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Comparative analysis on strains in asphalt pavement design using linear elastic and viscoelastic theories.

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Abstract. In Colombia it is common to design pavements using the AASHTO 93 method and to complement it with an elastic analysis of the deformations that cause fatigue and rutting; this has repercussions on the behavior of the structure since it does not take into account the viscoelastic behavior of the asphalt mixtures, In this research, a comparison of three structures at different velocity ranges is made to compare the variation in fatigue and rutting concerning the traditional method of analysis in Colombia and to analyze the differences that may occur in linear elastic analysis and viscoelastic analysis of rutting and fatigue.

1. Introduction
In Colombia, over the years, empirical methodologies have been used for the design of flexible pavement structures, such as the AASHTO 93 methodology [13], however, these designs have an empirical nature due to the design methodology was born from a large-scale test in the United States where through statistical analysis they determined pavement thicknesses from the recorded data and to an extent do not reflect the reality in the Colombian context where wheatear and traffic operating conditions may be different from those considered in the AASHTO Road Test.

In Colombia, the empirical mechanistic methodology is used for the verification of AASHTO pavement designs, which is known as the rational design methodology for flexible pavements. This methodology is based on the calculation of stress and strain to determine the fatigue and rutting life of asphalt pavement structures. This procedure is widely used in Colombia to design flexible pavements, compute layer thicknesses, and analyze strains related to fatigue and rutting in the pavement structure.

One of the oldest failure modes in flexible pavements is fatigue [10] [14]. Fatigue in flexible pavements is cracked in the bottom of the asphalt layer that over time are reflected in the surface, either longitudinally, transversely, or can turn into a system of interconnected cracks. Fatigue life in pavements is governed by the tensile strains generated at the bottom of the asphalt layer, because if the strains due to vehicular traffic exceed the maximum strain allowed by the asphalt concrete, the pavement fatigues, causing top-down cracks or bottom-up cracks [4] [6]. It is relevant to determine the impact of performing a viscoelastic analysis of the fatigue in asphalt caused by different load application speeds or temperature variations to know in what proportion it affects the analysis of these strains only as an elastic material.

On the other hand, rutting is a manifestation of both permanent strain and a surface impairment in flexible pavements, pavement design should aim to eliminate or reduce rutting in the pavement surface over a given period. The rutting criterion is based on limiting the vertical strain produced at the top of the subgrade because if the produced strain is greater than the allowed by the subgrade, rutting will occur [11]. Rutting can cause problems in the operating conditions of the road and it is not known what the impact of analyzing it only from an elastic perspective without considering the viscoelastic behavior of the asphalt material, variations in temperature or the frequency of load application can vary the dynamic modulus of the asphalt concrete affecting rutting behavior.

Most analytical models used for the design of flexible pavements are based on a linear elastic theory which assumes that each layer is homogeneous, isotropic, linearly elastic with a constant modulus of elasticity and the surface layer is free of shear and normal stresses. [12] However, it is interesting to know the response of the asphalt pavement in terms of stresses and strains, considering viscoelastic theories to compare with traditional elastic linear methods.

2. Input Data and Analysis Methodology

For making a comparison of fatigue and rutting in flexible pavements, a series of predefined variables were selected to calculate the thicknesses of the structure through the AASHTO 93 method [1], which is one of the most widely used in Colombia. The analysis methodology to consider the elastic and viscoelastic behavior of the material consists of predefining the input variables for the AASHTO 93 method, among the main ones are the traffic load, the elastic modulus of the granular layers, pavement type, and the average temperature, in addition to the remaining parameters such as serviceability and others specific to the AASHTO design method, these are shown in the following Table 1 in which some recommendations of INVIAS an AASHTO 93are specified. [1] [2] [3] [5] INVIAS is the governmental body responsible for roads in Colombia.

