Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 8, No. 07, July, 2022

Mechanical Analysis of Subgrades of Road Pavements in Life Cycle Assessment

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Received 01 April 2022; Revised 25 June 2022; Accepted 28 June 2022; Published 01 July 2022

Abstract

When evaluating the sustainability of a construction project, it is important to verify the influence of climate uncertainty and the depletion of natural resources that permeate the strategies to make infrastructure possible, especially those associated with the transportation sector, which have great potential to generate environmental impacts. Thus, the objective of this study is to evaluate the effect that subgrade material variation, which constitutes highway pavements with flexible surfacing, can generate in the Life Cycle Assessment (LCA) of these infrastructures. For this purpose, pavements that had the same materials and thicknesses for the execution of the base (gravel soil-NG') and the subbase (clay soil LG'), but with subgrades composed of different types of tropical soils, classified as lateritic and non-lateritic, were proposed. The combination of these elements enabled the elaboration of pavements with different service lives and atmospheric emissions. The scope of the study included the phases of extraction and production of the inputs necessary to build the roadway envisioned in each scenario, as well as the construction phase itself, considering the operation of construction equipment. The LCA focused on the emission of greenhouse gases (GHGs) and the quantity of primary energy employed in the phases considered. It was concluded that the materials used in this study have similar mechanical behavior, and therefore the results of the design of the thicknesses of the asphalt overlay were close and consequently result in similar energy consumption and greenhouse gas emissions.

Keywords: Life Cycle Assessment; Pavements; Road; Mechanical.

1. Introduction

The twentieth century has been marked by the rising consumption of non-renewable energy and the increased extraction of natural resources. To a great extent, emitting pollutant gases that contaminate the air, degrading environments, destroying ecosystems and intensifying greenhouse effects that promote global warming. There are numerous conflicts and little consensus on norms and behaviors to be effectively adopted to equate environmental protection and human development, due to the reports of the Intergovernmental Panel on Climate Change (IPCC), there is an attempt to reach a global scientific agreement on the effects of climate change.

Related to environmental climate change impacts and mitigation costs, Brazil is one of the best placed countries in the climate regime due to its energy matrix, scientific research, economic robustness, productive capacity, and natural resources, among other factors. However, this system evaluation tool, disassociated from other devices, favors the simple compensation of emissions by the capture of Greenhouse Gases (GHG), which does not encourage, by itself, a search

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http://dx.doi.org/10.28991/CEJ-2022-08-07-012

for greater efficiency. In this sense, it should be noted that Brazil is, simultaneously, among the ten largest emitters of GHG [1]. Thus, due to the harmful effects that global warming can cause on ecosystems, intensified by the release of GHGs into the atmosphere, commitments aimed at reducing emissions of such pollutants have been made, including for the transportation sector [2].

It is noteworthy that transportation is essential to modern life. Despite being indispensable to society in different social and economic activities, it causes multiple environmental impacts. Transportation infrastructure demands huge engineering work, and its operation is energy intensive, mostly coming from fossil fuels. Like any large-scale work, the construction of infrastructure for transportation systems directly interferes with the environment of a region as it occurs, occupies the physical space and causes deforestation, expropriation, earthworks, and other interferences that modify the physical, biotic, and anthropic environments of the region [3, 4].

According to Crawford et al. (2008) [5], there are numerous methods for assessing the environmental impacts of a given product or service. In the transportation sector, there has been an exponential increase in research and evaluation to determine the environmental impacts generated by all transportation infrastructure life cycle stages, from extraction to final disposal or recycling of materials [6].

In this sense, LCA has gained prominence as the most appropriate tool to accomplish this type of task since it is capable of the qualification, quantification, and comparison of the studied structures. Ultimately, this type of capability allows projects' implementation to be considered offensive to the environment [7]. According to IPEA (2014) [8], even with the wide dissemination of LCA in the international scenario, this tool is little disseminated and applied in Brazil. There are still a few studies found in the literature covering life cycle research in transportation infrastructure. The design of a pavement aims to calculate and verify the thicknesses and match the layers of materials so that the service life of the pavement corresponds to the project period. In other words, supporting the stresses generated by traffic and distributing these loads to the subgrade so that they can withstand them. Thus, the mechanical properties of this layer are of fundamental importance for the establishment of an adequate pavement since it works as the foundation.

