

Impact of layer thickness variations on pavement performance and life-cycle cost

Impacto da variabilidade da espessura das camadas no desempenho de pavimentos e no custo do ciclo de vida

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ABSTRACT

This study evaluates the impact of asphalt pavement layer thickness variations on structural performance and life-cycle costs. Factors such as materials quality, traffic load, and construction precision affect durability, with layer thickness deviations causing earlier failures and increased life cycle costs. This research combines pavement performance prediction and life-cycle cost analysis (LCCA) of pavements designed by the California Bearing Ratio (CBR) method and the Brazilian mechanistic-empirical (M-E) method. Eight scenarios, including designed and as-built structures, were analyzed based on field-extracted cores. The Monte Carlo method simulated thickness variability, assessing its effect on performance and costs over 120 months, focusing on cracking evolution. The results showed that M-E designs are initially more expensive but offer superior long-term cost-benefit by reducing maintenance. A 10% increase in layer thickness resulted in less maintenance and 63% cost reduction, highlighting economic advantage of better designs. The analysis can include other factors and other M-E methods.

RESUMO

Este estudo avalia o impacto das variações na espessura das camadas de pavimentos asfálticos sobre o desempenho estrutural e os custos do ciclo de vida. Fatores como a qualidade dos materiais, o carregamento do tráfego e a precisão construtiva afetam a durabilidade, sendo que desvios na espessura das camadas provocam falhas mais precoces e aumento dos custos ao longo do ciclo de vida. A pesquisa combina a previsão do desempenho dos pavimentos com a Análise de Custo do Ciclo de Vida (ACCV) de estruturas dimensionadas pelo método do Índice de Suporte Califórnia (CBR) e pelo método mecanístico-empírico (M-E) brasileiro. Foram analisados oito cenários, incluindo estruturas de projeto e executadas, com base em testemunhos extraídos em campo. O método de Monte Carlo foi utilizado para simular a variabilidade das espessuras, avaliando seus efeitos sobre o desempenho e os custos ao longo de 120 meses, com foco na evolução do trincamento. Os resultados indicaram que os projetos M-E apresentam custo inicial mais elevado, porém oferecem melhor relação custo-benefício no longo prazo, em função da redução das intervenções de manutenção. Um aumento de 10% na espessura das camadas resultou em menor necessidade de manutenção e em uma redução de custos de 63%, evidenciando a vantagem econômica de projetos mais robustos. A análise pode ser ampliada para incluir outros fatores e diferentes métodos M-E.



1. Introduction

The suitable long-term performance of an asphalt pavement depends on the complex interaction of several variables, such as the adequacy of the materials used, the predicted traffic over the design life, and the conceived structure itself (layer thicknesses). Generally, the construction of pavement layers must follow specific guidelines related to physical properties (such as air voids), geometric properties (such as thicknesses), and mechanical properties (such as stiffness), for which tolerance limits are established

to restrict their variability. Although all phases of a pavement structure project exhibit some level of variation, the construction is considered to have significant influence.

The pavement layer thicknesses resulting from the structural design phase may also vary due to construction errors, contributing to the development of premature failures. Furthermore, variability can be related to the reliability of the pavement performance (Liu, 2015). Rajbongshi (2014) defines reliability as the probability of not exceeding a certain level of pavement distress during the designed service life. Thus, the less precise the construction phase of a pavement structure is, especially if there are deviations from the design values, the lower the guarantee that the pavement will meet stakeholders' expectations.

Sultan & Joo (2000) demonstrate that proper compaction of layers during construction plays a crucial role, not only as a quality control measure but also by directly impacting costs and structural bearing capacity. Complementarily, Mazumder et al. (2021) indicate that ensuring uniformity in the compaction of layers can reduce life cycle costs by up to 62% due to the extended fatigue life. Both studies emphasize that strictly following design specifications, for layer thickness and degree of compaction, is fundamental to avoid early maintenance and to achieve economically efficient solutions.

The optimization of pavement layer thickness has been discussed as an important aspect to improve structural performance and to reduce costs throughout the pavement life. Dong & Huang (2012) investigated the effectiveness and cost-benefit of asphalt pavement rehabilitation, concluding that thicker layers provide superior long-term performance, with a lower rate of deterioration following rehabilitation and maintenance activities. Although initial implantation costs were higher, maintenance expenses were significantly reduced over time. The authors' findings corroborate the study presented herein, which also observed that variations in layer thickness directly influence total costs, confirming that optimized layers, especially thicker ones, can ensure longer-lasting performance and lower maintenance costs.

Similarly, Rajbongshi (2014) presented a reliability-based methodology for the design of asphalt pavements, aiming to optimize the thicknesses of asphalt and granular layers. The referred study demonstrated that precise adjustments to thicknesses can result in economically efficient solutions, minimizing maintenance costs. The optimization of these thicknesses allows for a balance between initial implantation costs and extended durability, a strategy also confirmed by the results presented in the present research. In a similar way, the study by Sakhaeifar et al. (2013) on perpetual asphalt pavements highlighted that adopting thicker layers with greater fatigue resistance can reduce the need for maintenance interventions by more than 55 years. This type of pavement, designed to bear higher loads for longer periods, resulted in lower total costs compared to conventional pavements, reinforcing the importance of design strategies that promote longevity and economic performance.

In that context, this research aims to estimate the impact of variability in pavement layer thicknesses on pavement performance, as well as to quantify its economic impact, by combining mechanistic-empirical (M-E) pavement performance estimation with life-cycle cost analysis. For this purpose, the variations observed in a monitored experimental test site were used as a reference to outline the different scenarios analyzed: (i) the pavement structure originally designed considering an empirical method based on the California Bearing Ratio (CBR) parameter; (ii) a first structure (Core 1) observed in a field-monitoring; (iii) a second structure (Core 2) observed in the same field-monitoring; and (iv) a redesigned structure considering observations from the field and a ME design method based on the prediction of cracked area over time. Comparisons were made considering the different scenarios in terms of the time need for maintenance and the corresponding estimated costs for implantation and maintenance of such pavements.

