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# Use of mechanistic-empirical method of pavement design for performance sensitivity analysis to asphalt pavement fatigue

## Emprego de método empírico-mecanicista de dimensionamento de pavimento para análise de sensibilidade do desempenho à fadiga de pavimento asfáltico

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## ABSTRACT

There are several factors (geometric, mechanical and loading) that can influence the design of the flexible pavement and its performance regarding the appearance of fatigue cracks. Therefore, the mechanistic-empirical methods for design are widely accepted and used in the field of paving engineering. However, for mechanistic analysis there is a range of fatigue models that can provide different pavement design. This study aimed to analyze the performance sensitivity to asphalt layer fatigue according to data derived from a mechanistic-empirical design of the pavement and considering different fatigue models. The following variables were considered in the fatigue models: the mechanical properties of the structural materials, the thicknesses of the structural layers and the load applied to the structure. The asphalt design mixtures contemplated in the research were defined according to the Marshall mixing design method, framed in two granulometric ranges applicable to asphalt concrete with polymeric binder. The mechanistic-empirical protocol involved the pre-design of pavement structures using the empirical method of the National Department of Transport Infrastructure (DNIT) and its mechanistic analysis using the computer program Elsym5, which considers that horizontal layers are formed by elastic-linear and isotropic materials. The results showed that fatigue performance and surface course layer design varied according to fatigue models applied in different scenarios. However, the sensitivity of performance to surface course fatigue determined by these models, given the variations of the factors studied, was approximately the same. Thus, it was concluded that the fatigue of surface course was more sensitive to the variation of the thickness of the surface course layer than to the variation of the applied load value, followed by the soil resilience module of the subgrade.

**Keywords:** SBS-modified asphalt mixtures, mechanistic-empirical analysis, fatigue models.

## 1. INTRODUCTION

Fatigue cracking of surface course is among the main of distress mechanisms of the pavement [1]. This defect consists of a progressive degradation of the material properties due to the application of cyclic stresses which value is lower than the material resistance [1]. It is typically caused by elastic strains derived from traffic load repetitions, which leads to failure of the surface course [2]. As each of these layers plays a particular role in the pavement structure and is comprised by a specific type of material, it is necessary to consider their respective elastic stiffness and thicknesses in the distribution of stresses and strains within the pavement.

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In Brazil, pavements have often been designed using empirical design method prescribed by the National Department of Transport Infrastructure - DNIT [3], based on the CBR test, on design curves developed by the United States Army Corps of Engineers (USACE) and on data obtained from the American Association of State Highway and Transportation Officials (AASHTO) Road Test in the late 1950s , adapted by engineer Murillo Lopes de Souza [4]. However, numerous variables can influence an empirical analysis, including traffic characteristics, parameters related to climatic factors and structural responses of the pavement (stresses and strains). Thus, the results derived from empirical methods do not always coincide with the conditions found in the field [5].

Therefore, the mechanistic-empirical method has been increasingly used for pavement design [2]. In the United States, Canada and some South American countries, the pavement are designed by the Mechanist-Empirical Pavement Design Guide (MEPDG) developed by AASHTO [5]. In Brazil, the new method of pavement design of DNIT [National Pavement Dimensioning Method (MeDiNa)] is in the implementation phase, which presents an mechanistic-empirical approach in the analysis of the structure of the pavements [6]. MeDiNa considers in design the stresses, strains and displacements of the layer system in relation to the applied loading, in addition to characteristics of the structural materials used, obtained in laboratory tests.

Different fatigue models are referenced in the literature and in software that allow an overview of the mechanical response of the pavement structure when subjected to traffic loads. These may include studies from PINTO [7], DNER [8], FHWA [9] and FRANCO [10]. However, it appears that each fatigue performance model of the surface course has its specific issues, which can be based on the composition of asphalt mixtures, on the condition of the fatigue test or the calibration of the model obtained in the laboratory.

Thus, in the light of the importance of mechanistic-empirical methods to the design of asphalt pavements and the need for applying fatigue models, it should be noted that the availability (or possible application) of different models can provide different layer thicknesses during the pavement design process. In addition, it should also be noted that variations in the resilient moduli of the subgrade soil and the surface course, and the load to which the structure is subjected can also play a role in the pavement performance and, consequently, in its service life.

Considering the above observations, this study aims to identify which components are most influential in the fatigue performance of the surface course of an asphalt pavement. In other words, this study aimed to analyze the performance sensitivity to asphalt layer fatigue according to data derived from a mechanistic-empirical pavement design method and taking into account different fatigue models. In this analysis, different structures were used, with variations in surface course thicknesses, load applied in the structure and mechanical properties of the subgrade and surface course layers.

In the technical-scientific literature on the subject, it is observed that research has analyzed the sensitivity of flexible pavements dimensioned by MEPDG in view of the effects of the variation of surface course thickness, base and subbase on the development of fatigue cracks [11, 12]. Other studies evaluated performance prediction models for fatigue rupture in cement treated gravel base layer (BGTC) [13]. However, it is identified the absence of studies that analyze the implications, on the dimensioning of asphalt pavements, resulting from the adoption of different fatigue models and the consideration of the possible additional influence of geometric variables (thickness), mechanics (engineering properties of structural materials) and loading (axle load) in the mechanistic-empirical protocol. It is assumed that this protocol can point out decision-making scenarios capable of conferring greater reliability to the design process and, consequently, to the paving design.

## 2. MATERIALS AND METHODS

### 2.1 Materials

The asphalt binder used in this investigation was modified with SBS copolymer (BETUFLEX 60/85-E), and it was supplied by Stratura Asfaltos S/A. The basic characteristics of this polymer-modified asphalt binder are shown in Table 1. The results of the aggregation characterization tests are shown in Table 2.

