Construction cost analysis related to the mechanistic design of pavements with different fatigue models

Análisis de costos de construcción asociados al diseño racional de pavimentos con diferentes modelos de fatiga

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Abstract

Rational design for flexible pavement uses fatigue models to determine allowed stresses and deformations in pavement structures which are compared with stresses and deformations calculated with response models. Fatigue models developed for different materials and climatic conditions produce different results. Due to this reason, fatigue models need to be calibrated for local conditions. No pavement fatigue models calibrations have been performed in Colombia. Pavement designers need to use fatigue laws developed for materials and conditions different to national ones, thus creating high uncertainty in the calculated pavement dimensions and long-term performance. The main goal of this research was to evaluate the effect of different fatigue laws used over the final dimensions and construction prime costs of flexible pavements. In order to do this, two pavement structures designed by the rational method were evaluated using the Bistar model and different fatigue laws. As a result, a large variation in costs and dimensions was found, thus confirming that the development and fatigue models calibration may result in significant savings when constructing pavements within the country.

Keywords: Pavements, fatigue, mechanistic, rational

Resumen

En el diseño racional de pavimentos flexibles se utilizan modelos de fatiga para estimar los esfuerzos y deformaciones admisibles, los cuales son comparados con los esfuerzos y deformaciones actuantes calculadas con modelos de respuesta. Los modelos de fatiga desarrollados para diferentes materiales y condiciones de servicio producen resultados diferentes, lo que genera la necesidad de realizar calibración de modelos para condiciones locales de uso. En Colombia no se han realizado esfuerzos de calibración de modelos de fatiga para pavimentos, los diseñadores de pavimentos se ven obligados a recurrir a leyes de fatiga desarrolladas en otros países, para materiales y condiciones diferentes a las nacionales, lo que genera imprecisiones en el dimensionamiento de los pavimentos y su desempeño a largo plazo. El objetivo de esta investigación es evaluar la incidencia de diferentes leyes de fatiga en el dimensionamiento y costos iniciales de construcción de pavimentos flexibles. Para esto se evaluaron dos estructuras diseñadas por el método racional, empleando el modelo de respuesta Bistar y diferentes leyes de fatiga. Se encontró gran variación en dimensiones y costos, revelando que el desarrollo y calibración de modelos de fatiga puede conllevar a ahorros significativos en la construcción de pavimentos en el país.

Palabras clave: Pavimentos, fatiga, mecanicista, racional

1. Introduction

The advancement of flexible pavement engineering has been considerable in recent years worldwide, allowing in turn to develop more reliable design methodologies enabling the design and construction of pavements with a more suitable cost-benefit ratio for the development of road infrastructure. According to this, high investments developed to build and maintain road infrastructure generate more profit, contributing to the economic development of nations. Flexible pavement design methodologies have evolved from empirical to mechanistic-empirical methods. Mechanistic-empirical methods requires to be calibrated to local conditions and are considered as the latest in pavement design methods, representing the state-of-the-art in the field.

Mechanistic or rational methods are a better alternative to pavement design empirical methods (Zheng et al., 2012), but its applicability in the domestic environment is limited, since no calibration stress needed has been performed for its application to be locally reliable. One of the main shortcomings of the application of mechanistic methods within the country is that there is not enough research on the

materials fatigue event used for flexible pavement design, which is one of the major steps for calibrating mechanistic methods (Huang, 2004) This situation occurs mainly due to the limited research on the subject at a domestic level and also by the limited supply of suitable equipment to perform field measurements and laboratory tasks. In Colombia, no fatigue laws have been developed showing the local materials fatigue behavior based on their mechanical, physical and rheological properties (Rondon et al., 2013)

In the absence of better information, Colombian designers are forced to resort to certain fatigue laws in other countries with different traffic, weather and materials conditions to the national ones, creating the problem and increasing it by having to choose among the wide variety of fatigue laws available, thus raising great uncertainty in the final result (Higera, 2007) This research aims to determine how fatigue laws for the rational design of flexible pavements impact thicknesses and construction prime costs of flexible pavement.

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2. Rational design of pavements

Rational methods of pavement design are focused on the mechanistic of materials, allowing a theoretical analysis of pavement performance facing load requests, such as traffic, as well as stress induced in the structure due to climatic variations (Valdes et al., 2012; Garnica and Correa, 2004). Rational methods require determining the properties of materials forming the pavement structure, mainly the Young's modulus and Poisson's ratio of each one of the forming structure layers. It is recommended to determine these properties through lab tests; however, in some cases the use of correlations or typical values are allowed. The methodology requires proper calibration of materials fatigue laws to more accurately predict the time evolution of damages that may occur, which is why calibration greatly increases design reliability (Huang, 2004; Garnica and Correa, 2004; Sun et al., 2003; Rodriguez et al., 2013; Orobio, 2011; Wang, 2011).