Table 1. Parameters and Values in AASHTO Design

Parameters		**Values**	**Recommendations**
Reliability	R%	95%	Main roads
Standard deviation	So	0.49	Considering transit variance
Initial serviceability	PSI Initial	4.2	Flexible pavements
final serviceability	PSI Final	2.5	Main roads
Subgrade resilient modulus	MR	10.500	Correlation CBR 7%
Asphalt structural coefficient	a1	0.3	Recommended by INVIAS for temperatures between 20-30 Celsius. [2]
Base structural coefficient	a2	0.14	Recommended by AASHTO for 28.000 psi granular base [1]
Subbase structural coefficient	a3	0.10	Recommended by AASHTO for 14.000 psi granular subbase [1]

Asphalt drainage coefficient	m1	1	Recommended by AASHTO for asphalt mix [1]
Base drainage coefficient	m2	1	Selected Value
Subbase drainage coefficient	m3	1	Selected Value

The procedure for the comparative analysis of strains taking into account the elastic and viscoelastic behavior of the asphalt pavement begins with the definition of the input data among which it was chosen to vary the traffic levels in three groups to obtain three pavement designs of different thicknesses using the AASHTO 93 method to compare fatigue and rutting in three structures of different thicknesses, Also, it has been chosen to vary the load application frequency and not the temperature, which will be kept constant, this is possible because the 3D Move Analysis software has the master curve of the selected asphalt, this allows us to know the asphalt modulus by varying the temperature or the load application frequency, for this analysis five levels of traffic speed were taken into account from 20 kph to 100 kph, which are the operating range of the roads in the region. The procedure for the comparative analysis of fatigue and rutting deformations is summarized in the following figure 1.