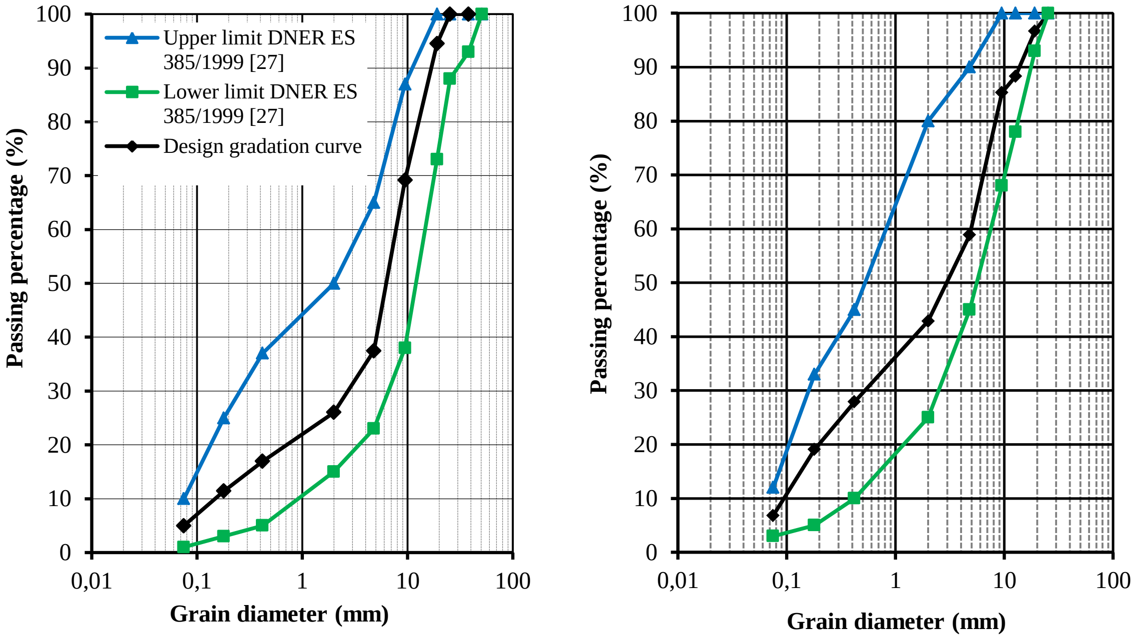
**Table 1:** Results of the basic tests conducted in the SBS-modified binder (BETUFLEX 60/85-E).

| CHARACTERISTIC | SPECIFICATION LIMITS (UNIT) | TEST METHOD | RESULT |
|---|---|---|---|
| Penetration 25°C, 5s, 100g | 40-70 (0.1mm) | DNIT ME 155/2010a [14] | 57 (0.1mm) |
| Softening Point (PA), min. | 60 (°C) | DNIT ME 131/2010b [15] | 75 (°C) |
| Flash Point, min. | 235 (°C) | ABNT NBR 11341/2004a [16] | 220 (°C) |
| Brokfield viscosity at 135°C, spindle 21, 20 rpm, max. | 3000 (cP) | ABNT NBR 15184/2004b [17] | 1120 (cP) |
| Brokfield viscosity at 150°C, spindle 21, 50 rpm, max. | 2000 (cP) | ABNT NBR 15184/2004b [17] | 620 (cP) |
| Brokfield viscosity at 177°C, spindle 21, 100 rpm, max. | 1000 (cP) | ABNT NBR 15184/2004b [17] | 235 (cP) |
| Phase Separation Test, max. | 5 (°C) | ABNT NBR 15166/2004c [18] | 2.8 (°C) |
| Elastic Recovery at 25°C, 20cm, min. | 85 (%) | - | 93 (%) |
| Effect of heat and air – RTFOT, 163°C, 85 minutes | | | |
| Mass variation, max. | 1 (% mass) | ABNT NBR 15235/2006 [19] | 0.89 (% mass) |
| PA variation, max. | (-5) to 7 (°C) | DNIT ME 131/2010b[15] | 0.5 (°C) |
| % Original Penetration, min. | 60 (%) | DNIT ME 155/2010a [14] | 73.5 (%) |
| % Original Elastic Recovery at 25°C, min. | 80 (%) | DNIT ME 130/2010c [20] | 99.8 (%) |

**Table 2:** Results of the characterization tests of the aggregates used in the study.

| CHARACTERIZATION TESTS ON AGGREGATES | STANDARD | RESULTS |
|---|---|---|
| Determination of "Los Angeles" abrasion for coarse aggregate | DNER ME 035/1998a [21] | 44.92% |
| Determination of adhesiveness to bituminous binders | DNER ME 078/1994a [22] | Unsatisfactory |
| Determination of the Shape Index – Gravel 0 | DNER ME 086/1994b [23] | 0.59 |
| Determination of the Shape Index – Gravel 1 | DNER ME 086/1994b [23] | 0.68 |
| Determination of absorption – Gravel 0 | DNER ME 194/1998b [24] | 0.68% |
| Determination of absorption – Gravel 1 | DNER ME 194/1998b [24] | 0.65% |
| Determination of specific mass of fine aggregate | DNER ME 194/1998b [24] | 2.782 g/cm$^3$ |
| Determination of real specific mass – Gravel 0 | DNER ME 081/1998c [25] | 2.791 g/cm$^3$ |
| Determination of real specific mass – Gravel 1 | DNER ME 081/1998c [25] | 2.796 g/cm$^3$ |

The results of the characterization of the asphalt binder and aggregates, except the adhesiveness of the binder to the aggregate, met technical specifications cited in Tables 1 and 2. The adhesiveness of the binder to the aggregate, which was measured according to the DNER ME 078/1994a method [22], was shown to be unsatisfactory. This limitation was addressed by means of the incorporation of 0.1% of additive by weight of the asphalt binder to improve adhesion. From the granulometric analysis carried out according to DNER ME 083/1998d [26], the compositions of the granulometric curves that fit the granulometric ranges B and C to dense-graded mixes of DNER ES 385/1999 [27] were determined, as illustrated in Figure 1. The design gradation curve for granulometric range B may be described as 32% stone powder, 41% crushed stone 0 and 27% crushed stone 1, while the design gradation curve for granulometric range C is composed of 53% stone powder, 35% gravel 0 and 12% gravel 1.



(a) Design gradation curve for granulometric range B (b) Design gradation curve for granulometric range C

**Figure 1:** Lower and upper limits of the DNER ES 385/1999 service specification [27] for the granulometric ranges B and C studied and their respective design gradation curves.

## 2.2 Methods

### 2.2.1. Marshall mix design method

In the design process of asphalt mixtures, the Marshall mix design method was used according to the DNER ME 043/1995 standard [28]. To determine the design content of the asphalt binder through the relationship between the voids content (VC) and voids filled with bitumen (VFB) parameters. Initially, asphalt mixtures were designed in five binder contents (4.2%, 4.7%, 5.2%, 5.7% and 6.2% by weight). According to SENÇO [29], asphalt mixtures prepared with such binder contents tend to show higher stability and strength and lower air void percentages. The mixture of aggregates with the binder was defined as enough to obtain a specimen of approximately 6.3 cm in height, 10.0 cm in diameter and 1200 g. The compaction energy corresponded to 75 strokes per face across the specimens.

From the graphical analysis of the VC and VFB values of the asphalt mixtures prepared with the above mentioned binder contents and by following the basic protocol contained in BERNUCCI *et al.* [30] and the limits established by DNER ES 385/1999 [27] for such parameters (3% ≤ VC ≤ 5%; 75% ≤ VFB ≤ 82%), the specific binder design contents were determined for the asphalt mixtures corresponding to the granulometric range B and C. For such binder contents, asphalt mixture samples were compacted and their volumetric parameters and basic mechanical properties were determined the volumetric parameters. Later, it was possible to verify their classification, within the limits established by DNER ES 385/1999 [27].