In a rational design of flexible pavements, the response before loading is given in terms of stress, deformations and deflections in each of the forming pavement layers (Selvaraja, 2012). Response models are mainly based on the multilayer elastic theory on which several computer programs have developed (Alize III, Kenpav, Depav, Cedem, Bisar, etc). Such programs have become an essential tool in determining stress and deformations in the pavement structure (Zheng et al., 2012; Quintana and Lizcano, 2007). These models are sensitive to input data, mainly the materials' Young's modulus and Poisson's ratio, so that the design process requires the accurate determination of these parameters.

On the other hand, fatigue laws allow to determine stress and deformations accepted in the structure, such as vertical strain deformation in the subgrade, stress on the lower level of the asphalt and the deflection of the structure, which, for purposes of rational design, allows to verify that the stress and deformations in the structure are less than allowable and, thus, control cracking and rutting of flexible pavement (Huang, 2004; Reyes, 2003; Quintana and Lizcano, 2007).

3. Acceptable radial deformation at the base of the asphalt layers

The cracking of asphalt concrete due to fatigue has been recognized as one of the main forms of structural damage in asphalt pavements (Zhi et al., 2012), which is why fatigue laws to control cracking in asphalt concrete mixtures over its lifetime have been determined through bending tests, simulating the expected operating temperature and applying stress in each repetition until failure of the cylinder occurs. In this way, the allowable deformation at the base of the asphalt concrete with the number of cycles (N) for a given period (Hafeez et al., 2013; Homsí et al., 2012; Tigdemir et al., 2002; Reyes 2003; Yeo et al., 2007; Valdes et al., 2011; Ambassa et al., 2013; Norambuena-Contreras et al., 2011) can be matched up. According to the general fatigue laws as per the radial deformation at the base of the asphalt layers, it is inferred that (Sun et al., 2003; Behiry, 2012.):

$$N = k_1 * \varepsilon^{k_2} * E^{k_3} \quad (1)$$

k_1, k_2 and k_3 : Calibration constants.

E (psi): Asphalt concrete Young's modulus.

ε : Acceptable radial deformation at the base of the asphalt layer.

N : Traffic design expressed in cumulative equivalent axles of 8.2 Tons in rail design.

Table 1 presents different models to estimate acceptable radial deformation at the base of the asphalt layers.

4. Vertical Deformation at the Subgrade

Vertical deformation at the subgrade is related to vertical stress due to load over the pavement structure. When the induced deformation exceeds the permissible values, rutting occurs which is one of the most common failures in flexible pavements. Various researchers have tried to prevent this type of failure in pavements and so they have developed fatigue models that allow linking the cyclic loadings generated by traffic during the design stage, with the value of acceptable vertical deformation (Reyes, 2003; Khana et al., 2013). Various fatigue laws have been recommended to determine the acceptable limit of the vertical deformation (Table 2). These equations' general form is as follows (Behiry, 2012):

$$\varepsilon_z = f_1 * N^{f_2} \quad (2)$$

f_1, f_2 : Calibration constants.

N : Traffic design expressed in cumulative equivalent axles of 8.2 Tons in rail design during the design stage.

Table 1. Fatigue laws for the acceptable radial deformation at the base of the asphalt layers

Instituto de Asfalto(1981)	$N = 0.0796 * \epsilon^{-3.291} * E^{-0.854}$ (Asphalt, 1981)	Fatigue law for any type of bituminous mixture
Model shell	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$ (Shell, 1978)	V_b = % of bitumen content S_{mix} = mixture modulus in Pa
US Army Corps of Engineers	$N = 497.156 * \epsilon^{-5} * E^{-2.66}$ (Khana et al., 2013)	Fatigue law developed by the US Army Corps of Engineers
Belgian Road Research Center	$N = 4.92 * 10^{-14} * \epsilon^{-4.76} E$ (Verstraeten et al., 1982)	Developed in the Belgium Road Research Center in 1982
UC-Berkeley	$N = 0.0636 * \epsilon^{-3.291} * E^{-0.854}$ (Craus et al., 1984).	Fatigue law determined in Universidad UC-Berkeley in California in 1984.
Transport and Road Research Laboratory	$N = 1.66 * 10^{-10} * \epsilon^{-4.32}$ (Powell et al, 1984)	Developed in the roads and transportation reserach center in 1984 (USA).
Illinois- Department of Transportation	$N = 5 * 10^{-6} * \epsilon^{-3}$ (Thompson, 1987)	Fatigue law determined in the state of Illinois in 1987 (USA).
U.S. Army model	$N = 478.63 * \epsilon^{-5} * E^{-2.66}$ (Defence, 1988)	Developed by a US army model in 1998.
Minnesota 1998	$N = 2.83 * 10^{-6} * \epsilon^{-3.21}$ (Timm et al., 1998)	Fatigue law determined in the state of Minnesota 1998 (USA).
Indian model	$N = 0.1001 * \epsilon^{-3.565} * E^{-1.4747}$ (Das y Pandey, 1999)	Trial frequency: 10Hz. Temprature between (20-30)°C, Technological Institute in India, test cargo between (80-800)N (India)

Tabla 2. Leyes de fatiga disponibles para uso en el cálculo de la deformación vertical admisible en la subrasante