2. Literature review

2.1. Variation on pavement layers thicknesses

Adequate compaction of asphalt layers during construction plays a critical role in pavement performance, as it directly affects in-place density and, consequently, the final thickness of the layers Hughes

(1989). Deviations in compaction quality may lead to unintended variations in thickness, influencing the mechanical response and durability of the pavement structure.

Discrepancies between designed and constructed layer thicknesses increase uncertainty in pavement response and negatively affect reliability, even when thicknesses exceed design values (Réus & Fontenele, 2021; White, 2022). Increased variability reduces the likelihood that pavement distress levels remain within acceptable limits during the design life. In addition, incompatibilities between layer stiffnesses caused by thickness deviations may create localized regions of reduced structural capacity, which act as weak points and initiate pavement distress (Sandoval & Orobio, 2013; Toan et al., 2023).

Several studies have quantified the effect of construction variability on pavement performance. Patel & Thompson (1998) showed that reducing the standard deviation of asphalt layer thickness significantly increases fatigue life, while increasing variability leads to substantial reductions in fatigue resistance, particularly for thinner layers. Dalla Valle & Thom (2020) also identified a strong correlation between thickness variability and fatigue life, even when construction tolerances are met, and observed that variations in asphalt and subbase thickness influence predicted rutting. More recently, Toan et al. (2023) demonstrated that variability in layer thicknesses and stiffness has a pronounced impact on permanent deformation and pavement reliability, with upper layers playing a dominant role.

Previous investigations using ground penetration radar (GPR) and destructive coring techniques have consistently shown that variability in pavement layer thicknesses is common and can significantly affect structural performance and design reliability. Attoh-Okine & Roddis (1994) reported standard deviations on the order of 10 mm for asphalt and base layers and nearly 20 mm for subbase layers, values that have been corroborated by subsequent studies (Selezneva, Jiang & Mladenovic, 2002; Jiang et al., 2003; Dinegdæ, Ahmed & Erlingsson, 2023). Although most long-term pavement performance sections present coefficients of variation below 10%, extreme cases with substantially higher variability have also been documented.

Comparisons between as-designed and as-constructed pavement structures further indicate systematic differences in layer thicknesses. Mladenovic et al. (2003) observed that thinner designed layers tend to be constructed thicker than specified, while thicker designed layers are often underbuilt. These deviations can generally be represented by normal probability distributions, reinforcing the importance of accounting for construction variability in pavement performance assessment and reliability-based design.

2.2. Life-cycle cost analysis

Life cycle cost analysis (LCCA) principles have been proposed over the past decades as a tool to assist in the selection of pavement projects from various alternatives (AAPTP, 2006). In addition, it contributes to the evaluation of major maintenance and rehabilitation (M&R) strategies (Babashamsi et al., 2016) and supports decision-making in multi-year management plans in infrastructure (Carneiro, Durán & Oliveira, 2023). LCCA has been widely adopted to predict potential cost impacts related to different maintenance and construction techniques Feitosa & Oliveira (2018). This method not only embraces the analysis of initial costs but also considers all costs and benefits during the pavement service life and might be extended from the stages of extraction of raw materials to its recycling and disposal (Cardoso et al., 2024; Oliveira et al., 2024).

According to Xu & Tsai (2012), the concept of LCCA applied to pavement engineering has the objective of covering all relevant costs throughout the pavement structure life cycle — from construction to operation — including M&R activities. These costs can be divided into three categories: (i) managing costs, which account for the initial construction investment and expenses for repairs, rehabilitation, and maintenance; (ii) user costs, which are related to fuel consumption, tire wear, time of travel, vehicle depreciation, traffic congestion, discomfort, and potential accidents; and (iii) environmental costs, which include greenhouse gas emissions (GGE) during the construction and the maintenance phases, as well as soil and water pollution due to water runoff in the surface layer. In general, the application of LCCA has been studied for evaluating alternative pavements using different materials under the same traffic and climatic conditions (Oliveira et al., 2024), considering different pavement failure criteria (Carneiro,

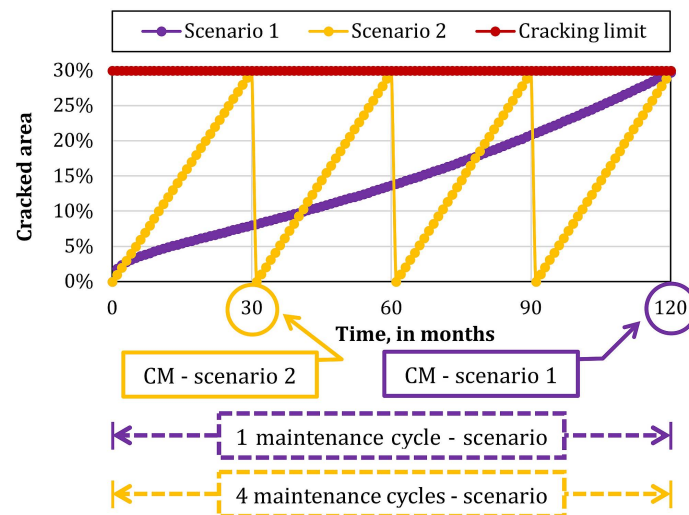


Figure 1 • Identification of critical months and maintenance cycles in two hypothetical pavement scenarios

Durán & Oliveira, 2023), by means of various M&R strategies (Karnikowski, 2019), and in view of different assumptions within the method adopted (Mandapaka *et al.*, 2012; Zhang *et al.*, 2021; Cardoso *et al.*, 2024).

The integration of pavement performance prediction and LCCA has proven to be a relevant strategy for assessing the technical and economic feasibility of pavement structures throughout their service life. Cardoso *et al.* (2024) and Oliveira *et al.* (2024) demonstrated that the use of mechanistic-empirical methods allows the simulation of pavement behavior based on structural parameters, such as the cracked area of the asphalt surface layer. Based on this approach, the authors referred to this technique as s-LCCA, in which the index “s” represents the incorporation of structural parameters into LCCA. The aforementioned studies indicated that, although pavements with thicker layers present higher initial costs, they may provide long-term savings due to reduced maintenance requirements. In this context, the present paper adopts the same technique proposed by these authors and therefore uses the s-LCCA nomenclature throughout the study, in order to highlight the consideration of structural parameters in economic analyses.