In the mechanical aspect, pavement had significant advances in the field of structural layer design and material characterization. According to Silva (2009) [9], it is a consensus that pavement should be designed to predict their behavior closer to reality. As consequence, several factors are known to affect the predictive capacity of pavement design and mechanical performance. Given the evolution of pavement design projects, the mechanistic empirical models have the purpose of gathering tests and techniques correlating the data of the materials, environmental conditions, and the traffic of the sections to be paved, in order to define the thicknesses of the layers and verify if they meet the conditions of stresses and strains imposed in the design [10].

This study aims to evaluate the mechanical effects of subgrade materials that compose highway pavements with flexible surface courses and the respective influences on life cycle assessment (LCA) of these infrastructures, based on the method proposed by Nascimento et al. (2020) [11] and Gouveia et al. (2021) [12]. Therefore, this study does not verify the effects on the permanent deformations of subgrade. This article is organized in six sections including this introduction. Second section contains a brief review of the relevant literature on LCA, highway pavement design of and their resilient modulus. Third section presents the materials and methods used, and fourth describes the case study. Fifth section presents the results and discusses of simulations of the pavement designed by the MeDiNa method for different types of subgrades, cracked area criteria and forecasts of the environmental impacts. Sixth section contains our final considerations.

2. Bibliographic Review

2.1. LCA

Ideally, an environmental impact analysis produced by a system, under the life cycle approach, should address from the stages of obtaining raw materials to the end of the service life of this system [2]. According to Li et al. (2019) [13], an LCA receives different names according to the life cycle stages considered. Thus, when evaluating the stages from the extraction of inputs to the final disposal of waste and considers the recycling of the elements that made up the system, it is titled from Cradle to Cradle. The scope of the stages is partial, such as from Cradle to Gate when the stages of exploration and production of inputs, production of materials and construction are considered, and from Cradle to Grave when they cover the stages of the previous type, adding the stages of use/operation, maintenance/rehabilitation and end of life, without considering the total recycling of the elements that made up the system. According to Andrade (2016) [2], the standard establishes general concepts, not particularizing specific techniques for each stage of evaluation or for a particular product/service.

The standards of ISO 14000 family define general requirements for conducting LCA (Table 1). The ISO 14040 [14] establishes rules for this assessment of environmental aspects and potential environmental impacts throughout the product/service life cycle, from the extraction of raw materials, through production, use, end-of-life treatment, recycling, and final disposal. In turn, ISO 14044 [15] standard guides organizations on improvements related to the management of activities in the environmental aspect and criteria for analysis of simulations.

Table 1. ISO standards series for LCA

Standard	Title
ISO 14040 (2006) [14]	Environmental Management - Life Cycle Assessment - Principles and Framework
ISO 14044 (2006) [15]	Environmental Management - Life Cycle Assessment - Requirements and Guidelines
ISO/TR 14047 (2012) [16]	Environmental management - Life cycle assessment - Illustrative examples on how to apply ISO 14044 to impact assessment situations
ISO/TR 14049 (2012) [17]	Environmental management — Life cycle assessment — Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis
ISO/TS 14071 (2014) [18]	Environmental management — Life cycle assessment — Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006

2.1.1. Structural Elements of LCA

LCA is a structured methodology for determining the types and quantities of impacts generated over the life cycle of a given system, i.e., from the extraction of natural resources to the use and final disposal of the product. This methodology consists of four main phases, as presented in ISO 14040 [14]:

- Definition of the study's objective and scope, with determination of its limits and level of detail;
- Inventory analysis which covers data collection and estimation of environmental impact;
- Evaluation of impacts which estimates the potential environmental impacts from the systemic considerations of the phases as a whole;
- Interpretation of results which provides the final conclusions of the results obtained in the inventory analysis and impact assessment phases.

In recent literature, the application of the method can be observed in the works of several authors, as shown in Table 2. There still is no consensus about the life cycle steps and the indicators to adopt, which depend on the scope and objective of each situation studied.