### 2.2.2. Mechanical tests

The Diametral Tensile Strength test according to the DNIT ME 136/2010d [31] standard and the Resilient Modulus test according to the procedures outlined by DNIT ME 135 / 2010e [32] were performed.

### 2.2.3. Mechanistic-empirical methodology

To analyze the sensitivity of the fatigue life of the surface course regarding the variation of its thickness, the soil resilience modules of the subgrade and asphalt mixture, the load applied by axis and the fatigue model adopted, a mechanistic-empirical protocol was used. Initially, different pre-design pavement structures were determined according to the empirical method presented in the DNIT Paving Manual [3], for a period of 10 years. In the mechanistic analysis, the Elsym 5 Program (KOPPERMAN *et al.* [33], FHWA [9]), aiming to obtain the structural responses necessary for the application of pavement fatigue life models was used. Figure

2 shows, in a simplified way, the methodological protocol applied in this study.

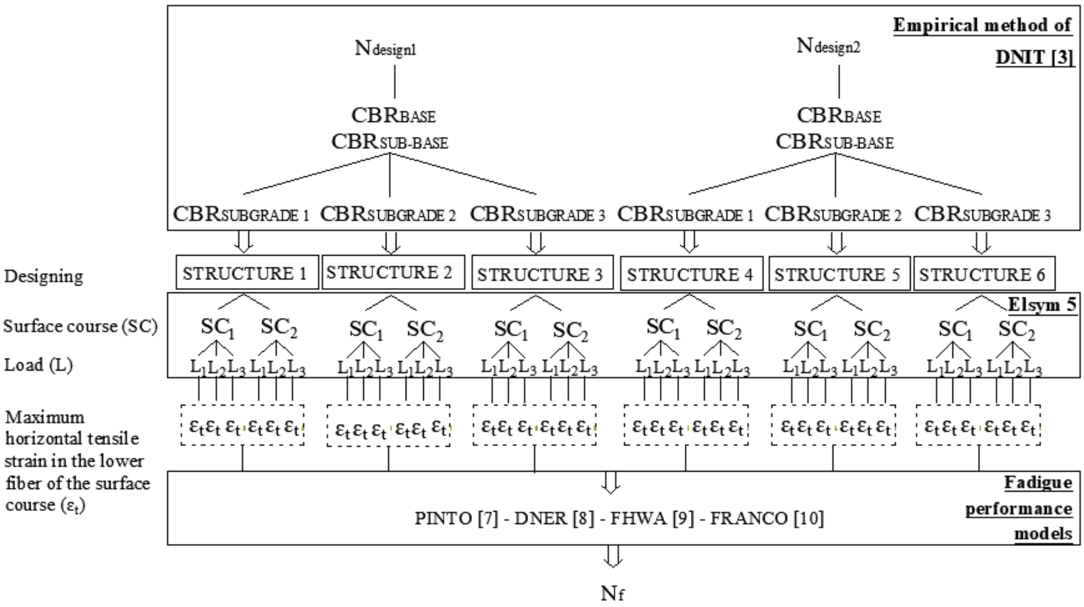


**Figure 2:** Methodological protocol used in the analysis of the mechanistic-empirical designing.

It should be noted that the design of the asphalt pavement structure according to the empirical method of DNIT [3] is performed according to the number of load repetitions of the standard axis of 8.2 tons (N) applied to the pavement, as well as the CBR (California Bearing Ratio) values of the materials that compose the respective layers, except for the surface course. The characteristics of the materials that compose the pavement structure in this study are shown in Table 3.

The determination of the thickness of the surface course was made according to the "$N_{design}$" [3]. For this purpose, two values of "$N_{design}$" were chosen. In order to carry out simulations closer to real pavement structures, "$N_{design}$" values from real traffic situations were chosen. It was also decided to use materials in the base, sub-base and subgrade layers that would constitute typical road pavement structures, such as those in the state of Rio Grande do Sul, Brazil [34]. The fact that the Resilient Modulus of the sub-base is superior to the Resilient Modulus of the base finds support on common results obtained in retroanalysis of asphalt pavements in this state [3].

**Table 3:** Characteristics of the variables that dictate the pavement structure according to the DNIT method [3].

| VARIABLES | CHARACTERISTICS |
|---|---|
| Number of load repetitions for the standard axis of 8.2 tons | - $N_{design1}$ = 1.56x$10^7$: number of load repetitions for the standard axis of 8.2 tons in 2013 at km 541 of BR 116, in the municipality of Pavão, state of Rio Grande do Sul [34];<br>- $N_{design2}$ = 10.4x$10^7$: number of load repetitions for the standard axis of 8.2 tons in 2013 at km 816 of BR 040, in the municipality of Simão Pereira, state of Rio Grande do Sul [34]. |
| Asphalt mix | - Bituminous concrete with asphalt binder modified by polymer type SBS (BETUFLEX 60/85-E). |
| Base | - RM= 250 MPa;<br>- Poisson's ratio equal to 0.35. |
| Sub-base with dry macadam | - RM=300 MPa;<br>- Poisson's ratio equal to 0.35. |
| Subgrade soil | - CBR $_{SUBGRADE\ 1}$ = 4% and RM = 40 MPa;<br>- CBR $_{SUBGRADE\ 2}$ = 10% and RM = 100 MPa;<br>- CBR $_{SUBGRADE\ 3}$ = 16% and RM = 160 MPa.<br>- Poisson's ratio equal to 0.35. |

The mechanistic analysis consisted of verifying the performance of the pavement structure based on failure of the surface course by fatigue cracking. This was made by determining the “$N_f$” number in the fatigue performance models of the surface course, see equations in Table 4. If this number is equal or exceeds the number “$N_{design}$”, the designing was considered appropriate for paving applications.