For the implementation of the s-LCCA technique and the calculation of costs associated with construction and maintenance, equivalent construction and maintenance costs are defined, obtained through the joint consideration of the assumptions adopted in the methodology.

The s-LCCA technique uses the Critical Month (CM) parameter, defined as the month in which the simulated structures reach the cracked area percentage threshold, set in this study at 30%. As a maintenance and rehabilitation strategy, and in order to ensure comparability among the analyzed scenarios, cold milling with total and immediate reconstruction of the surface layer was adopted, maintaining the same thickness as the original condition whenever the CM was reached. In the simulations, a new maintenance cycle was implemented at each occurrence of the CM, fully restoring the structural and functional conditions of the pavement. It was assumed that the underlying layers maintain their structural capacities throughout the service life. Further details on this technique can be found in Oliveira *et al.* (2024) and Cardoso *et al.* (2024).

Figure 1 illustrates the evolution of cracking in two hypothetical pavement scenarios. In Scenario 1, the critical month is reached only in month 120, resulting in a single maintenance cycle at the end of the analysis period. In Scenario 2, the critical month is reached in month 30, requiring four maintenance cycles within the same comparison interval of 120 months.

3. Materials and methods

The methodological approach adopted in this study was structured into three main stages. The first stage comprised field activities, including the monitoring of an experimental pavement section, extraction

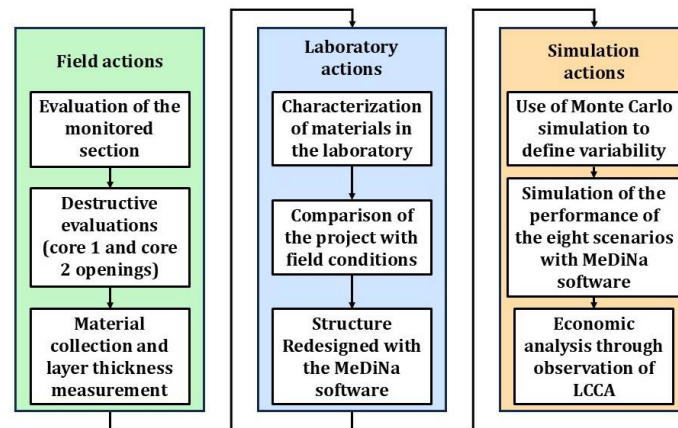


Figure 2 • Summary of methodological steps: field, laboratory and computer simulation actions

of pavement cores, collection of materials, and measurement of layer thicknesses. The second stage involved laboratory characterization of the collected materials, comparison between as-designed and as-constructed conditions, and the redesign of pavement structures using a mechanistic-empirical approach. The third stage consisted of numerical simulations and analyses, encompassing the representation of construction-related variability, pavement performance prediction, and economic evaluation through life-cycle cost analysis (Figure 2).

3.1. Analysis scenarios

For comparison purposes, eight scenarios were analyzed. Scenario 1 represents the pavement structure under the original design conditions (as designed), considering the materials and layer thicknesses specified in the official road project. This structure was designed using the traditional Brazilian empirical method based on the CBR, in which layer thicknesses are defined as a function of the subgrade support capacity and the expected accumulated traffic loading, represented by the number of equivalent standard axle loads (ESALs), which was calculated by means of the USACE method and resulted in 1.07×10^8 . In this approach, empirical relationships and design charts are used to determine the required structural configuration, aiming to ensure adequate performance by preventing excessive deformation and shear failure of the subgrade over the design life. As an empirical method, it does not explicitly account for mechanistic responses such as stresses, strains, or damage evolution over time.

After construction, two field cores were extracted, revealing that the design was not fully replicated in the field, as the constructed layer thicknesses differed from those specified in the project. In addition, laboratory testing showed that the materials used in the embankment and subbase did not correspond to the design specifications, presenting better mechanical properties. Then, scenarios comprising these different field material conditions were considered.

Scenarios 2 to 5 represent the mentioned as-constructed conditions. Scenarios 2 and 3 are associated with Core 1 and reproduce the layer thicknesses observed in the field, considering, respectively, the field-measured material properties and the materials originally specified in the project. Scenarios 4 and 5 follow the same approach for Core 2, with Scenario 4 adopting field materials and Scenario 5 adopting project materials.

The Brazilian mechanistic-empirical pavement design method (MeDiNa) was applied to develop additional scenarios. Scenarios 6, 7, and 8 were defined assuming the same materials specified in the original project, as if the structure were redesigned using the same input data adopted in the CBR-based design. Scenario 6 represents a redesigned pavement structure targeting a cracked area of 30% after 10 years of service life. As the version of MeDiNa used in this study (version 1.1.5.0) does not provide the monthly evolution of permanent deformation for each individual layer, presenting this parameter in a layer-by-layer manner only for the final analysis month (120 months) and, for the remaining periods, only

Table 1 • Pavement layers thicknesses for different configurations

Scenario	Layer thickness (mm)				
	Asphalt surface	Binder course	Surface treatment	Chemically stabilized base layer	Soil-aggregate subbase layer
1 (As designed)	50	60	25	150	150
2 (As constructed, core 1, with field materials of the subbase layer and embankment)	40	50	25	150	270
3 (As constructed, core 1, with project materials)	40	50	25	150	270
4 (As constructed, core 2, with field materials of the subbase layer and embankment)	45	50	25	150	270
5 (As constructed, core 2, with project materials)	45	50	25	150	270
6 (Redesigned)	71	150	25	150	150
7 (Redesigned reduced thickness)	64	135	25	150	150
8 (Redesigned increased thickness)	78	165	25	300	300

the total accumulated deformation of the structure, fatigue cracking was adopted as the sole performance indicator in this study. To assess the impact of thickness variability, Scenarios 7 and 8 were proposed, considering typical execution-related variability obtained from data of six asphalt layers constructed in the same geographical area. For each case, within-lot variability was estimated by pooling individual lot variances, following the approach proposed by [Burati Jr. \(2006\)](#) (Equation 1):

$$s_p^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2 + \dots + (n_k - 1)s_k^2}{n_1 + n_2 + \dots + n_k - k} \quad (1)$$

where s_p^2 : pooled estimate for the within-lot process variance; s_i^2 : variance for lot i ($i = 1, 2, \dots, k$); n_i : number of values for lot i ; and k : number of lots in the project.