Table 2. Life cycle steps and environmental indicators examined in recent studies

Article/Theme	Step of the life cycle analyzed						Environmental indicators								
	Extraction/ production of materials	Transport of materials	Construction	Use	Maintenance	Recycling	Greenhouse gases (CO_2 eq)	Energy consumption (MJ)	Carbon dioxide (CO_2)	Carbon monoxide (CO)	Methane (CH_4)	Sulfur oxides (SO_x)	Nitrogen oxides (NO_x)	Inhalable particulate matter (PM10)	Nitrous oxide (N_2O)
Yu et al. (2014) [19]		•	•	•		•			•						
Araújo et al. (2014) [20]	•	•	•	•	•	•		•							
Santos et al. (2015a) [21]	•	•	•	•	•	•	•	•	•	•	•	•	•		•
Santos et al. (2015b) [22]	•	•	•	•	•	•	•	•	•	•	•	•	•		
Liu et al. (2015) [23]	•	•	•	•	•	•	•								
Mauro et al. (2016) [24]	•	•	•	•	•	•		•	•	•		•	•	•	
Chen et al. (2016) [25]	•		•	•		•			•	•	•	•	•	•	
Butt et al. (2016) [26]	•	•	•				•	•	•		•				•
Chong e Wang (2017) [27]	•	•	•	•	•	•	•	•							
Santos et al. (2017) [28]	•	•	•	•	•	•	•								
Moretti et al. (2017) [29]	•	•													
Liu et al. (2018) [30]	•		•				•								
Hong et al. (2018) [31]	•	•	•	•	•	•		•							
Gulotta et al. (2019) [32]	•	•	•	•	•	•		•							
Wang et al. (2019) [33]	•	•	•	•	•			•	•		•				
Cong et al. (2020) [34]	•	•	•		•	•		•	•	•	•	•	•		•
Vega et al. (2020) [35]	•	•	•				•	•							
Huang et al. (2021) [36]	•	•	•	•	•		•	•		•	•	•	•	•	•
Ma et al. (2021) [37]		•	•		•		•	•							
Bressi et al. (2022) [38]	•	•	•				•	•							
Salehi et al. (2022) [39]	•	•					•	•							

2.2. Pavement Design

Pavement design establishes the thickness and materials of each layer, which in turn are intended to resist, transmit and distribute the pressures resulting from traffic to the subgrade, avoiding deformations, ruptures or considerable surface wear. In addition to withstand all traffic loads, the pavement must offer users comfort and safety, which makes the design process extremely important in the construction of the road [40].

Good design elaboration should consider the characteristics of the materials, their behavior in relation to the application of the loads imposed by traffic, and how the structure will respond, besides considering all the local climate variations [41]. Given the evolution of pavement design projects, the empirical-mechanistic model is based on mathematical models obtained from regressions of laboratory test data, seeking to convert stresses, strains and displacements in order to make them compatible with the state of admissible stresses and strains for a given design life. As for empiricism, this is found in the calibration factor between the field and the laboratory [42].

In 2021, occurred a transition to a flexible pavement design Brazilian software a mechanistic-empirical method, MeDiNa. The procedures can be verified from the new Service Instruction (IS) specific for the preparation and implementation of projects based on the new flexible pavement design method - MeDiNa, the IS-247 discusses the preparation of geological-pedological studies, geotechnical studies, study of asphalt mixtures, presentation of reports and results and other relevant observations [43].

2.3. Pavement Mechanics

In the field of pavement mechanics, analyses are performed based on the theory of elasticity, considering the structure of the pavement as a multi-layered system [44]. The behaviour of stress (σ) and deformation, or strain (ε), is represented by the resilient modulus (M_R). The objective of determining the M_R is to reflect the real load conditions imposed on the soil layers of the pavement structure when submitted to the passage of traffic. Loading stresses simulation, strain and displacement can be performed in the laboratory using the equipment called repeated load triaxial that relates the vertical deflection stress and resilient strain. According to DNIT (2006) [45], the resilient strain modulus can be determined by the following Equation 1:

$$M_R = \frac{\sigma_d}{\varepsilon_r} \tag{1}$$

whereby M_R is the Resilient Modulus (MPa), σ_d is the repeated maximum axial deviator stress (σ_1 - σ_3) (MPa), ε_r is the recoverable axial deformation (mm/mm).