University of Nottingham	$\epsilon_z = 2.16 * 10^{-2} N^{-0.28}$	Quoted in (Reyes, 2003)
LCPC	$\epsilon_z = 2.1 * 10^{-2} N^{-0.24}$	Fatigue law for subgrades in new roads, (LCPC- Setra, 1997)
Belgium research center	$\epsilon_z = 1.1 * 10^{-2} N^{-0.23}$	(Verstraeten et al., 1982)
Chevron	$\epsilon_z = 1.05 * 10^{-2} N^{-0.223}$	Quoted in (Higuera, 2007)
Dormon and Mercalf	$\epsilon_z = 1.16 * 10^{-2} N^{-0.21}$	Quoted in (Hidalgo, 2007)
TRRL	$\epsilon_z = 1.49 * 10^{-2} N^{-0.253}$	Vertical deformation law with 85% reliability: Quoted in: Quoted in (Higuera, 2007)
Shell	$\epsilon_z = 2.8 * 10^{-2} N^{-0.25}$	Vertical deformation law with 50% reliability: Quoted in (Shell, 1978)
Shell	$\epsilon_z = 2.13 * 10^{-2} N^{-0.253}$	Vertical deformation law with 85% reliability: Quoted in (Shell, 1978)
Shell	$\epsilon_z = 1.79 * 10^{-2} N^{-0.253}$	Vertical deformation law with 95% reliability: Quoted in (Shell, 1978)
INGLESA	$\epsilon_z = 0.56 * 10^{-2} N^{-0.24}$	Quoted in (Higuera, 2007)
Asphalt Institute	$N = 1.36 * 10^{-9} * \epsilon_z^{-4.477}$	(Asphalt, 1981)

5. Acceptable vertical stress at the subgrade

Vertical stress at the subgrade, such as the vertical deformation at the subgrade, is directly related to load affecting the pavement structure and the structural capacity of the layers comprising it. When the vertical stress at the subgrade is higher than the acceptable, rutting is produced. Laboratory researches and field tests have been developed using duplicated loading and considering soil properties to determine the permanent soil deformation and the acceptable vertical stress at the subgrade for a certain number of loading cycles (Hidalgo, 2007; Suh et al., 2010; Khana et al., 2013) Equations 3 and 4 (Higuera, 2008; Rodríguez et al., 2012.) determine the acceptable stress at the subgrade:

$$\sigma_z = C * \frac{ESr}{(1+0.7 \log_{10}(N))}; (Kg/cm^2) \quad (3)$$

$C=0.008$ (Jeuffroy)

$C=0.007$ (Dormon and Kerhoven)

$C=0.006$ (Acum and Fox)

Criteria of the Belgium CRR, (Rodríguez et al., 2012; Higuera, 2008)

$$\sigma_z = \frac{0.09607 * CBR^{1.2}}{N^{0.229}}; (Kg/cm^2); CBR \text{ en } \%. \quad (4)$$

6. Deflection Behavior

Deflection of a pavement relates to the type and magnitude of the loading affecting the structure. Loads affecting the structure are generally cyclic loading induced by traffic. Fatigue laws have been developed in various research centers related to the maximum vertical deformation generated by vehicles and the acceptable vertical deformation that can withstand the pavement structure during its design stage (Higuera, 2007) Equations 5 and 6 present acceptable deflection behavior law:

$$\log \Delta_{z adm} = E - F \log N \quad (5)$$

$$\Delta_{z adm} = E * N^{-F} \quad (6)$$

$\Delta_{z adm}$ = Acceptable deflection of the flexible pavement structure.

E, F : Calibration constants

N : Traffic design expressed in cumulative equivalent axles of 8.2 Tons in rail design during the design stage.

Traffic design expressed in cumulative equivalent axles of 8.2 Tons in rail design during the design stage (Higuera, 2007).

Table 3. Fatigue laws available to calculate the acceptable deflection of the pavement structure (Higuera, 2007)

Author	Fatigue law (mm)
Criteria from the Asphalt Institute	$\Delta_{z adm} = 25.64 N^{-0.2383}$ (Asphalt Institute, 1969)
Czechoslovakian criteria	$\Delta_{z adm} = 8.035 N^{-0.16}$
Yang H. Huang criteria	$\Delta_{z adm} = 26.3 N^{-0.2438}$
Criteria from the RTAC in Canada	$\Delta_{z adm} = 65.024 N^{-0.3}$ (Transportation Association of Canada, 1997)
Ivanow criteria	$\Delta_{z adm} = 5.248 N^{-0.12}$
Ruiz criteria	$\Delta_{z adm} = 24.76 N^{-0.2523}$
Criteria from the AASHTO Road Test (Pt=2.5)	$\Delta_{z adm} = 63.735 N^{-0.2383}$
Criteria from the CGRA in Canadá	$\Delta_{z adm} = 52.275 N^{-0.237}$
Belgium criteria	$\Delta_{z adm} = 242 N^{-0.334}$

7. Methodology

To analyze the impact of fatigue laws in the pavement construction prime cost, two flexible pavement structures were assessed using the rational design methodology. To achieve this, different combinations of fatigue laws were performed and thickness was determined in each one using the Shell response model (Bisar 3). Combinations only included fatigue laws applicable to the types of structures assessed. After that, the construction prime cost for one kilometer of track was calculated for each structure resulting from the combination of fatigue laws. Finally, variations of costs and layers thicknesses from the structures with certain combinations of fatigue laws were analyzed. Prime cost was

calculated only considering the cost of layers forming the pavement structure. The methodology used is stated in Figure 1.