**Table 4:** Fatigue performance models of the surface course applied in the mechanistic-empirical method adopted in the research.

| AUTHOR/DESCRIPTION | FATIGUE PERFORMANCE MODEL OF THE SURFACE COURSE |
|---|---|
| PINTO [7]<br>- Based on the analysis of 82 fatigue tests at controlled tension, at a temperature of 25ºC, of six asphalt mixtures.<br>- The calibration of the model is based on observations and analysis of field behavior in stretches of the BR 101 highway.<br>- This model was incorporated into the PAVE program [35] and can be used in the AYMA program [36]. | $N_{LAB} = 9{,}07.10^{-9}.\left(\frac{1}{\varepsilon_t}\right)^{2{,}65}.\left(\frac{1}{RM\,(\text{kgf/cm}^2)}\right)^{-0{,}033}$ (1)<br>$N_f = 10^4.N_{LAB}$ (2) |
| DNER [8]<br>- Model based on asphalt mixtures with CAP 20 modified by SBS polymer, in the proportion of 6% incorporation. | $N_{LAB} = 3.10^{-12}.\left(\frac{1}{\varepsilon_t}\right)^{3.68}$ (3)<br>$N_f = 10^5.N_{LAB}$ (4) |
| FHWA [9]<br>- Model calibrated from data obtained from AASHO Road Test experimental tracks. | $N_f = 1.092.10^{-6}.\left(\frac{1}{\varepsilon_t}\right)^{3.512}$ (5) |
| FRANCO [10]<br>- Model obtained for asphalt mixtures with binders modified by polymer SBS or EVA, from the analysis of 51 of these asphalt mixtures, with $R^2 = 0.813$.<br>- PREUSSLER and PINTO [37] recommend the use of a laboratory/field factor of the order of $10^5$ for a structural analysis in terms of specific tensile strain. | $N_{LAB} = 4.455.10^{-7}.\left(\frac{1}{\varepsilon_t}\right)^{3.798}.\left(\frac{1}{RM\,(\text{MPa})}\right)^{1.493}$ (6)<br>$N_f = 10^5.N_{LAB}$ (7) |

$N_{LAB}$: allowable number of load repetitions for cracking by fatigue in the laboratory;
$N_f$: allowable number of load repetitions for cracking by fatigue in the field;
$\varepsilon_t$: maximum horizontal tensile strain in the lower edge of the surface course;
RM: Resilient Modulus of the asphalt mixture.

To determine the maximum horizontal tensile strain in the lower edge of the surface course ($\varepsilon_t$), the Elsym 5 program was used. The input data were related to the number of layers and their corresponding thicknesses, as well as the Resilient Moduli and the Poisson's ratios of the structural layers of the pavement and the subgrade. The Resilient Modulus of the surface course, which may be designated as surface course 1 ($SC_1$) or surface course 2 ($SC_2$) depending on the gradation curve (B and C, respectively), was determined through mechanical testing as shown above.

Then, the following loading data were considered in the analysis: the load value per tire (L/4), the pressure of each tire (80 psi or 5.63 kgf/cm²) and the load positioning along the X axis. As the single axle with double wheels is symmetric in relation to the X axis, only the loads on the left side of the axis were reported, in positions X = 0 cm and X = 34 cm. This study took into account the following load levels per axle:

- $L_1$ = 80 kN (8.2 tf): load corresponding to the standard axis of 18,000lb;
- $L_2$ = 98 kN (10.0 tf): maximum load allowed by Brazilian legislation for single axle with double wheels;
- $L_3$ = 118 kN (12.0 tf): load 20% above the maximum allowed value and with the percentage of 5% as the maximum tolerance. The objective of adopting a load 20% above the one allowed was to expose the consequences caused to asphalt pavement structures researched when there is excess load on the axles of commercial vehicles [38].

Finally, the reference points in the Cartesian axes (X, Y, Z) were determined for conducting the structural analyses. In this case, the most critical points were defined as the places where the load is applied, in centimeters, either in "X" equal to 0 cm or equal to 34 cm. The point positioned on the "Z" axis corresponds to the location of the lower edge of the surface course, that is, the interface between the surface course and the base layer. Its value was dependent on the thickness of the surface course according to the DNIT design method [3].

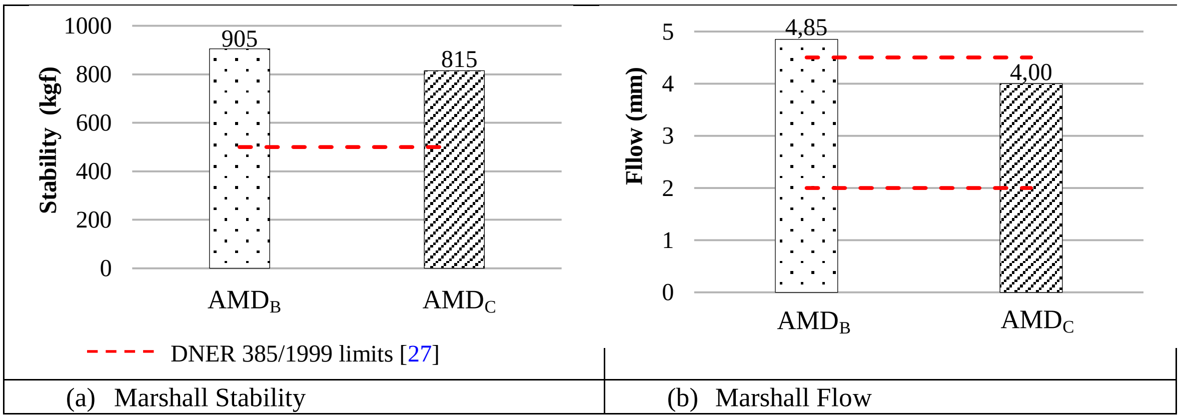
From the maximum horizontal tensile strain values in the lower edge of the surface course the number of load repetitions to fatigue failure ($N_f$) and for each scenario were determined. The models reported in Table 4 were compared with the number of load repetitions defined in the design ("$N_{design1}$" or "$N_{design2}$"). When the "$N_f$" value is lower than the value of "$N_{design}$", the pavement structure needs to be redesigned because of the hypothesis of premature failure by fatigue cracking.

## 3. RESULTS AND DISCUSSION

### 3.1 Marshall mix design

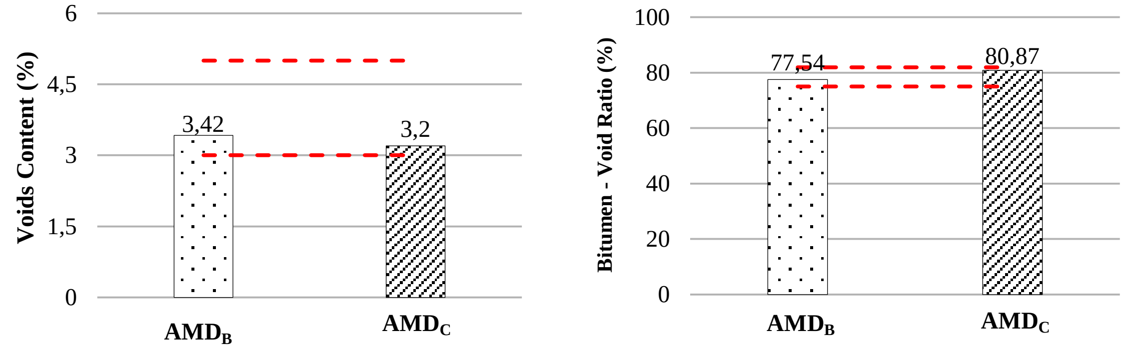
From the application of the protocol contained in BERNUCCI *et al.* [30] and using the results of the volumetric parameters "VC" and "VFB" of the asphalt mixtures of granulometric ranges B and C, the values of 4.80% and 5.20% were defined for the contents of asphalt binder in the design asphalt mixtures of these respective granulometric range.

