimum strain at the top compression of subgrade will mostly be achieved when the minimum thickness of each layer, lower CBR of subgrade, and low Modulus of Elasticity values of asphalt layers are taken into account. Additionally, the addition of a capping layer will cause minimum strain to occur at the bottom tension of asphalt layers.

- The minimum total cost of pavement layers having low Modulus of Elasticity values in bituminous layers are much economical compared to their counterparts having higher values. By reducing the overall thickness of pavement layers, the subgrade CBR value will crucially determine lower total cost when the subgrade is strong enough. Incorporating capping layer into the pavement structure was observed to contribute to lower total cost

compared to the same pavement structure without a capping layer according to the overall design thickness configurations. The capping layer will reduce the required strength of bituminous layers for pavement design of major collectors, as well as minor and major arterials.

- In order to design fatigue- and rutting-resistant pavements with high ESAL applications over weak subgrades, the addition of a capping layer becomes feasible for CBR less than 3%; while the utilization of high modulus asphaltic materials provide better results when the CBR is greater than 3%.

Future research in this field should be encouraged to deal with the study of environmental behavior and mechanical properties of inferior quality materials – particularly industrial and solid wastes – as alternative for capping layer construction in order to clearly confirm their suitability and cost effectiveness in pavement industry.

8. Conflicts of Interest

The authors declare no conflict of interest.

9. Nomenclature

ABC:	Asphalt binder course	AWC:	Asphalt wearing course
CBR:	California bearing ratio	ESAL:	Equivalent single axle load
GCL:	Greywacke capping layer	HBBC:	Hot bituminous base course
HMA:	Hot mix asphalt	PMSC:	Plant-mix subbase course
TP:	Total price	UP:	Unit price

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