Stage 1

Stage 1 defines the mechanistic properties of the materials forming the two flexible pavement structures in the analysis. Typical values of the region (Guzman y Marin, 2007) were used. With the purpose of comparing results, two modulus values for the asphalt concrete were considered: 1500 MPa and 687MPa. The lowest value represents critical conditions at high operating temperatures. Materials properties are presented in Tables 4, 5 and 6.

Figure 1. Methodolgy used for the design of two flexible pavement structures

Table 4. Mechanistic properties of materials forming structure No. 1

Material	Module (Mpa)	Poisson
Asphalt concrete	687-1500	0.35
Granular base	245	0.40
Sub base	147	0.40
Subgrade	50	0.50

Table 5. Mechanistic properties of materials forming structure No. 2

Material	Module (Mpa)	Poisson
Asphalt concrete	687-1500	0.35
Granular base	245	0.40
Soil-Cement	343	0.22
Subgrade	50	0.50

Table 6. Load parameters and properties of the asphalt layer

PARAMETERS			
Traffic growth rate per year (%)	3		
Design period (years)	15		
Number of days with traffic during the year	365		
Bearing capacity of the subgrade, CBR (%)	5		
Asphalt volume in the mixture, Vb (%)	10.8		
Aggregate volume in the mixture, Vg (%)	85.2		
Load application time, t (seg)	0.02		
Asphalt penetration	48	75	90
Asphalt penetration temperature (°C)	20	25	28
Load radius, a (cm)	10.8		
Tire axle spacing, s(cm)	32.4		
Contact pressure, q (kg/cm)	5.57		

Traffic was defined in $2.84 \cdot 10^6$ equivalent axles of 8.2 Ton. Loads configuration is shown in Figure 2. A double tire was assumed with a load of 4.1Tn (40 KN) formed by two loads of 2.05Tn (20 KN) separated by 32.4 cm. and applied to a ratio circumference of 10.8cm. indicating two deformations of 0.546 MPa.

Stage 2

This stage selected among all available fatigue laws those which apply to the type of material proposed. This selection was made based on the recommendations of the models' authors and the bibliography consulted. The proper application of every fatigue law was analyzed, depending on the material's properties defined in each of the two structures tested in this research. Table 3 and equations 3 and 4 state fatigue laws presented. Subsequently, and as a point of comparison, a base structure was defined which was designed applying the most commonly used fatigue laws in rational design in Colombia, Table 7.

Finally, designs were checked at the base structure. The conclusion was that the fatigue laws at the base of the asphalt layer showed variations, while other fatigue laws used at the definition of the base structure were constant. A similar procedure was performed for the vertical deformation at the subgrade and structure deflection; that is to say the base structure design was checked using a different fatigue law each time. The number of fatigue law combinations is shown in Table 8.

Figure 2. Load configuration over pavement

Table 7. Fatigue laws commonly used in Colombia

Radial Deformation at the Base of the Asphalt Layer (Shell)	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$
Vertical Deformation at a Subgrade Level (Shell 85%)	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$
Vertical stress at a Subgrade Level (Dormon and Kerhoven (MPa))	$\sigma_z = \frac{0.07 * CBR}{1 + 0.7 * \log(N)}$
Structure Deflection (Yang H. Huang (mm))	$\Delta_z = 26.32202 * N^{-0.2438}$

Table 8. Radial deformation fatigue laws combinations at the base of the asphalt layers

Combination	Acceptable Radial Deformation (ϵ_r)	Acceptable Vertical Deformation (ϵ_z)	Acceptable Vertical Stress (σ_z)	Acceptable Deflection (Δ_z)
Base structure	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
1	$N = 497.156 * \epsilon^{-5} * E^{-2.66}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
2	$N = 0.0796 * \epsilon^{-3.291} * E^{-0.854}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
3	$N = 4.92 * 10^{-14} * \epsilon^{-4.76} E$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
4	$N = 0.0636 * \epsilon^{-3.291} * E^{-0.854}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
5	$N = 1.66 * 10^{-10} * \epsilon^{-4.32}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
6	$N = 5 * 10^{-6} * \epsilon^{-3}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
7	$N = 478.63 * \epsilon^{-5} * E^{-2.66}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
8	$N = 2.83 * 10^{-6} * \epsilon^{-3.21}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
9	$N = 0.1001 * \epsilon^{-3.565} * E^{-1.4747}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
10	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 1.79 * 10^{-2} N^{-0.253}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$