To determine the typical variability of the process, a Monte Carlo simulation was performed. Due to the small sample size, a triangular probability distribution was assumed for the standard deviations of thickness ([Thomopoulos, 2017](#)). Thus, it was established that the characteristic variability value would be the sample mode after 100,000 iterations, resulting in a value of 0.49 cm for the investigated pavements. Taking the designed pavement (Scenario 1, with a surface layer of originally 5.0 cm) as a reference, the typical variability of the process is approximately 10% of the design thickness. For this reason, this percentage was adopted for the construction of Scenarios 7 (decreasing surface layer thickness) and 8 (increasing surface layer thickness). This is compatible with the literature ([Attoh-Okine & Roddis, 1994](#); [Selezneva, Jiang & Mladenovic, 2002](#); [Jiang et al., 2003](#); [Dinegdae, Ahmed & Erlingsson, 2023](#)) that reported variability for other regions, disregarding extreme variations, expected in cases of greater sample sizes.

In Scenario 7, the thicknesses of the asphalt surface layer and the binder course were reduced by 10%, while the base and subbase layers were maintained at 15 cm. In Scenario 8, the asphalt surface layer and the binder course thicknesses were increased by 10%, and the base and subbase thicknesses were raised from 15 cm to 30 cm. [Table 1](#) shows the layer thicknesses for the eight scenarios.

All materials were characterized in the laboratory, except for the surface treatment, whose stiffness value was obtained from the design software database (1,000 MPa). Variations in subbase thickness observed among the analyzed sections indicate that pavement performance may differ spatially. The thickness of the surface treatment was assumed as 25 mm.

Post-construction surveys focused on verifying layer thicknesses and characterizing the materials. Core extractions at two locations (Core 1 and Core 2) revealed discrepancies between as-designed and as-constructed thicknesses, which may affect pavement performance. Subbase and subgrade materials (embankment layer) were tested in the laboratory using triaxial tests to determine resilient modulus and permanent deformation parameters, which were subsequently used as input data for the simulations.

Field activities were conducted on a 300 m-long monitored section. [Figure 3](#) illustrates the monitored section and the position of the extracted cores, based on Google Earth imagery, as well as the field

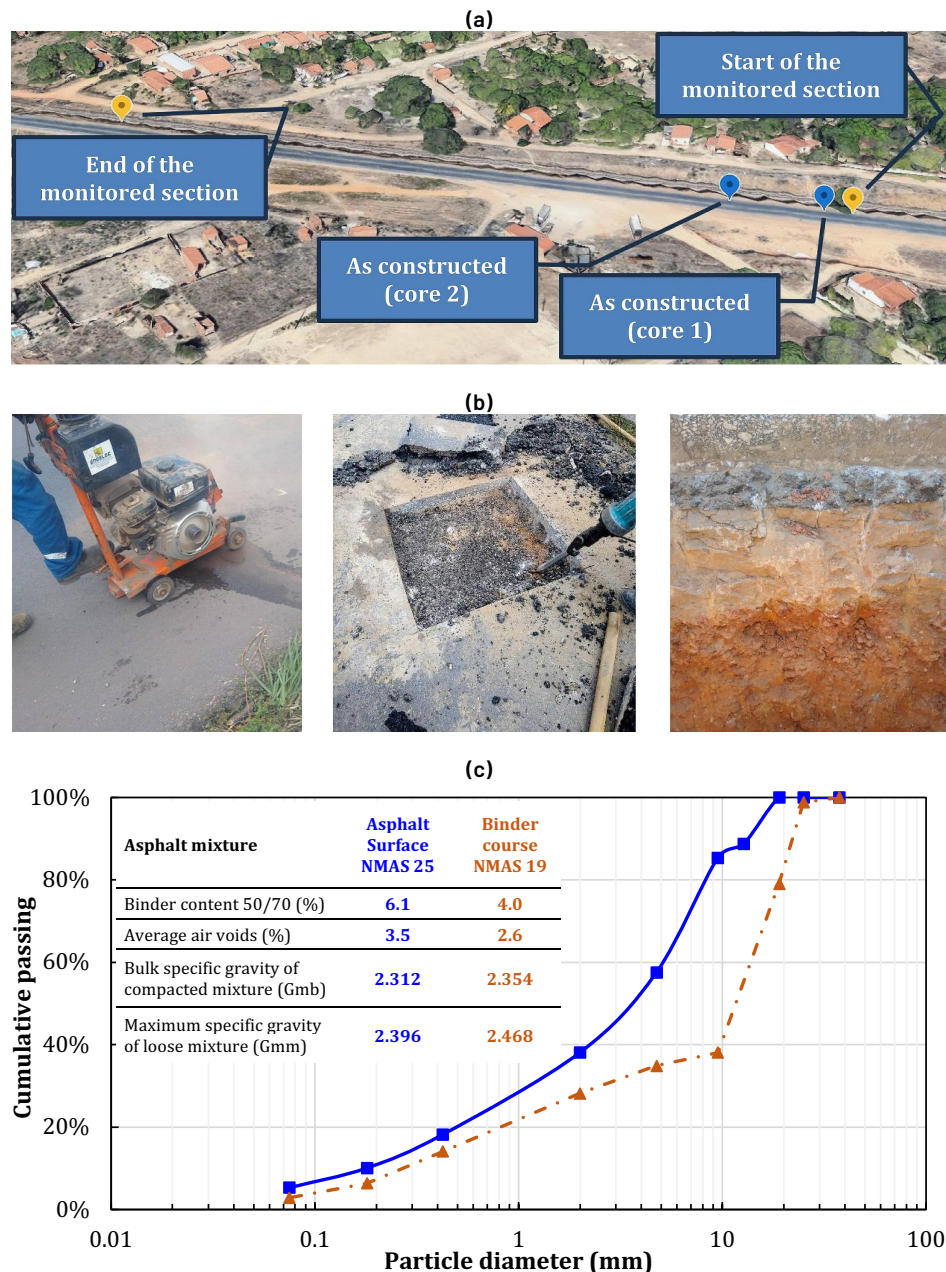


Figure 3 • Illustration of the monitored section, position of the extracted cores (a); core extraction procedure (b); and mixtures characterization (c)

coring procedure and the visual characterization of the materials, and the characterization results of the extracted asphalt mixtures.