Medina and Motta (2015) [46] point out that for each soil the M_R can be expressed as a function of the stress states applied during the test. The most common of stresses and strain function models most often used in Brazil to obtain the resilient modulus are presented in Table 3.

Table 3. Resilient Modulus models obtained in the literature

Reference	Models	Equation
Seed et al. (1967) [47]	$M_R = k_1\ \theta^{k_4}$	(1)
Hicks (1970) [48] Barksdale and Hicks (1973) [49]	$^*M_R = k_1\ \sigma_3^{k_2}$ $^{**}M_R = k_2 + k_3\ (k_1 - \sigma_d)$ for $k_1 > \sigma_d$ $^{**}M_R = k_2 + k_4\ (k_1 - \sigma_d)$ for $k_1 < \sigma_d$	(2) (3) (4)
Allen e Thompson (1974) [50]	$M_R = k_1\ \theta^{k_2}$	(5)
Svenson (1980) [51]	$M_R = k_1\ \sigma_d^{k_2}$	(6)
May e Witczak (1981) [52]	$M_R = k_3 \left(\frac{\theta}{P_a}\right)^{k_4} \left(\frac{\sigma_d}{P_a}\right)^{k_5}$	(7)
Witczak e Uzan (1988) [53]	$M_R = k_1\ \theta^{k_2}\ \tau_{oct}{}^{k_3}$	(8)
Farrar e Turner (1991) [54]	$^{***}M_R = 30280 - 359\ S - 325\ \sigma_d + 237\ \sigma_c + 86\ PI + 107\ S_{200}$	(9)
Macêdo (1996) [55]	$M_R = k_1\ \sigma_3^{k_2}\ \sigma_d^{k_3}$	(10)
Lee et al. (1997) [56]	$^{***}M_R = \text{a}\ S_{u1\%}$	(11)
Parreira et al. (1998) [57]	$M_R = 4{,}5231\ E_0{}^{0{,}3158}\ \sigma_d^{-0{,}3436}\ \theta^{0{,}4393}$ $^{****}M_R = 0{,}8481\ E_0{}^{0{,}4559} + 1{,}1472\ \theta^{0{,}8630}$	(12) (13)
ARA (2004) [58] - MEPDG	$M_R = k_1 P_a \left(\frac{\sigma_d}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}\right)^{k_3}$	(14)
Franco (2007) [42]	$M_R = k_1\ \sigma_3^{k_2}\ \sigma_d^{k_3}\ \theta^{k_4}$	(15)

Notations: *Granular Soils; **Soils with cohesive behavior; M_R: Resilient Modulus in MPa; ***M_R: Resilient Modulus in *psi*; θ: bulk. stress; σ_3: confining stress; σ_d: deviator stress; P_a: atmospheric pressure; τ_{oct}: octahedral shear stress; σ_c: compressive stress; S: degree of soil saturation; PI: Plasticity Index; S_{200}: percentage passing N°200 sieve; a: constant as a function of deviation stress; $S_{u1\%}$: stress corresponding to 1% and axial strain in the simple compression test; E_0: initial tangent modulus; [d] Soils classified as sandy; k_1, k_2, k_3, k_4 e k_5: constants obtained by linear regression.

3. Methods and Materials

The proposal of this research aims to verify the effect pavement mechanical behavior of in their LCA, based on the proposal of Nascimento et al. (2020) [11] and Gouveia et al. (2021) [12]. The scope of the study encompasses the extraction and production phases of the inputs required for the implementation of the idealized road for each scenario, as well as the construction stage itself, considering the operation of the engineering equipment. The LCA narrows its focus on the emission of greenhouse gases (GHG) and the amount of primary energy covered by the mentioned phases.