Combination	Acceptable Radial Deformation (ϵ_r)	Acceptable Vertical Deformation (ϵ_z)	Acceptable Vertical Stress (σ_z)	Acceptable Deflection (Δ_z)
Base structure	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
11	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.8 * 10^{-2} N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
12	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.16 * 10^{-2} N^{-0.28}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
13	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.1 * 10^{-2} N^{-0.24}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
14	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 1.1 * 10^{-2} N^{-0.23}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
15	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 1.05 * 10^{-2} N^{-0.223}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
16	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 1.16 * 10^{-2} N^{-0.21}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
17	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 1.49 * 10^{-2} N^{-0.253}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
18	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 0.56 * 10^{-2} N^{-0.24}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
19	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.16 * 10^{-2} N^{-0.28}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
20	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 25.64 N^{-0.2383}$
21	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 8.035 N^{-0.16}$
22	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 65.024 N^{-0.3}$
23	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 5.248 N^{-0.12}$
24	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 24.76 N^{-0.2523}$
25	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 63.735 N^{-0.238}$
26	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 52.275 N^{-0.237}$
27	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.007 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 242 N^{-0.334}$
28	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.008 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
29	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.006 * E}{1 + 0.7 * \log(N)}$	$\Delta_z = 26.32202 * N^{-0.2438}$
30	$\epsilon_r = (0.856 V_b + 1.08)(10^6 E)^{-0.36} \left(\frac{N}{K}\right)^{-0.2}$	$\epsilon_z = 2.1 * 10^{-2} * N^{-0.25}$	$\sigma_z = \frac{0.0960 * CBR^{1.2}}{N^{0.229}}$	$\Delta_z = 26.32202 * N^{-0.2438}$

Stage 3

After defining the various combinations of fatigue laws, the calculation of thicknesses from the two pavement structures for each combination of fatigue laws was performed. In order to do this, the rational design methodology of flexible pavements was used, as well as the BISAR 3.0 response model to calculate stress and deformations at the pavement structure. Such calculations were compared with accepted stress and deformations determined by fatigue laws. On the other hand, it was also considered that the thickness of each layer forming the structure will be appropriate when meeting reliability requirements determined by the rational approach.

To perform the variation analysis of the construction

prime costs associated with the structures resulting from each combination of fatigue laws, the cost for one kilometer of track with a width of 7.3 m. was calculated. To do this, the amount of m representing each material per kilometer was determined and multiplied by the unit cost in m , Table 9. Reference prices from Departamento del Valle del Cauca (Gobernación del Valle, 2013) were used, as well as construction companies (Sispac, 2012) Formula used to calculate the cost of each thickness per kilometer is shown in Equation 7

$$\text{cost}^{(USD)} / \text{Km} (7.3m * h * 1000m) \left(\text{layer cost}^{(USD)} / m^3 \right) \quad (7)$$

Where h is the thickness of the material (m) layer

Table 9. Construction unit cost of each layer

Layer	Unit	Cost (USD)
Asphalt Concrete	M ³	210.91
Granular Base	M ³	39.15
Granular SubBase	M ³	34.71
Soil-Cement	M ³	61.48

It is made clear that in construction cost calculation per kilometer, construction cost of the asphalt concrete, granular base, granular subbase and soil-cement were considered.

8. Analysis of the results

After being designed both pavement structures for 30 fatigue laws combinations described in Table 8, a large variation in the thicknesses of the structures was observed. Fatigue laws with more influence regarding the variation of the thickness in the asphalt layers are radial deformation at the base of the asphalt layer considering that in these combinations in most cases design was controlled by a very low radial deformation acceptable value. Given that the thickness contributing the most to the radial deformation to be less than the acceptable thickness of the asphalt, it became difficult to control high thicknesses at the asphalt layer when acceptable values of radial deformation were too low. Thicknesses at the asphalt layer considerably increase when a lower layer modulus (687 MPa) is assumed with respect to higher modulus values obtained (1500 MPa) (Figure 3)

Combinations 1, 5, 6, 8, 9 and 18 which corresponds to fatigue laws from the US Army Corps of Engineers, Transport and Road Research Laboratory, Illinois-Department of Transportation, Minnesota 1998, Indian and English models, respectively, as per the two structures and two modulus values assessed, required higher asphalt layer thicknesses (greater than 18 cm) to meet design criteria. In cases such when the thicknesses at the asphalt layer are higher, reshaping the flexible pavement structure will be required by placing a pavement steady base on which the wearing course is placed. This result is also due to acceptable values obtained through these fatigue laws which are quite demanding compared to different fatigue laws studied.

When analyzing the effect of using different fatigue laws for vertical deformation at the subgrade and structure deflection, in most cases certain thicknesses are very similar to those obtained for the combination of fatigue laws forming the base structure. Consequently, it is considered that the influence of these fatigue laws in the thickness variation is minimal compared to the influence of fatigue laws for the radial deformation at the base of the asphalt layer.