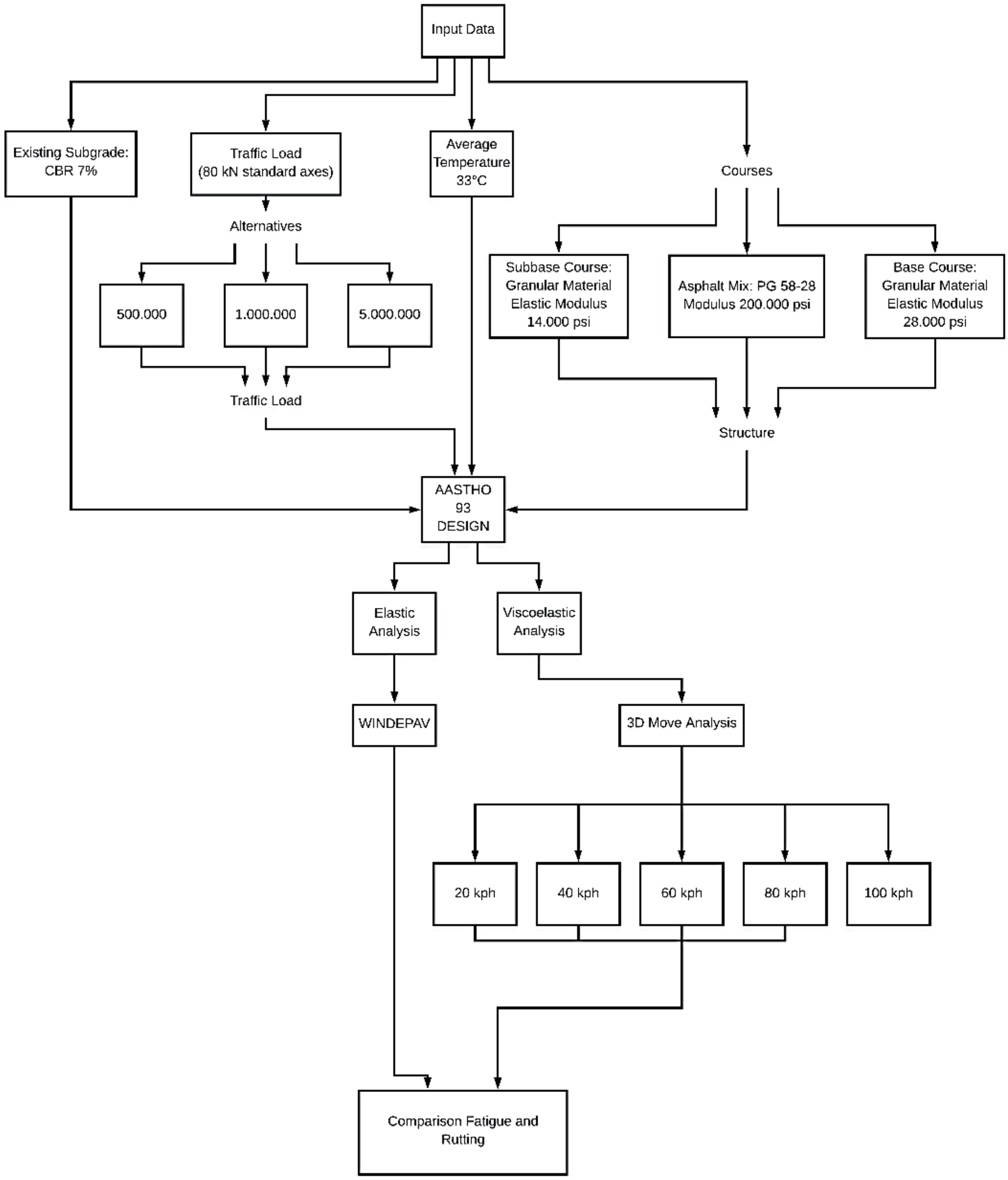


Figure 1. Comparative analysis procedures schema

The three pavement structures have a surface course with PG 58-28 asphalt, a base course in granular material with a modulus of 28,000 psi, a subbase in granular material with a modulus of 14,000 psi over a subgrade with a CBR percentage of 7% or a resilient modulus of 10,500 psi using the Heukelomp and Klomp correlation [8]. The asphalt modulus for the elastic analysis consists of the value at the average temperature in the Caribbean region of Colombia and an average speed of 60 kph as an intermediate value between urban and extra-urban roads.

The temperature chosen for the thickness designs is an average of 33°C [7] (because it is the average temperature in the Caribbean region where Barranquilla is) and varying the speed from 20 kph to 100 kph for the evaluation considering the viscoelastic behavior of the asphalt.

The software used for the pavement design is "Método AASHTO para el diseño de pavimentos" by engineer Luis R. Vasquez which allows the calculation of the thicknesses of the structures, an image of the configuration of the software is shown in Figure 2 the software is only available in Spanish. For the fatigue and rutting analysis considering only the elastic behavior of the material, the WINDEPAV software, and for the viscoelastic analysis the 3D MOVE ANALYSIS software [9].

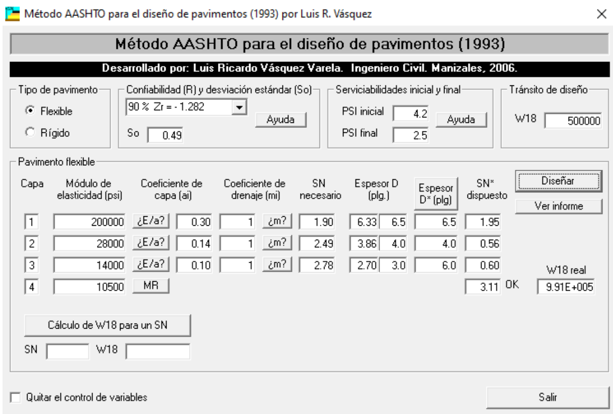
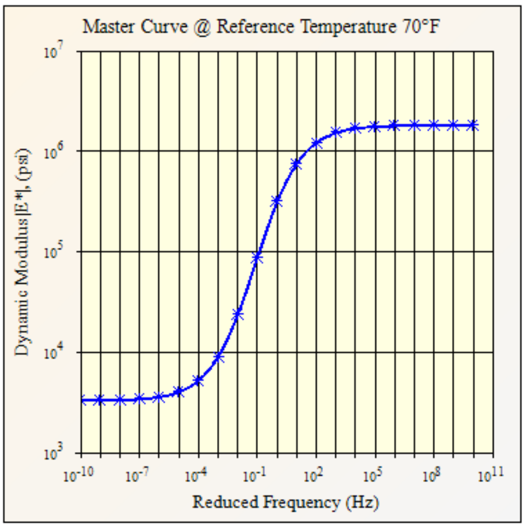


Figure 2. Software configuration for AASTHO design

The master curve of the selected asphalt is the following shown in Figure 3 which is entered into the 3D MOVE ANALYSIS software used for the deformation analysis considering the viscoelastic behavior of the asphalt.