For the specimens molded with the asphalt mixtures designed for the granulometric ranges B ($AMD_B$) and C ($AMD_C$), the average values of the volumetric parameters VC and VFB and the mechanical parameters Marshall Stability, Marshall Flow, Diametral Tensile Strength (TS) and Resilient Modulus (RM) were determined. These values were compared with the limiting values established by DNER ES 385/1999 [27] for such parameters (except for RM), as shown in Figure 3.



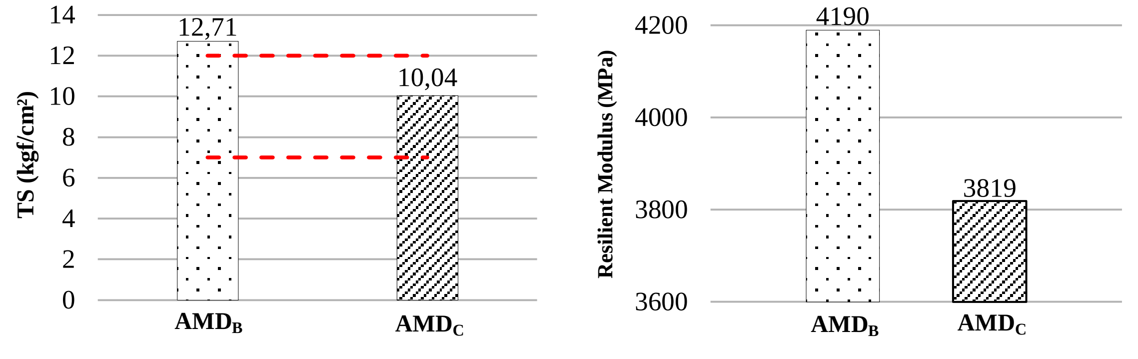
(a) Marshall Stability

(b) Marshall Flow



(c) Voids Content (VC)

(d) Voids Filled with Bitumen (VFB)



(e) Diametral Tensile Strength (TS)

(f) Resilient Modulus (RM)

**Figure 3:** Volumetric parameters (VC, VFB), Marshall parameters (Stability, Flow), TS and RM for the asphalt mixtures designed for each of the granulometric ranges B (AMD$_B$) and C (AMD$_C$).

The values of the volumetric parameters (VC and VFB) of the asphalt mixtures met the requirements of the DNER ES 385/1999 specification [27]. However, it should be noted that AMD$_B$ presented the Marshall Flow value 0.35 mm higher than the maximum limit established in this same specification. Yet, it is worth mentioning that this parameter is no longer used [39] and the DNIT ES 031/2006 specification [40] is applied only to asphalt concrete mixtures without the addition of polymers.This new specification does not even make reference to the Marshall Flow parameter.

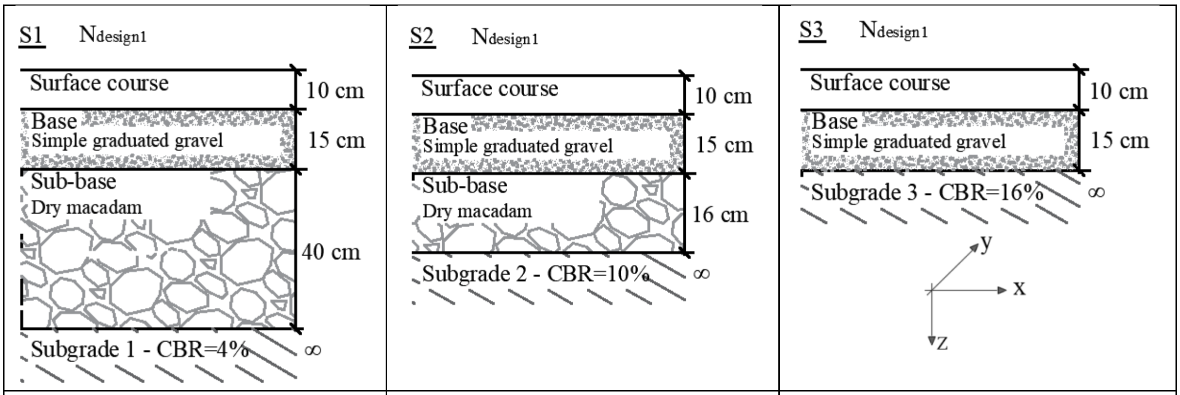
From the analysis of the results of TS, it is noted that the values obtained for the AMD$_C$ asphalt mixtures are in the range of 7 kgf/cm² to 12 kgf/cm², in accordance with the DNER ES 385/1999 specification [27]. In turn, the AMD$_B$ mixture specimens exceeded the upper limit foreseen by them, but their results were close to the maximum allowed limit.

It is known that the asphalt binder provides flexibility and elasticity to bituminous mixtures, while the coarse aggregate provides greater stiffness to them. Based on this, the AMD$_B$ mixtures were, the ones with the highest percentage of coarse aggregate and also presented values of Marshall Stability, TS and RM superior to those of the AMD$_C$ mixtures.

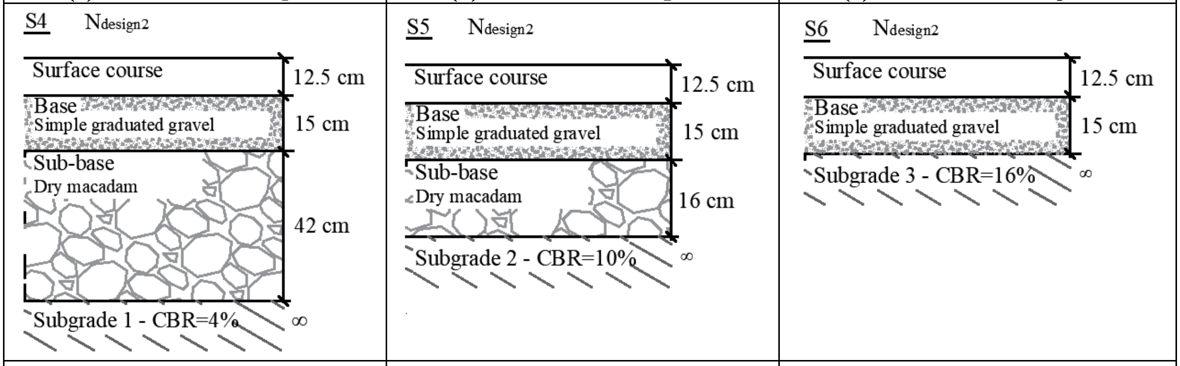
The values of the volumetric (VC and VFB) and mechanical (Marshall Stability and TS) parameters of the AMD$_B$ and AMD$_C$ mixtures meet the limits established by DNER ES 385/1999 [27]. Thus, such asphalt mixtures can be used as an surface course in pavement structures.