In line with the proposed objectives and the methodological procedure, the LCA was structured in four steps, as indicated below:

- Determination of the pavement layers;
- Design of the pavement layers;
- Assessment of the life cycle impacts of the phases of extraction, production of materials and construction; and
- Integrated assessment of the environmental impacts.

The proposed methodological procedure is illustrated in Figure 1.

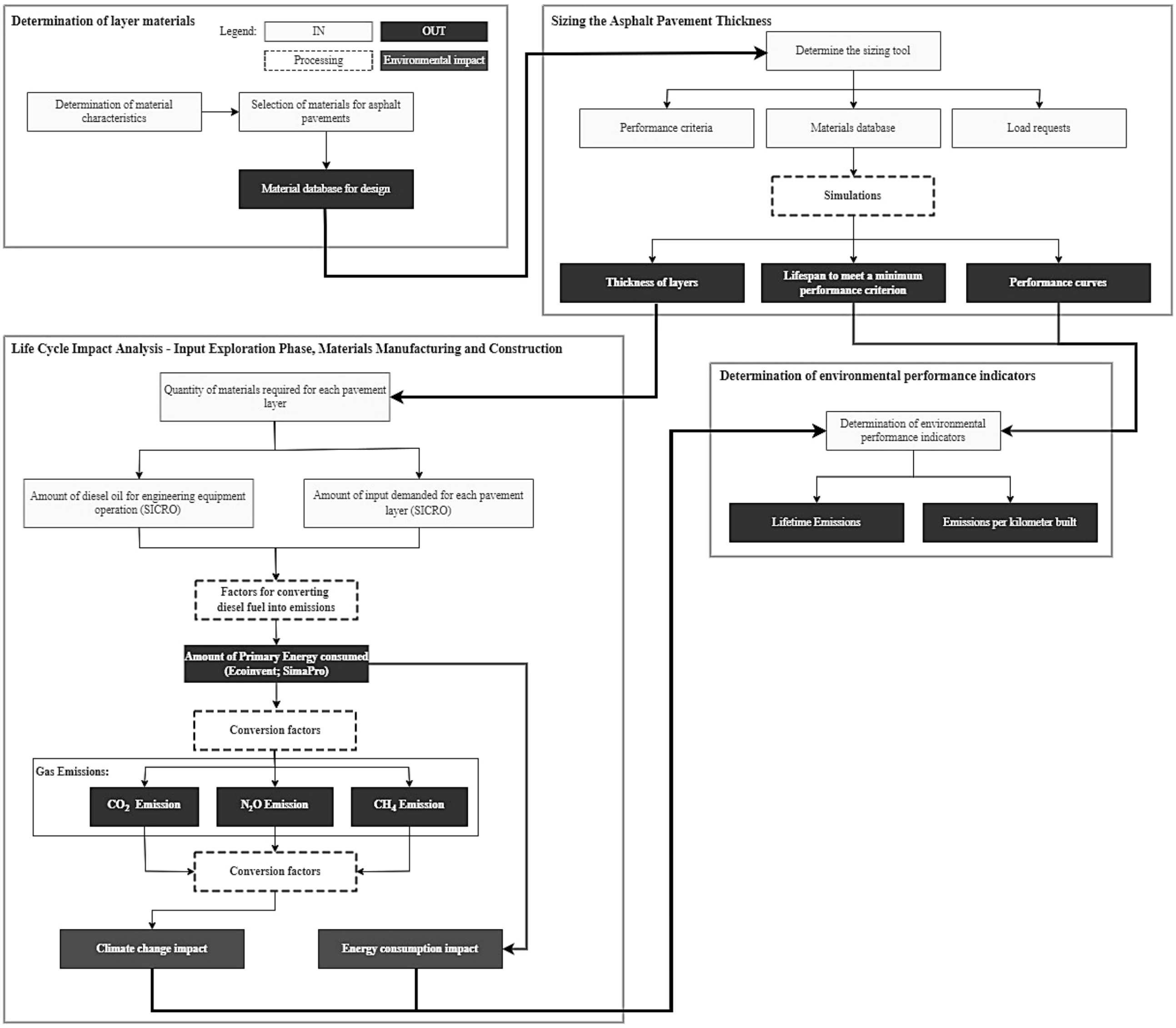


Figure 1. Proposed methodological procedure of this research

3.1. Layers Materials Determination

In this step pavement layers materials of the structure must be defined by classifying them pursuant to a mechanistic-empirical methodology. According with DNIT Guide [45] and the User Guide of the MeDiNa program [59], natural materials can be used for subgrade, subbase, base, and overlay.