The variation range of thicknesses for the soil-cement layers and granular subbase in the structure 2, for both cases of modulus, it is very similar and it is considered smaller as compared with the variation range of the asphalt layer. This is also due to the demands for acceptable values for this structure when using stress fatigue laws and deformation at the subgrade are lower compared to some radial deformation fatigue laws at the base of the asphalt layer.

Structure 2 shows the soil-cement layer placed at the subgrade. This allows a greater dissipation of the stresses and deformations affecting the subgrade. For that reason, cases where the design is controlled by stresses or deformations at the subgrade, thicknesses of the granular base decreases. This is evident when comparing granular base thicknesses in structure 1 which does not include a steady layer and granular base thicknesses in structure 2 which does include a steady layer.

In the case of the structure 1, Figure 3 shows a number of combinations of fatigue laws where the variation of granular layer thicknesses is low, presenting thicknesses very similar to those at the base structure. However, in the case of the asphalt layer, the number of combinations with similar thicknesses to the base structure is reduced, indicating greater sensitivity of this layer to the use of different fatigue laws. As per structure 2, a higher number of combinations having little thickness variability as of the asphalt layer is observed, indicating that when a steady layer is used, the effect of using different fatigue laws in the required thickness variability at the asphalt layer is reduced.

In all cases, the range of variation of the prime cost was high (Table 10) Figure 4 shows that only a small percentage of fatigue laws combinations caused more than US\$ 421.052. In most cases when the cost of the structure is greater than US\$ 421.052, combinations appropriate to these costs were those obtained by changing radial deformation fatigue laws at the base of the asphalt layer. This is why it is considered that the incidence of these fatigue laws in the cost structure is high.

Figure 3. Variation of thicknesses for pavement structures

Table 10. Variation of each pavement structure cost (U\$)

Structure	MPa	Variation Range	Range
N°1	1500	215.726 - 813.316	597.589
	687	231.446 - 997.739	766.292
N°2	1500	218.884 - 803.010	584.125
	687	268.635 - 979.008	710.373

In both pavement structures for both modulus values of asphalt layer, about 50% of the combinations caused a prime cost close to the base structure cost (Figure 4). In order to do this, all fatigue laws combinations in a cost range of $\pm$ U\$ 52,631 at the base structure cost were taken. Fatigue laws corresponding to these combinations are:

- Radial deformation fatigue laws: Belgian Road Research Center.
- Vertical deformation fatigue laws: Shell 95%, Shell 50%, LCPC, Dormon y Mercalf.
- Vertical stress fatigue laws at the subgrade: Jeuffroy, Acum y Fox.
- Structure deflection fatigue laws: Asphalt Institute, Czechoslovakian Criteria, RTAC Canada Criteria, Ivanov Criteria, ASHTO Road Test, CGRA Canada Criteria, Belgium Criteria.

It is observed that most of the fatigue laws for the deflection of the structure caused a similar prime cost to that at the base structure. Most combinations for radial deformation fatigue laws at the base of the asphalt layer caused a higher cost to that of the base structure, mainly due to the high incidence of these fatigue laws in the thicknesses of the asphalt layer, and, consequently, costs present a higher variation since the cost of the asphalt concrete is the highest

among the materials forming the pavement structure.

As per the above, it is not recommended the selection of fatigue laws generating the lower prime cost as per the analysis of the study results. This would be a wrong conclusion since to obtain the best cost-benefit ratio in the mechanistic pavement design, local calibration of fatigue laws should be performed. The analysis results show that there is high variability in construction prime costs when used in the design of fatigue laws not locally calibrated. Additionally and by having the calibrated design method, a better performance in the life cycle of the pavement by reducing maintenance costs is achieved.

Figure 4. Cost variation of the pavement structures

9. Conclusions

The analysis shows that there is significant variation of the layer thicknesses obtained by designing a pavement with different fatigue laws, even when fatigue laws used are developed for the same type of materials. This creates a lot of uncertainty in the mechanistic pavement design, reaffirming the need to perform local efforts as per local calibration fatigue laws to meet solutions appropriate to the projects' needs.

The variation on the construction prime costs resulting from the uncertainty in design with different fatigue laws is large, meaning that when a calibrated method is not used there is great uncertainty over construction prime costs and durability of the structure.

When analyzing the effect of using different fatigue laws for vertical deformation at the subgrade and deflection of the structure, in most cases certain thicknesses are very similar to those obtained for the combination of fatigue laws forming the base structure. Consequently, it is considered that the influence of these fatigue laws in the thickness variation is minimal compared to the influence of fatigue laws for the radial deformation at the base of the asphalt layer.

As per the analysis conditions, there is higher sensitivity to the fatigue law when determining the thickness of the asphalt layers that in determining the thickness of granular layers, setting out uncertainty in project cost since the asphalt concrete is a material with a high impact in the construction costs of flexible pavements.

Calibration of the rational or mechanistic methods of flexible pavement design is a necessary component to be used by this design methodology. Results confirm that designing with non-calibrated fatigue models leads to high uncertainty in the construction prime costs of pavements.