The characterization results of the extracted asphalt surface and binder course indicated air void contents of 3.5% and 4.6%, associated with binder contents of 5.5% and 4.0% for mixtures with nominal maximum aggregate sizes (NMAS) of 25 mm and 19 mm, respectively. The bulk specific gravity of the compacted mixtures was 2,312 kg/m³ and 2,354 kg/m³, while the maximum specific gravity (Gmm) of the loose mixtures was 2,396 kg/m³ and 2,468 kg/m³. These results correspond to the asphalt surface and binder course, respectively.

It is emphasized that the cores collected in this study (Cores 1 and 2) are not intended to statistically represent construction variability along the evaluated segment. Their use is aimed at defining plausible as-built conditions, allowing comparison with the design condition. The variability considered in the analysis was treated in a parametric manner, through the definition of scenarios and the incorporation

Table 2 • Input parameters for pavement simulations

Type of layer	Input parameters		
	Stiffness	Fatigue	Permanent deformation
Asphalt layers	Resilient modulus in the diametral compression test at 1 Hz and 25 °C	Fitted coefficients for the fatigue Wöhler curve from the diametral compression test	Flow number (only as an acceptance criteria of the asphalt mixture)
Granular and soil layers	Fitted coefficients of the triaxial resilient modulus modeling	—	Fitted coefficients of the constitutive model by Guimarães (2009) from the triaxial test
Chemically stabilized layers	Sigmoidal resilient modulus according to the compressive strength test	Fitted coefficients of the indirect tensile fatigue test	—

of thickness variations in the simulations, including Monte Carlo-based approaches, in line with the objective of the study to evaluate the influence of these variations on pavement performance and life-cycle cost.

3.2. Simulation of the pavement structure performance

The Brazilian software MeDiNa was used to perform mechanistic-empirical (M-E) design and evaluation of asphalt pavement structures. The software computes stresses and strains through multilayer elastic analysis and uses these results to predict pavement distresses, namely fatigue cracking and permanent deformation, expressed as percentage of cracked area and rut depth. MeDiNa assumes materials to be linear elastic, isotropic, and homogeneous, obeying Hooke's law, with finite layers over a semi-infinite subgrade.

The required input parameters include:

- (i) Poisson's ratios and resilient moduli (RM) of all layers and the subgrade.
- (ii) Permanent deformation parameters of granular and soil layers, modeled according to [Equation 2](#) and fitted to laboratory test results [Guimarães \(2009\)](#):

$$\epsilon_p^{esp} (\%) = \psi_1 \cdot \frac{\sigma_3^{\psi_2}}{\rho_0} \cdot \frac{\sigma_d^{\psi_3}}{\rho_0} \cdot N^{\psi_4}, \quad (2)$$

where ϵ_p^{esp} (%): specific permanent deformation; σ_3 : confining stress; σ_d : deviator stress; ψ_1, ψ_2, ψ_3 , and ψ_4 : calibration coefficients; ρ_0 : reference stress (atmospheric stress); and N : number of load application cycles.

- (iii) Fatigue cracking parameters of asphalt layers, defined by [Equation 3](#) and obtained from indirect tensile fatigue tests ([DNIT, 2018e](#)).
- (iv) Resilient modulus (RM) and fatigue parameters of chemically stabilized layers, determined following DNIT 181/2018-ME and DNIT 434/2021-ME ([DNIT, 2018d, 2021](#)) (Equations 4 and 5).

Surface treatment or anti-reflection crack layers were not assigned damage resistance parameters, as they are assumed not to contribute to the structural response of asphalt pavements. All input parameters are summarized in [Table 2](#).

Mechanical characterization included repeated load triaxial tests to determine RM ([DNIT, 2018d,a](#)) and permanent deformation parameters ([DNIT, 2018d,c](#)). The permanent deformation test comprised 150,000 load cycles to support damage prediction in the M-E analysis. Six stress combinations ($\sigma_3 \times \sigma_d$, in kPa) were applied to each analyzed mixture: (40 × 40), (40 × 120), (80 × 80), (80 × 240), (120 × 240), and (120 × 360), at a loading frequency of 2 Hz. The coefficients obtained from fitting the model proposed by [Guimarães \(2009\)](#) were used as input in the simulations.

The RM test, recommended by DNIT standard 135/2018-ME (DNIT, 2018b), was conducted for the asphalt mixtures stiffness determination while the indirect tensile fatigue cracking resistance test was conducted as per MeDiNa (Brazilian software) requirements. The diametral compression fatigue test was conducted following the guidelines established in DNIT 183/2018-ME (DNIT, 2018e). For this study, the stress levels considered were 30, 40, and 50% of the indirect tensile strength (ITS) values of the materials analyzed. The representation of the fatigue curve, known as the Wöhler curve, is done through log-log plots, which model the fatigue behavior by obtaining a linear regression equation between the number of cycles at failure and the loading level (Equation 3):

$$N_f = k_1 \cdot \varepsilon_t^{k_2}, \quad (3)$$

where N_f : number of load cycles at failure; ε_t : tensile strain observed at the beginning of the test, mm/mm; and k_1 and k_2 : calibration coefficients.

The RM of the layers with stabilized materials decreases with the accumulation and increase of fatigue damage, and the mathematical representation used in MeDiNa is done through the sigmoidal function (DNIT, 2018b). The sigmoidal function uses two parameters to define its shape. These are the constants A and B, requested as input data for the properties of the stabilized materials. By default, MeDiNa uses the constants $A = -4$ and $B = 14$, which have been defined by Ayres (1997) for the AYMA program (Equation 4):

$$RM = RM_{\min} + \frac{RM_{\max} - RM_{\min}}{1 + e^{-4+14Di}}, \quad (4)$$

where, $RM_{\min}$: minimum resilient modulus, representing the lowest value that RM can reach when the damage is maximum ($Di = 1$); $RM_{\max}$: maximum resilient modulus, representing the initial value of RM when the damage is zero ($Di = 0$); and Di : damage index, which ranges from 0 to 1, reflecting the accumulation of fatigue damage in the stabilized material layers, with 0 indicating no damage and 1 indicating complete damage.