3.2. Dimensioning of the Pavement

From the point of view of using the mechanistic-empirical method for pavement design evaluated in this work, the following steps can be specified:

- Pavement layers materials determination;
- Evaluation period determination;
- Traffic load determination, common to all solutions;
- Layer thicknesses establish;
- Calculate the performance of each pavement for each failure criterion;
- Verify if the layer arrangements (materials and thicknesses) meet the failure criteria for the evaluation period.

The simulations were performed without changing materials of base, sub-base and asphalt surface course. The only variation that took place was made in the subgrade materials for each scenario. Thus, it was possible to investigate the main changes in the thicknesses of asphalt surface course layers designed, inspection of the percentage of cracked area and verification of the impact on the service life of the pavement, from the various variations of subgrade that were performed.

3.3. Life Cycle Assessment Inventory Determination

According to ISO 14040 [14], LCA has four phases: objective and scope, life cycle inventory - LCI, life cycle impact assessment - LCIA and interpretation of results, which must also compose this step. For this study, LCA phases determination was based on the methodology adopted by Nascimento et al. (2020) [11] and Gouveia et al. (2021) [12]. According to Balaguera et al. (2018) [60], the most used functional unit (FU) in LCA of roads is a unit of impact for 1 km of constructed road. Thus, the scope of this step is delimited to phases of exploration and production of inputs, production of materials, transportation of inputs required for the activities foreseen in each scenario and finally construction, which covers the operation of engineering equipment. The construction phase was simplified by the fuel consumption of the engineering equipment, according to its productive hours.

The LCIA was performed by measuring the greenhouse gas emissions and energy consumption, both in the manufacture of inputs and in the construction of structures. Since materials quantities needed for structures, construction were distinct, individualized evaluations were generated. The main criterion estimated was diesel oil consumption of equipment. Further, as in Chen and Wang (2018) [61], Wang et al. (2020) [62] and Islam et al. (2016) [63], inventories were used to obtain information about the unit values of CO_2, N_2O, and CH_4 emissions, as well as the energy consumption employed in the construction alternatives. For this purpose, Simapro® software, Ecoinvent® database, and CML LCIA method were used. It should be noted that to calculate the amounts of CO_2 equivalent, the GWP_{100} values shown in Table 4 were used.

Table 4. Relative contributions of the main greenhouse gases: adapted from [64]

		GWP	
Chemical symbol	**Lifetime (years)**	**Cumulative effect (20 years)**	**Cumulative effect (100 years)**
CO_2	indetermined	1	1
CH_4	12.4	84	28
N_2O	121.0	264	265
CF_4	50000.0	4880	6680

Some of the main aspects that directly interfere with the intensities of environmental impacts in virtually all phases are: service life and its various estimation methods; frequency and type of maintenance, which also has a wide range of possibilities and effects [65]; functional units [66]. Furthermore, although theoretically unexpected, the software used for analysis affects the results and possible comparisons between studies, even if they contain the same databases and methods [67]. In possession of the above information, aside the fact that studies do not share the same considerations, comparisons between studies are valid, but with caveats.

4. Case Study

Three scenarios were elaborated having in common the materials of the asphalt mixture, base and sub-base, as described in Table 5, as well as the thicknesses of the last two layers 15 and 30 centimeters respectively (Figure 2).