### 3.2 Mechanistic-empirical analysis

Figure 4 reports the six asphalt pavement structures designed in accordance with the empirical method of DNIT [3] and by considering the different values of "N$_{design}$" and the three subgrade soils, as shown in Table 3. The structures with "N$_{design1}$" and "N$_{design2}$" presented, 10 cm and 12.5 cm of surface course, respectively.



(a) Structure 1 - “$S_1$” (b) Structure 2 - “$S_2$” (c) Structure 3 - “$S_3$”



(d) Structure 4 -“$S_4$” (e) Structure 5 -“$S_5$” (f) Structure 6 -“$S_6$”

**Figure 4:** Asphalt pavement structures designed according to the DNIT method [3].

From the simulation of these structures in the Elsym 5 software and with the application of the axle loads “$L_1$”, “$L_2$” and “$L_3$”, the maximum horizontalspecific strain of traction ($\varepsilon_{tmax}$) were determined in the lower edge of the surface course. In structures in which asphalt layer thickness is 10 cm (“$S_1$”, “$S_2$” and “$S_3$”), the values $\varepsilon$tmax were determined at point A (0; 0; 9.99), and in structures whose asphalt layer thickness is 12.5 cm (“$S_4$”, “$S_5$” and “$S_6$”), the values $\varepsilon$tmax were determined at point B (0; 0; 12.49)

Figures 5 and 6 represent the results of $\varepsilon$tmax corresponding to $AMD_B$ ($SC_1$) and $AMD_C$ ($SC_2$) asphalt mixtures, respectively.

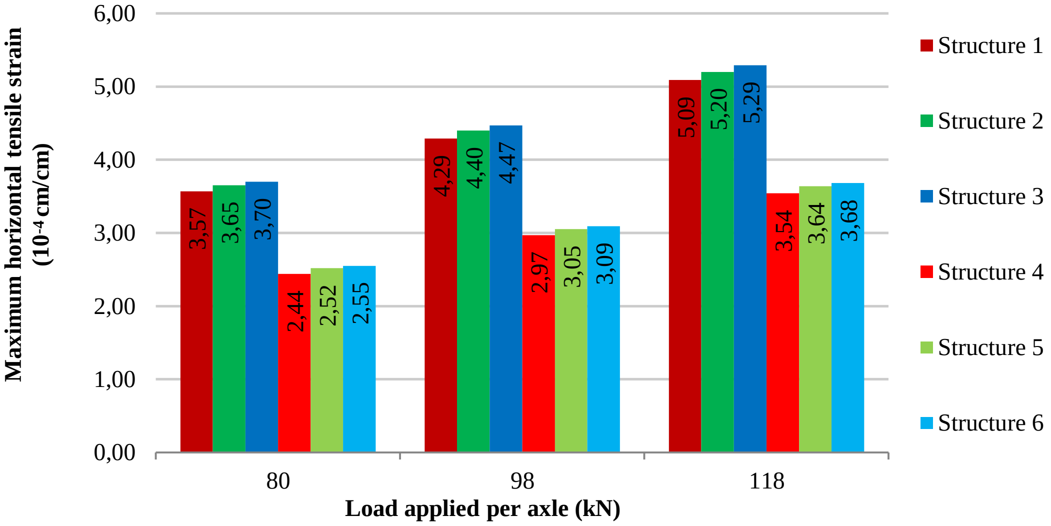


**Figure 5:** Results of the maximum horizontal tensile strain in the lower edge of the surface course corresponding to $AMD_B$ ($SC_1$).

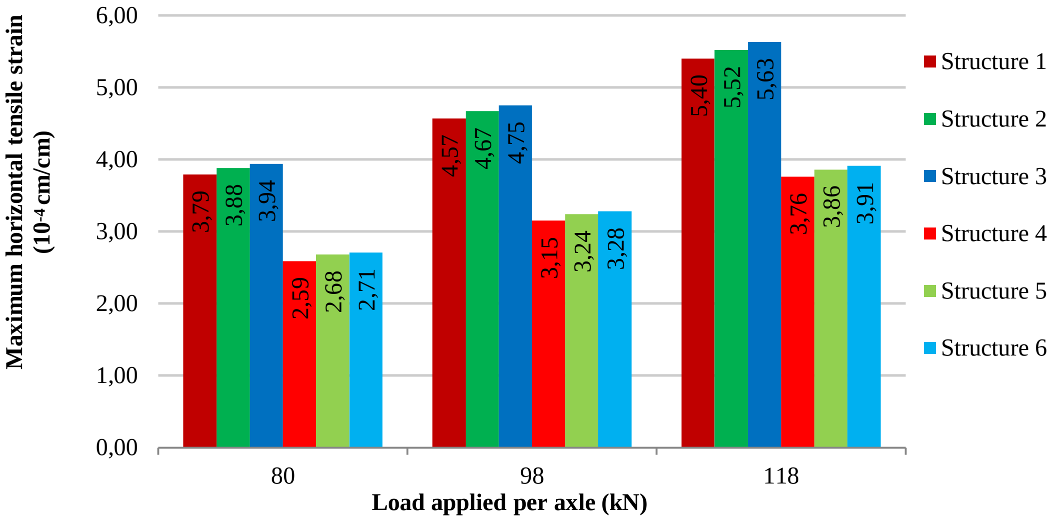


**Figure 6:** Results of the maximum horizontal tensile strain in the lower edge of the surface course corresponding to $AMD_C$ ($SC_2$).

It should be noted that the εt values for the “$S_1$”, “$S_2$” and “$S_3$” structures are, on average, approximately 19.80% higher than those presented by the “$S_4$”, “$S_5$” and “$S_6$” structures, respectively. Such behavior is explained by the difference of 2.50 cm between the thicknesses of the surface course of each structure, since those with greater thickness presented lower strain values.

Regardless of the applied load, the “S3” and “S6” structures presented the worst performance in relation to the εt value. In both cases, the absence of the sub-base layer caused an increase in stresses in the top of the subgrade, which explains the increase in tensile strains in the lower edge of the surface course. The εt value at the bottom of the asphalt layer was higher in structures with a higher applied load per axle. The 20% increase in load (118kN) in relation to the maximum allowed value provided increases of about 18.80% in the strains of the surface course, which corresponds to both asphalt mixtures of the design under study. This is an evidence of the prejudicial structural implications that increased load on the pavement design process can cause.