More research needs to be done within the country in the area of flexible pavements. To develop fatigue models for domestic materials, considering pavements climatic conditions, the use of fatigue models developed for foreign materials and different climatic conditions to national or regional may cause overruns in the initial construction of pavements or excessive costs as per their maintenance. Local calibration allows for identifying appropriate fatigue laws for each region achieving the determination of the pavement layers thicknesses to ensure a better performance during their design stage and also with a better cost-benefit ratio.

10. References

- Ambassa Z., Allou F., Petit C., and Eko R. M. (2013)**, Fatigue life prediction of an asphalt pavement subjected to multiple axle loadings with viscoelastic FEM. *Construction and Building Materials*, 43, 443-452. doi:10.1016/j.conbuildmat.2013.02.017
- Asphalt Institute. (1981)**, Thickness design asphalt pavements for highways and streets (No. 1). Asphalt Institute.
- Asphalt Institute (1983)**, Asphalt Overlays for Highway and Street Rehabilitation, Manual Series No. 17 (MS-17). College Park, Maryland.
- Behiry A. E. A. E. M. (2012)**, Fatigue and rutting life in flexible pavement. *Ain Shams Engineering Journal*, 3(4), 367-374. doi:10.1016/j.asej.2012.04.008. Listado de Precios Oficiales. Gobernación del Valle del Cauca. Consultado el 2 de Octubre de 2013, de <http://www.valledelcauca.gov.co/descargar.php?id=11186>
- Craus J., Yuce R., and Monismith C. L. (1984)**, Fatigue behavior of thin asphalt concrete layers in flexible pavement structures. In *Association of Asphalt Paving Technologists Proceedings* (Vol. 53).
- Das A. and Pandey B. B. (1999)**, Mechanistic-empirical design of bituminous roads: an Indian perspective. *Journal of transportation engineering*, 125(5), 463-471.
- Defense D. O. (1988)**, Pavement design for roads, streets, and open storage area: multiple layer method. Technical Manual TM (Vol. 53), Washington, D.C.
- Garnica Anguas P. y Correa A. (2004)**, Conceptos mecanicistas en pavimentos. Publicación Técnica, (258). Instituto Mexicano del Transporte.
- Guzmán M. y Marín C. (2007)**, Comparación de módulos dinámicos de probetas elaboradas por el método Marshall y por el método Superpave. *Revista Ingenierías Universidad de Medellín*, 6(10), 67-76.
- Hafeez I., Kamal M. A., Mirza M. W. y Bilal S. (2013)**, Laboratory fatigue performance evaluation of different field laid asphalt mixtures. *Construction and Building Materials*, 44, 792-797.
- Hidalgo Andrade F. A. (2007)**, Definición moderna de los parámetros para el diseño de pavimentos. Escuela Politécnica del Ejército, Ecuador.
- Higuera C. H. (2007)**, Leyes de comportamiento de la deflexión admisible en pavimentos flexibles. *Revista Facultad de Ingeniería UPTC*, 22(0121-1129), 7-14.
- Higuera C. H. (2011)**, Leyes de comportamiento de la deformación radial admisible de tracción en pavimentos flexibles. *Revista Facultad de Ingeniería UPTC*, 16(23).
- Higuera C. H. (2007)**, Leyes de comportamiento de la deformación vertical admisible de compresión en pavimentos flexibles. *Revista Facultad de Ingeniería UPTC*, pp. 17-24.
- Higuera C. H. (2008)**, Comportamiento de las variables de las leyes de fatiga, deformación y deflexión en un estructura de pavimento flexible. *Revista Facultad de Ingeniería UPTC*, 17(24), pp. 51-68.
- Homsí F., Bodin D., Breyse D., Yotte S. and Balay J. M. (2012)**, A multi-linear fatigue life model of flexible pavements under multiple axle loadings. In 7th RILEM International Conference on Cracking in Pavements (pp. 697-706). Springer Netherlands.
- Huang Y. (2004)**, Pavement Analysis and Design. Segunda ed, Pearson.
- Khana S., Nagabhushanaba M., Devesh T. and P.K. J. (2013)**, Rutting in Flexible Pavement: An approach of evaluation with Accelerated Pavement Testing Facility. *Procedia-Social and Behavioral Sciences*, 2013, vol. 104, p. 149-157. doi:10.1016/j.sbspro.2013.11.107
- LCPC-SETRA. (1997)**, French Design Manual for Pavement Structures. Paris: Laboratoire Central des Ponts et Chaussées and Service d'Etudes Techniques des Routes et Autoroutes.
- Norambuena-Contreras J., Castro-Fresno D., Del Coz J. y García P. (2011)**, Simulación numérica de una mezcla asfáltica usando MEF y diseño de experimentos. *Revista de la Construcción*, 10(2), pp. 4-15.
- Orobio A. (2011)**, Sensitivity analysis of flexible pavement performance parameters in the mechanistic-empirical design guide. ProQuest. 194p.