Master Curve equation

$$\log E^* = \delta + \frac{\alpha}{1 + e^{\beta + \gamma[\log(t) - c(\log(\eta) - \log(\eta_{T_r}))]}}$$

Shifting equation

$$log[a(T)] = aT^2 + bT + c$$

Fitting Parameters

Parameter	Value
δ	2.7403
α	-0.9535
β	0.5203
γ	0.8715
c	1.5542

Shifting Parameters

Parameter	Value
a	0.0004
b	-0.1424
c	8.2668

Figure 3. Master Curve for PG 58-22 asphalt.

3. Results

The three different structures obtained from the software for the AASHTO 93 method are as follows, Figure 4. The characteristics of the layers are the same for the structures, the only thing that changes are the value of the number of standard axes that the structure must support.

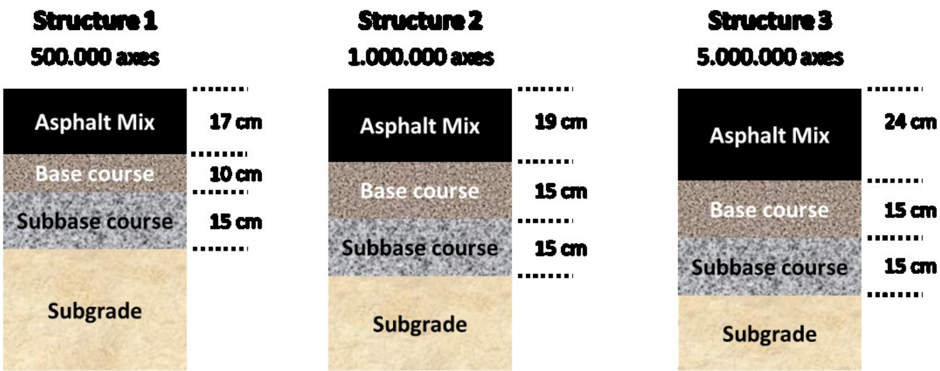


Figure 4. Final design structures at different traffic levels using AASHTO 93 method design.

The results of the deformation analyses in WINDEPAV and 3D MOVE ANALYSIS software are summarized in the following table according to the type of analysis performed in each of the software and for the different speed values from 20 kph to 100 kph, the values of the deformations of the tensile strains at the bottom of the asphalt layer (fatigue) and the compressive strains above the subgrade (rutting) are shown in Table 2 the values are expressed in microstrain.

Table 2. Fatigue and Rutting strains in the three structures in different analysis

	Strain	Structure 1	Structure 2	Structure 3
Elastic Analysis	Fatigue	-287	-246	-193
	Rutting	486	388	305
Viscoelastic Analysis 20 KPH	Fatigue	-350	-291	-235
	Rutting	627	500	425
Viscoelastic Analysis 40 KPH	Fatigue	-311	-256	-206
	Rutting	580	461	388
Viscoelastic Analysis 60 KPH	Fatigue	-283	-236	-189
	Rutting	555	440	365
Viscoelastic Analysis 80 KPH	Fatigue	-266	-222	-176
	Rutting	535	420	350
Viscoelastic Analysis 100 KPH	Fatigue	-254	-210	-168
	Rutting	521	414	339

4. Analysis

First, we compare the values for fatigue in the shown Figure 5.