It was observed that the values of etmáx of the structures whose surface course corresponds to $AMD_C$ (RM = 3819MPa) (Figure 6) were on average 6.20% higher than the values presented by the structures whose surface course corresponds to $AMD_B$ (RM = 4190MPa) (Figure 5). A possible explanation for this fact is the greater resilient stiffness of $AMD_B$, considering that the RM and the said strain present an inverse proportionality.

The values of “Nf” according to the application of the fatigue performance models proposed by PINTO [7], DNER [8], FHWA [9] and FRANCO [10] to each of the possible scenarios, are presented in Figures 7 and 8 for the parameters “$N_{design1}$” and “$N_{design2}$”, respectively. Due to the great amplitude between the values of “$N_f$” and “$N_{design}$”, the graphs were plotted on a logarithmic scale for better representation.

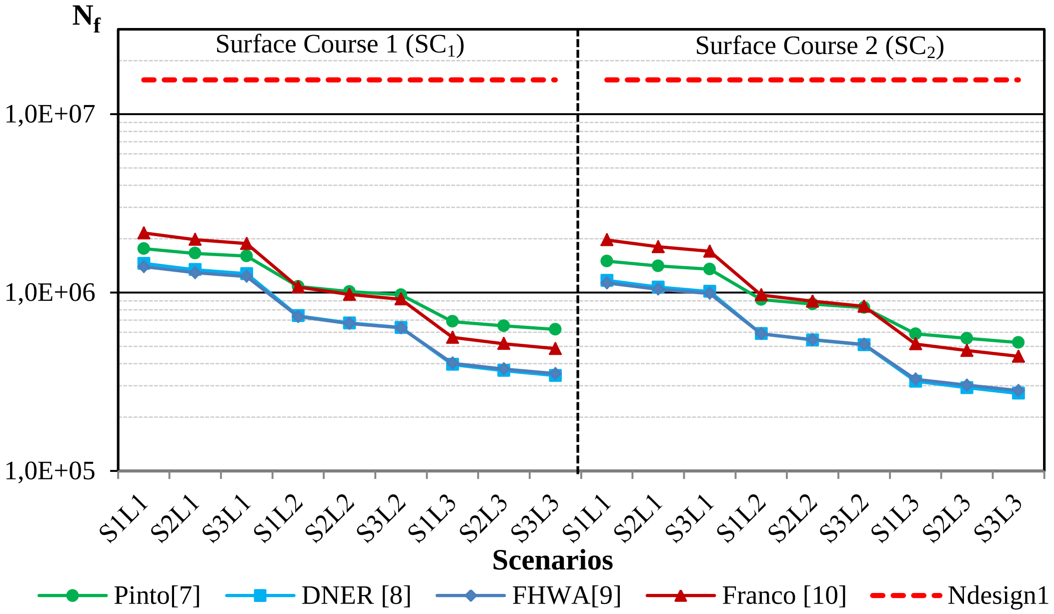


**Figure 7:** "$N_f$" values obtained by the different fatigue models for the "$S_1$", "$S_2$" and "$S_3$" structures.

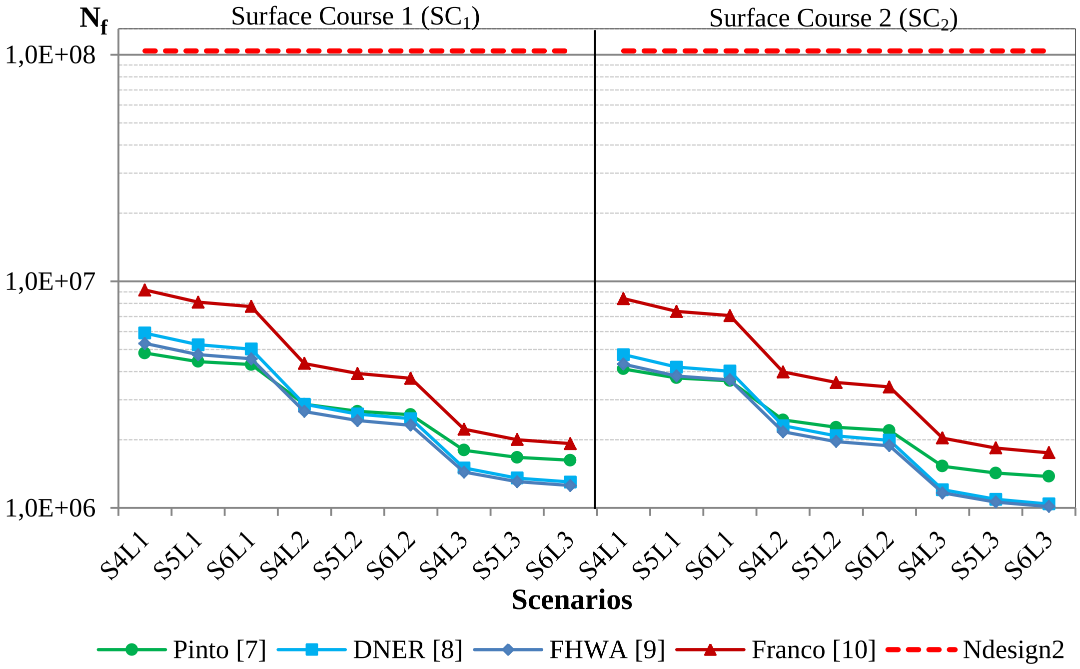


**Figure 8:** "$N_f$" values obtained by the different fatigue models for the "$S_4$", "$S_5$" and "$S_6$" structures.

According to the results presented in Figures 7 and 8, it is noted that, regardless of the value "$N_{design}$" and the applied fatigue model, the number of load repetitions for the standard axis of 8.2 tons is lower than the number of load repetitions for the standard axis of 8.2 tons considered in the designing of the pavement structure by the empirical method of DNIT [3] ("$N_f$" <<<< "$N_{design}$"). Thus, the structure would not support the expected loads and fatigue cracking would occur in the surface course before completing the 10-year design life.

The proximity of the "$N_f$" values determined by the application of the fatigue performance models proposed by DNER [8] and FHWA [9] is verified for both "Ndesign" bands and in all scenarios. In this regard, it is worth noting that the models proposed by DNER [8] and FHWA [9] are the only ones that relate the "$N_f$" value to the of the maximum horizontal tensile strain value in the lower edge of the surface course, as shown in Table 4.