The fatigue damage model considered in the MeDiNa software is based on the relationship (%RF) between the tensile stress in the bottom fiber of the layer and the flexural tensile strength of the material at 28 days (Equation 5):

$$N_{fad} = 10^{(k_1 + k_2 \cdot \%RF)}, \quad (5)$$

where, N_{fad} : number of load cycles until failure; k_1 and k_2 : calibration coefficients; and %RF: ratio between the applied tensile stress and the tensile strength of the material, expressed as a percentage.

In terms of resilient modulus (RM), the stiffness values of the materials used in all eight scenarios were 4,650, 6,114 and 1,000 MPa, for the asphalt surface layer, the binder course and the surface treatment, respectively. The RM and fatigue parameters of the asphalt materials used in the simulations and stiffness values for the base, subbase, and embankment materials are presented in Table 3. It is highlighted that for the asphalt surface layers, for the binder course and for the base layer, the material properties used as input data were the same for both the project conditions (as-designed) and field conditions (as-built). The materials (soil-aggregate subbase layer and remaining structure) were obtained at two distinct stages: (i) during the construction (Project conditions), and (ii) after construction, with field sampling [Field conditions (Cores 1 and 2)]. The RM and permanent deformation parameters were experimentally determined in the laboratory for materials collected at both stages. Therefore, both design and field conditions were represented by experimental data, enabling a consistent comparison between pre- and post-construction materials.

3.3. Economic analysis

For the s-LCCA, equivalent implantation and maintenance costs of the eight pavement scenarios were estimated using the Brazilian reference cost system for infrastructure construction (SICRO), published by the National Department of Transport Infrastructure (DNIT), considering data from the state of

Table 3 • Mechanical properties and constitutive model parameters of the pavement materials used in the simulations

(a) RM and fatigue parameters of the asphalt materials used in the simulations					
Layer	RM (MPa)	Fatigue curve coefficients			
		k_1	k_2		
Asphalt surface	4,650	5.14E-7	-2.44		
Binder course	6,114	3.36E-10	-3.16		

(b) Sigmoidal resilient modulus and fatigue parameters of the base layer						
Layer	Sigmoidal modulus curve coefficients				Fatigue curve coefficients	
	$RM_{\max}$ (MPa)	$RM_{\min}$ (MPa)	A	B	k_1	k_2
Chemically stabilized base layer	753	64	-4.00	14.00	17.14	-19.61

(c) RM and permanent deformation parameters of the granular materials used in the simulations								
Layer	RM (MPa)				Permanent deformation model coefficients			
	k_1	k_2	k_3	k_4	ψ_1	ψ_2	ψ_3	ψ_4
<i>Project conditions</i>								
Soil-aggregate subbase layer	646	0.537	-0.160	-0.001	0.016	-0.487	1.633	0.142
Remaining structure	584	0.300	-0.270	-0.600	0.032	-0.988	2.799	0.122
<i>Field conditions (Cores 1 and 2)</i>								
Soil-aggregate subbase layer	1,749	0.460	-0.290	0.080	0.011	-0.158	1.534	0.086
Remaining structure	668	0.420	-0.270	-0.060	0.022	-1.209	1.337	0.009

Ceará. Costs of asphalt materials were obtained from the National Agency of Petroleum, Natural Gas, and Biofuels (ANP) for the northeast region. Physical and constructive parameters and unit costs adopted in the analyses are presented in Table 4. To keep the evaluation focused on project-related elements, economic factors such as cash flow, discount rates, and price variations (e.g., inflation) were not considered, although the approach can be adapted to other contexts.

The costs refer to a 1,000 m-long and 7.0 m-wide pavement section, assuming uniform materials and structure along this length, which allows proportional scaling to longer sections. The authors acknowledge that the s-LCCA is context-specific and based on Brazilian costs and assumptions; therefore, broader applicability would benefit from sensitivity analyses addressing key inputs such as analysis period, unit costs, and maintenance strategies.

The milling costs considered in this study were calculated based on the thicknesses of the asphalt layers in each scenario analyzed. The unit costs presented in Table 4 were applied according to the structural configuration of each pavement, ensuring consistency between the adopted maintenance strategy and the cost estimation.

The costs used in this study were obtained from the SICRO database of January 2023. In this version, the costs of acquisition and transportation of asphalt materials are not fully included in the service item used and were therefore considered separately in the cost composition presented in Table 4.

In all eight pavement scenarios, the predicted percentage of cracked area (%CA) was adopted as the sole performance indicator, consistent with the mechanistic-empirical approach implemented in MeDiNa (Franco & Motta, 2020). For all scenarios, the maintenance strategy consisted of cold milling of the entire asphalt surface layer followed by reconstruction using the same materials as in the initial phase. Simpler maintenance actions, such as crack sealing, were not considered. Over the 10-year analysis period, maintenance was triggered whenever the fatigue cracking limit of 30% CA in the asphalt surface layer was reached. After each maintenance cycle, the pavement was assumed to return to its initial structural and functional condition, initiating a new service cycle.