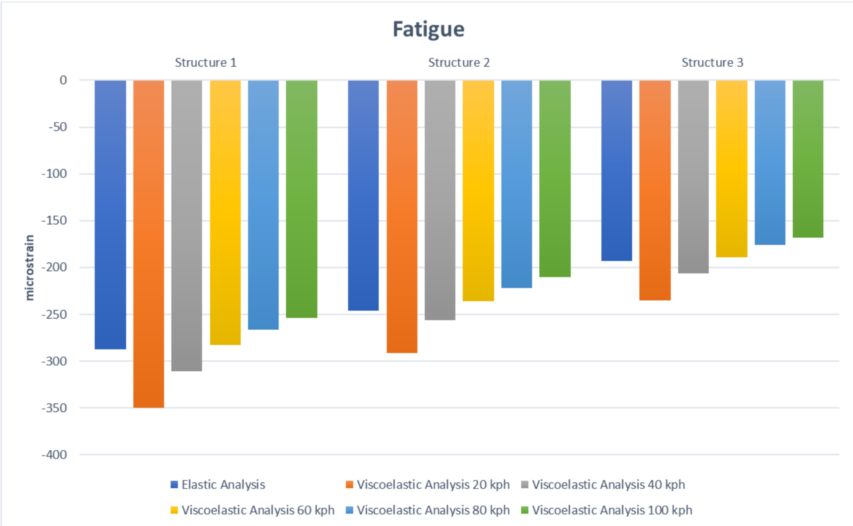


Figure 5. Fatigue strain comparison.

For fatigue, it can be seen that the design of pavements with the AASHTO 93 method and only an elastic analysis of the asphalt layers can consider fatigue strains much lower than the real behavior of the asphalt for speeds below 40 kph, being very similar for the value of 60 kph because the modulus considered in the elastic analysis and the calculation of layer thicknesses employing the AASHTO 93 method is that of an asphalt layer for a modulus of 200,000 psi equivalent to the value of 60 kph and a temperature of 33°C according to its master curve. However, if the variations in the viscoelastic behavior of the asphalt are not taken into account, fatigue values may be much lower than the real values for the operating conditions of the road at lower speeds.

It is also important to clarify that when the analysis is carried out at low speeds, a greater deformation is obtained in the viscoelastic analysis compared to the elastic one, given that at lower speeds, the asphalt performs with a lower dynamic modulus [15] and therefore more strains are generated.

While for rutting we can observe that not considering the viscoelastic behavior of the asphalt considering a fully elastic behavior will outcome in rutting results always lower than the results obtained under viscoelastic behavior, even if the comparison is made at the same load application speed and the same average environment temperature. Note in Figure 6 that the value of the viscoelastic analysis rutting at 60 kph is much higher than the elastic analysis in all three structures regardless of the volume of traffic that the structure must bear.

Figure 6. Rutting strain comparison.

5. Conclusion

In Colombia, most flexible pavement designs are carried out using the AASHTO 93 method to determine the thicknesses of the structure, and then a check is made by the rational methodology in which stresses and strains are calculated at the bottom of the asphalt layer and above the subgrade to estimate the service life of the pavement due to fatigue and rutting, respectively, but only considering the linear elastic behavior of the asphalt. This represents a serious problem especially for rutting analysis in flexible pavements used in warm regions, where it is more prone to suffer from this degradation due to the lower modulus value of the asphalt mix at high temperatures [15] However, fatigue can represent a problem for speeds lower than the design speed of the flexible pavement because of the cases where values well above those estimated in the elastic analysis are found and an advantage for values higher than the design speed of the pavement where fatigue values are estimated well above the values considering the viscoelastic behavior.

Due to the variation in results and the differences between viscoelastic and elastic analysis for different speed and temperature values, it is necessary to review pavement designs that are currently performed only under elastic analysis and that do not consider operating conditions below and above the preset speed and temperature values.

Therefore, it demonstrates the importance of performing designs under viscoelastic analysis and avoiding underestimation of rutting and fatigue values in flexible pavements that may represent problems in the short or medium-term due to variations in the operating conditions of the roads. Besides, it should be noted that one of the main limitations of this research is that the analysis is being carried out with theoretical assumptions that may vary from reality, among these variations are the characteristics of the materials and the characteristics of the traffic, It is therefore recommended for future research to analyze the results with field measurements of a pavement structure to analyze the behavior of the asphalt in real conditions and compare them with the proposed design for the structure, and that the analysis of the stresses and deformations only considers the elastic behavior of the asphalt, likewise, for future research to carry out this analysis using different types of asphalt; such as modified asphalt, warm mixes, recycled mixes, cold mixes, among others.

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