- Powell W. D., Potter J. F., Mayhew H. C. and Nunn M. E. (1984)**, The structural design of bituminous roads (No. LR 1132 Monograph), Transportation and Road Research Laboratory, London.
- Quintana H. A. R. y Lizcano F. A. R. (2007)**, Metodologías de diseño de pavimentos flexibles: tendencias, alcances y limitaciones. *Ciencia e Ingeniería Neogranadina*, 17(2), 41-65.
- Reyes Lizcano F. A. (2003)**, Diseño racional de pavimentos. Pontificia Universidad Javeriana y Escuela Colombiana de Ingeniería, 1a edición, Bogotá DC.
- Rodríguez Moreno M., Theboux Zeballos G., y González Vaccarezza A. (2013)**, Evaluación probabilística del agrietamiento de pavimentos asfálticos en carreteras de Chile. *Revista de la construcción*, 12(2), 152-165.
- Rodríguez N., Torres F. y Arias A. (2012)**, Definición de alternativas del diseño del pavimento vía Arauca – Caracol, municipio de Arauca. *L'esprit Ing énieux*, pp. 104-113.
- Rondón-Quintana H. A., Reyes-Lizcano F. A. y Vacca-Gómez H. A. (2013)**, Caracterización dinámica de una mezcla asfáltica sometida a las condiciones ambientales de Bogotá. *Revista EIA*, 7(14), 135-145.
- Selvaraj S. I. (2012)**, Review on the Use of Instrumented Pavement Test Data in Validating Flexible Pavement Mechanistic Load Response Models. *Procedia-Social and Behavioral Sciences*, 43, 819-831.
- Shell S. P. D. M. A. (1978)**, Pavements and Overlays for Road Traffic. Shell International Petroleum, London.
- Concretos y Cementos (2012)**. Consultado el 02 de Septiembre de 2013, de Sispac Ltda: <http://www.sispac.com.co/concretosycementos.pdf>.
- Suh Y.-C., Cho N.-H. and Munb. S. (2010)**, Development of mechanistic-empirical design method for an asphalt pavement rutting model using APT. *Construction and Building Materials*, 25(4), pp. 1685-1690. doi:10.1016/j.conbuildmat.2010.10.014
- Sun L., Hudson W. R. and Zhang Z. (2003)**, Empirical-mechanistic method based stochastic modeling of fatigue damage to predict flexible pavement cracking for transportation infrastructure management. *Journal of transportation engineering*, 129(2), 109-117.
- Thompson M. R. (1987)**, ILLI-PAVE based full-depth asphalt concrete pavement design procedure. In Sixth International Conf. on Structural Design of Asphalt Pavements, Ann Arbor, Michigan.
- Tigdemir M., Karasahin M. and Zekai S. (2002)**, Investigation of fatigue behaviour of asphalt concrete pavements with fuzzy-logic approach. *International Journal of Fatigue*, 24(8), pp. 903-910. doi:10.1016/S0142-1123(01)00183-9
- Timm D., Birgisson B. and Newcomb D. (1998)**, Development of mechanistic-empirical pavement design in Minnesota. *Transportation Research Record: Journal of the Transportation Research Board*, 1629(1), 181-188.
- Transportation Association of Canada (1997)**, Pavement design and management guide. Transportation Association of Canada. Canada.
- Valdés G., Pérez F. y Botella R. (2011)**, Ensayo Fénix, una Nueva Metodología para Medir la Resistencia a la Fisuración en Mezclas Asfálticas. *Revista de la Construcción*, 8 (1), pp. 114-125.
- Valdés G., Pérez-Jiménez F. y Martínez A. (2012)**, Influencia de la temperatura y tipo de mezcla asfáltica en el comportamiento a fatiga de los pavimentos flexibles. *Revista de la Construcción*, 11(1), pp. 88-101.
- Verstraeten J., Veverka V. and Francken L. (1982)**, Rational and practical designs of asphalt pavements to avoid cracking and rutting. In *Proceedings, Fifth International Conference on the Structural Design of Asphalt Pavements*(Vol. 1, pp. 45-58).
- Wang L. (2011)**, Mechanics of Asphalt Microstructure and Micromechanics. Mc Graw Hill. 480p.
- Yeo L., Suh Y. and Mun S. (2007)**, Development of a remaining fatigue life model for asphalt black base through accelerated pavement testing. *Construction and Building Materials*, 22(8), pp. 1881-1886. doi:10.1016/j.conbuildmat.2007.04.015
- Zheng L., Hai-lin Y., Wan-ping W. and Ping C. (2012)**, Dynamic stress and deformation of a layered road structure under vehicle traffic loads: Experimental measurements and numerical calculations. *Soil Dynamics and Earthquake Engineering*, Agosto, Volumen 39, pp. 100-112. doi:10.1016/j.soldyn.2012.03.002
- Zhi S., Gun W. W., Hui L. X. and Bo T. (2012)**, Evaluation of fatigue crack behavior in asphalt concrete pavements with different polymer modifiers. *Construction and Building Materials*, 27(1), 117-125. doi:10.1016/j.conbuildmat.2011.08.017