To determine the timing of maintenance activities more precisely, the progression curve of %CA was

Table 4 • Physical, constructive, and cost parameters used in the pavement cost evaluation

(a) Physical and constructive parameters used in cost evaluations

Parameters	Units	Values
Pavement structure length	m	1,000.00
Pavement structure width	m	7.00
Pavement structure area	m ²	7,000.00
Bulk specific gravity (surface course)	kg/m ³	2,396
Bulk specific gravity (binder course)	kg/m ³	2,468
Bulk specific gravity (double surface treatment)	kg/m ³	2,300
Bulk specific gravity (prime coat emulsion)	kg/m ³	980
Bulk specific gravity (tack coat emulsion)	kg/m ³	980
Application rate (prime coat)	L/m ²	1.0
Application rate (tack coat)	L/m ²	1.0
Asphalt content (surface course)	%	5.5
Asphalt content (binder course)	%	4.0
Average haul distance	km	5.0

(b) Unit costs used in the calculation of the implantation costs of the pavement structures analyzed

Items/materials	Units	Unit cost (BRL)*
Surface course (asphalt concrete)	t	200.26
Tack coat	m ²	0.28
Binder course (asphalt concrete)	t	195.85
Double surface treatment	m ²	5.86
Prime coat	m ²	0.41
Base (cement-treated crushed stone)	m ³	264.66
Subbase (fine, silty or clayey soil)	m ³	11.54
Asphalt cement acquisition (asphalt courses)	t	3,678.99
Asphalt emulsion acquisition (tack coat)	t	2,755.39
Asphalt emulsion acquisition (prime coat)	t	2,397.57
Asphalt cement transportation (asphalt courses)	t.km	1.98
Asphalt emulsion transportation (tack coat)	t.km	1.98
Asphalt emulsion transportation (prime coat)	t.km	1.98
Milling of the surface course	m ³	57.81
Milling of the binder course	m ³	50.37
Milling of the double surface treatment	m ³	88.11
Reclaimed asphalt pavement (RAP) transportation (surface + binder + double surface treatment courses)	t	3.14

* 1 BRL $\approx$ 0.19 USD at the time this study was carried out

used to identify the month at which the 30% CA threshold was reached, defined as the critical month (CM). The ratio between the total service life (120 months) and the CM was then calculated to estimate the number of maintenance cycles over the analysis period.

MeDiNa allows two types of analyses based on a user-defined pavement structure: (i) a design option, in which layer thicknesses are adjusted to achieve approximately 30% CA at 120 months; and (ii) an evaluation option, in which the structure is kept unchanged and only damage progression is simulated. In this study, only Scenario 6 was designed using the first option, while all other scenarios were evaluated using the second option.

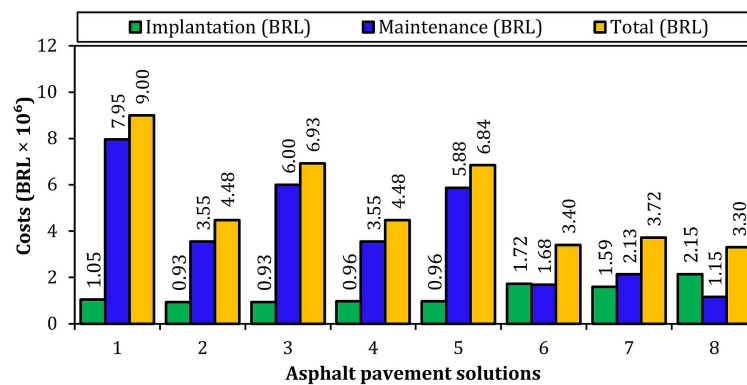
4. Discussion of results

Table 5 shows the critical months, number of maintenance cycles, and the implantation, equivalent maintenance, and equivalent total costs of the eight scenarios. Figure 4 is dedicated to illustrating only the equivalent costs.

For comparability purposes among the analyzed scenarios, an additional procedure was adopted in cases where the critical month occurs after the 120-month analysis horizon. In such situations, a partial maintenance cycle was implemented within the analysis period, in order to ensure that all structures

Table 5 • Critical months (CMs), number of maintenance cycles, and equivalent implantation, maintenance and total costs

Scenarios	CMs	Maintenance cycles	Implantation (10 ⁶ BRL)	Maintenance (10 ⁶ BRL)	Total (10 ⁶ BRL)
1 (As designed)	13.6	8.8	1.05	7.95	9.00
2 (As constructed, core 1, with field materials of the subbase layer and embankment)	25.5	4.7	0.93	3.55	4.48
3 (As constructed, core 1, with project materials)	15.1	8.0	0.93	6.00	6.93
4 (As constructed, core 2, with field materials of the subbase layer and embankment)	27.1	4.4	0.96	3.55	4.48
5 (As constructed, core 2, with project materials)	16.2	7.4	0.96	5.88	6.84
6 (Redesigned)	123.8	1.0	1.72	1.68	3.40
7 (Redesigned reduced thickness)	83.8	1.4	1.59	2.13	3.72
8 (Redesigned increased thickness)	191.3	0.6	2.15	1.15	3.30

**Figure 4** • Graphical representation of the equivalent implantation and maintenance costs of the eight scenarios

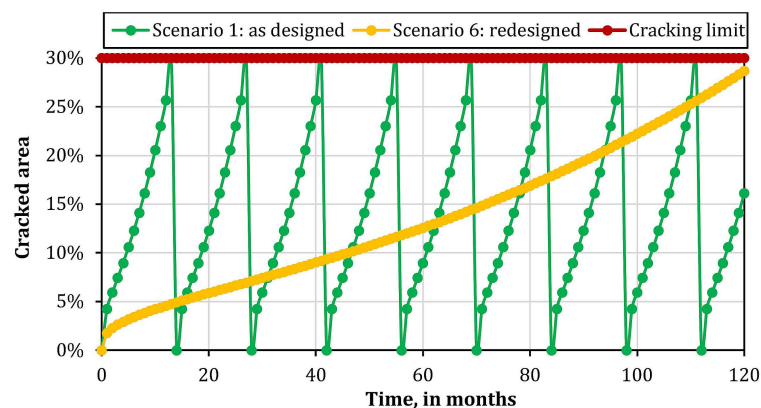
reached the end of the 120 months under the same structural condition (%CA = 0%).

This approach allows for the standardization of the final pavement conditions, ensuring that the comparison among scenarios is performed on equivalent bases, without differences in the structural condition at the end of the period unduly influencing the cost and performance results.

Scenario 1 (as designed) presented an equivalent implantation cost (1.05×10^6 BRL) 11.4% and 8.6% higher than those associated with Core 1 (Scenarios 2 and 3, 0.93×10^6 BRL) and Core 2 (Scenarios 4 and 5, 0.96×10^6 BRL), respectively. This difference is explained by the fact that some granular materials employed in the field exhibited better mechanical properties than those assumed in the design, as confirmed by laboratory testing (Table 3). For instance, the coefficient k_1 of the triaxial resilient modulus model for the subbase layer was almost three times higher, which tends to increase resilient modulus values and field performance. It is important to note that Scenarios 2 to 5 represent as-built conditions and were not obtained through any design method, being solely influenced by construction deviations.