The values of "$N_f$" established by the application of the model proposed by FRANCO [10] are higher and are different in relation to most of the values established by the other models under study. This fact occurs mainly in scenarios with the application of the lowest load values that, as observed in Figures 5 and 6, cause lower strains in the surface course and consequently higher values of "N", due to the ratio of inverse proportionality between the value of "N" and the "$\varepsilon_t$". It is noteworthy that, in the determination of the values of "N", the model proposed by FRANCO [10], different from the other ones, considers the inverse of the RM of the susface course and raises the term referring to "εt" to a higher power than those presented by the other fatigue models

It is noted that, regardless of the applied model, when comparing the values of "Nf" of the structures constituted by "$SC_1$" (RM = 4190 MPa) and "$SC_2$" (RM = 3819 MPa), the SC1 structures (with a greater Resilience Modulus) have higher "Nf" values than those of "$SC_2$" structures and it is possible to infer that the highest values of surface course Resilience Module provide higher "N" values.

It is observed that the values of the "$N_f$" defined by the application of the model proposed by PINTO [7], compared with those defined by the application of the other fatigue performance models, undergo less change with the variation of the load applied in the pavement structure and with the thickness of the surface course. This demonstrates that the "$\varepsilon_t$" influence less on the value of the "$N_f$" defined by the application of the model proposed by PINTO [7] when compared to the other models studied.

Thus, in light of the previous observations, it appears that the fatigue performance models proposed by DNER [8] and FHWA [9] are the most recommended for the mechanistic analysis of the designing of the investigated asphalt pavement structures.

In order to determine the "$N_f$" value that is at least equal to "Ndesign" for all the selected pavement structures, either for considering "$N_{design1}$" or "$N_{design2}$", it was necessary the redesign the surface course. Since the objective was to verify the thickness of the surface course determined by the fatigue performance forecasting models between the scenarios, the redesign process was performed only for the scenarios of the structures with "$SC_1$" surface course, with a greater Resilient Modulus, as shown in Figure 9 for "$N_{design1}$" and "$N_{design2}$".

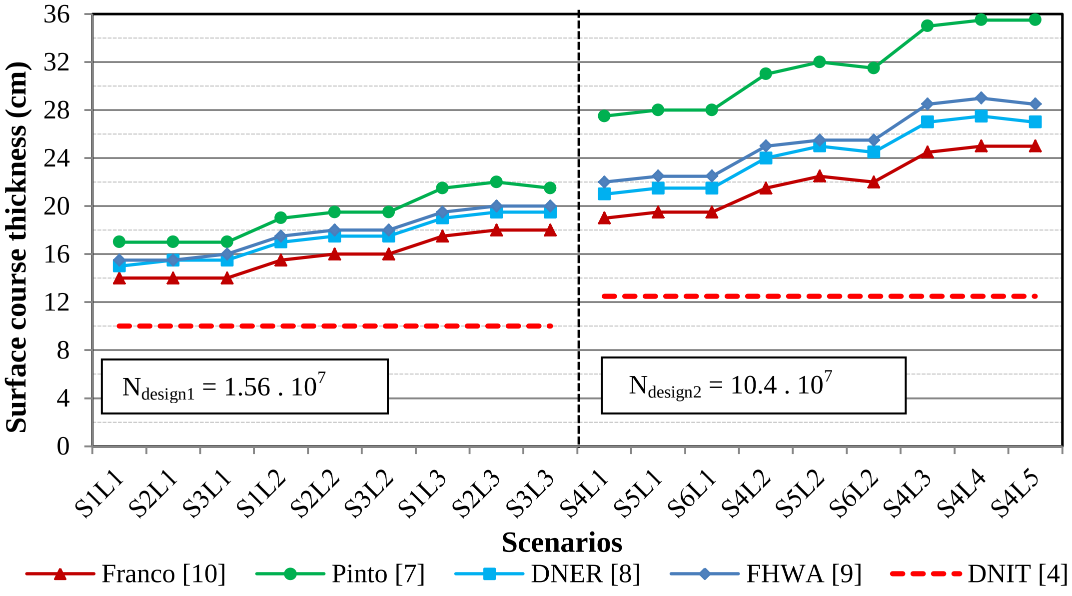


**Figure 9:** Redesigning the thickness of the surface course for structures made up of "$SC_1$".

In view of the results presented in Figure 9, it is noted that the difference between the thickness of the asphalt layer defined by the DNIT method [6] and those defined by the fatigue performance prediction models varies according to the values of the "$N_{design}$", the applied load and the subgrade soil Resilience Modulus. Thus, it was possible to infer that the factors that most influenced the redesign of the thickness of the asphalt layer, in descending order, were the "$N_{design}$", followed by the applied load and the subgrade soil Resilience Modulus.

It is observed, from the application of the models for predicting the number of allowable requests for fatigue cracking proposed by DNER [8] and FHWA [9], that the values of the thicknesses of the surface course for both models are approximately equal.

From the results, it is observed that the model proposed by FRANCO [10] is the less conservative one, especially when compared to the model from PINTO [7]. The thicknes variations in the thickness of the surface course according to these models were about 3.0 cm. However, when comparing the thicknesses of the surface course of the models between the structures with different "$N_{design}$" values, it is noted that the thicknesses determined by the model from PINTO [7] do not differ from those obtained by applying the models proposed by DNER [8] and FHWA [9], as occurs for "$N_{design2}$".

There is also a variation in determining the thickness of the surface course as to the application of different fatigue models, especially in scenarios where the applied load values are higher. In these cases, the trends in the results obtained by the model proposed by PINTO [7] is significantly different from those according to the models proposed by FHWA [9], DNER [8] and FRANCO [10].

## 4. CONCLUSIONS

Based on the results presented in this study, it can be concluded that fatigue performance and asphalt layer design varied according to fatigue models applied in different scenarios. However, the sensitivity of performance to surface course fatigue determined by these models, given the variations of the factors studied, was approximately the same. Thus, it is concluded that the fatigue of asphalt layer is more sensitive to the variation of the thickness of the asphalt layer than to the variation of the applied load value, followed by the subgrade soil Resilience Modulus.

Among the fatigue performance models applied in this study, it is concluded that those proposed by DNER [8] and FHWA [9] are the most recommended for mechanistic-empirical analysis of asphalt pavement structure design, since they resulted in "$N_f$" and surface course thickness values approximately equal.

It is observed the limitation of the empirical method of design the DNIT [4], evidencing the importance of the adoption of mechanistic-empirical methods, in which the Resilience Modulus and the Poisson coefficient of the materials of the structural layers of the pavement are considered. It is also emphasized the need to carry out, through weighing stations installed in stretches of the Brazilian paved road network, more rigorous and efficient inspections regarding the maximum load applied on the pavements.

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