When equivalent maintenance and total costs are considered, Scenario 1 exhibited the highest values. Although the project was not strictly replicated in the field, thinner layers combined with better materials resulted in locally more resistant structures, which positively affected maintenance needs. In contrast, the structures designed using the mechanistic-empirical method (Scenarios 6, 7, and 8) presented thicker asphalt surface layers (42%, 28%, and 56%, respectively) and binder courses (150%, 125%, and 175%, respectively), as well as doubled base and subbase thicknesses in Scenario 8. These characteristics increased equivalent implantation costs, with Scenario 8 costing approximately twice as much as Scenario 1. Nevertheless, equivalent maintenance and total costs of the M-E-designed scenarios were substantially lower, making Scenario 1 the least efficient solution, with equivalent total costs almost three times higher than those of the other scenarios.

A comparison between the field-observed scenarios shows that equivalent implantation costs were similar for Scenarios 2 and 3 (Core 1) and Scenarios 4 and 5 (Core 2), with slightly higher values for Core 2 due to an additional 5 mm in the asphalt surface layer. This increase significantly reduced equivalent

Figure 5 • Cracking occurrences and maintenance cycles in Scenarios 1 and 6

maintenance and total costs, indicating that more robust structures, characterized not only by increased asphalt layer thickness but also by improved mechanical behavior of the underlying layers, lead to higher initial equivalent costs but generate medium- and long-term savings for the analyzed conditions.

Regarding the scenarios designed with MeDiNa, the 10% reduction in asphalt concrete thickness in Scenario 7, relative to Scenario 6, shortened pavement lifespan and increased equivalent maintenance and total costs. Conversely, the 10% increase in asphalt thickness combined with thicker base and subbase layers in Scenario 8 reduced maintenance requirements, positioning it as the most cost-effective alternative among the analyzed scenarios.

Figure 5 illustrates that the fatigue cracking limit was reached eight times in Scenario 1, whereas it was not reached in Scenario 6, highlighting the greater number of maintenance cycles required by the structure with poorer performance.

Overall, the results are strongly influenced by the number of maintenance cycles required by each solution. Mechanistic-empirical design methods, such as MeDiNa, tend to produce more robust pavements with higher equivalent implantation costs but significantly reduced maintenance demands. Future studies should include field validation to assess the consistency of the proposed scenarios with the performance of constructed pavements.

5. Conclusions

This paper analyzed the effects of asphalt layer thickness variability on pavement performance and long-term costs by combining mechanistic-empirical (M-E) performance prediction with life-cycle cost analysis. Eight scenarios were evaluated, including one structure designed using the empirical CBR-based method, four as-constructed structures with material properties from design specifications or field testing, and one M-E-designed structure with two thickness variations reflecting field-observed variability and literature data. Based on the analyses, the following conclusions can be drawn:

- The proposed life-cycle cost assessment method proved adequate, as it relies on official Brazilian unit costs for services and materials. The approach can be readily adapted to other regions by adjusting unit costs and incorporating additional economic parameters when necessary.
- Pavement structures designed using the Brazilian empirical method based on CBR resulted in less robust and less durable solutions, requiring frequent maintenance interventions and leading to the highest life-cycle costs among the analyzed scenarios.
- Variations in layer thickness and material quality directly affect pavement service life and maintenance needs. Thinner layers than those specified in the design increase maintenance frequency and life-cycle costs for the investigated case.
- Redesigned structures with a 10% increase in layer thickness and reinforced base layers were the most efficient, requiring fewer maintenance cycles and resulting in lower overall costs over the 10-year analysis period. These results indicate that combining pavement design with life-cycle cost analysis can lead to more cost-effective solutions.

- The use of mechanistic-empirical design methods leads to more robust and durable pavements. Although these solutions increase equivalent initial construction costs, they significantly reduce life-cycle equivalent costs by decreasing maintenance requirements.
- The combined application of mechanistic-empirical design and life-cycle cost analysis enhances predicted pavement performance and supports more effective strategic planning of infrastructure investments.
- Advanced design methods must be accompanied by adequate construction quality and material control to ensure that predicted performance levels are achieved. Controlling construction variability is essential for both technical performance and economic efficiency.
- The results should be interpreted with caution, as they are limited to the scenarios evaluated. Future sensitivity analyses are required to assess the influence of key input parameters and to support broader generalizations.

Regarding research limitations, this study did not include in-service fatigue cracking data from the monitored section to validate the mechanistic-empirical predictions. Future work should incorporate systematic field monitoring to assess model accuracy. In addition, the analyses were based on local cost data and fixed economic assumptions; therefore, wider applicability will require sensitivity analyses of the most influential life-cycle cost parameters.

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CRediT authorship contribution statement

Jardel Andrade de Oliveira: Conceptualization, Methodology, Investigation, Formal analysis, Funding acquisition, Writing – original draft, Writing – review & editing; *Iuri Sidney Bessa*: Formal analysis, Data curation, Funding acquisition, Writing – original draft, Writing – review & editing; *Jorge Luis Santos Ferreira*: Formal analysis, Data curation, Writing – review & editing; *Lucas F. A. L. Babadopulos*: Formal analysis, Funding acquisition, Writing – review & editing; *Juceline Batista dos Santos Bastos*: Methodology, Formal analysis, Data curation, Funding acquisition, Writing – original draft, Writing – review & editing; *Beatriz Chagas Silva Gouveia*: Writing – review & editing; *Jorge Barbosa Soares*: Supervision, Funding acquisition, Writing – review & editing.

Use of artificial intelligence-assisted technology

The authors declare that the ChatGPT tool was used exclusively to assist in the translation of sections of the manuscript. The authors assume full responsibility for the content of the article, including its technical accuracy, the interpretation of the results, and the final version of the text.

Competing interests statement

No competing interests have been declared with regard to this paper or its contents.

Data availability statement

All data generated or analyzed is included in this article and in the supplementary information files.

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