Table 5. Subgrade materials

	Pavement		
	PAV 1	**PAV 2**	**PAV 3**
Subgrade	**Soil 1**	**Soil 2**	**Soil 3**
MCT Classification	LA(1) (Sand)	LG'(2) (Clay)	NA'(3) (Sandy)

Notations: (1) LA: Laterite sand soil; (2) LG': Lateritic clay soil; (3) NA': Non-lateritic sandy soil

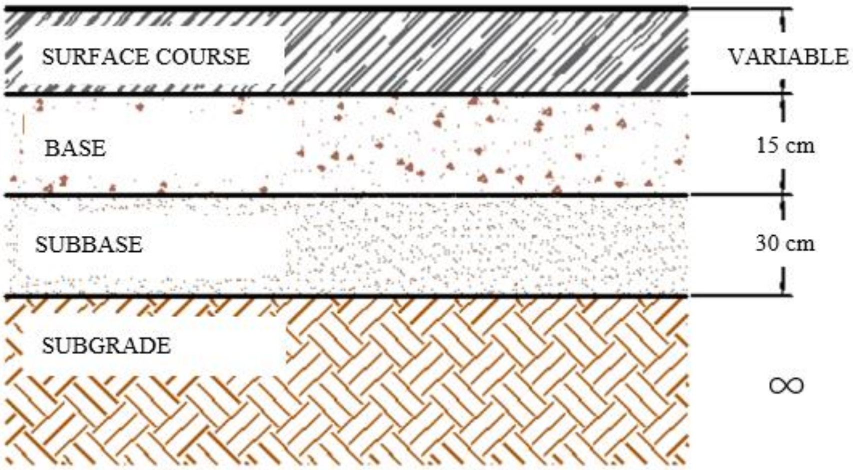


Figure 2. Layers of flexible pavement

MeDiNa Software's own database was adopted for base, subgrade and overlay layers materials. The main difference in these pavements was subgrade layer materials diversification. However, a total of 13 materials, of 3 soil types, extracted from different locations, were evaluated, as presented in Table 6 their mechanical characteristics, being 5 LA, 5 NA' and 3 LG'. This study considered a 1 km track highway, single lane pavement with a platform width of 3.60 meters and did not consider shoulder as part of the evaluation. The representation of the platform structure can be seen in Figure 3. In determining the traffic data, a Primary Arterial System Road was considered, presenting, according to DNIT (2006) [45] and adopted by MeDiNa [59], a reliability of 85% and a cracked area of 30% (minimum performance criterion adopted by the Brazilian method of road pavement design). Thus, the average daily volume (ADV) in the opening year of traffic (ADV 1st year), being, according to the type of road, 1500 cars, with no increases during the course of time, due to the fact of having considered a growth rate of 0%, these values were fixed throughout the research.

Table 6. Mechanical test data of the soils and classification according to the MCT

MCT Classification			**Laboratory**		**M_R Parameters**			
MCT	**e'**	**c'**	**Wot(1)**	**MEAS(2) (g/cm³)**	**k1(3) (MPa)**	**k2(3) (MPa)**	**k3(3) (MPa)**	**R^2**
NA´	1.326	1.329	19.583	1.706	33.267	0.237	-0.452	0.916
LA	1.108	0.400	8.837	2.158	564.974	0.209	-0.388	0.272
LA	1.111	0.191	23.596	1.812	1046.663	0.658	-0.055	0.995
LA	0.884	0.574	14.799	1.984	375.335	0.248	-0.027	0.520
LG'	1.098	1.530	17.776	1.759	820.297	0.638	-0.124	0.937
LA	1.384	0.574	30.537	1.377	79.688	0.441	-0.036	0.756
NA'	1.190	1.508	34.011	1.433	110.995	0.378	-0.188	0.780
NA'	1.190	1.508	34.011	1.433	108.320	0.378	-0.188	0.780
LG'	0.933	1.993	29.298	1.442	284.740	0.528	-0.165	0.960
LG'	1.104	1.508	26.627	1.424	79.149	0.265	-0.196	0.701
NA'	1.203	1.508	21.696	1.535	368.572	0.525	-0.162	0.976
NA'	1.203	1.508	25.927	1.499	667.863	0.748	-0.042	0.970
LA	1.049	0.572	29.158	1.394	254.499	0.501	-0.150	0.931

Notations: (1) Wot: Optima Moisture Content; (2) MEAS: dry bulk density; (3) k1, k2, k3: parameters of the MR.

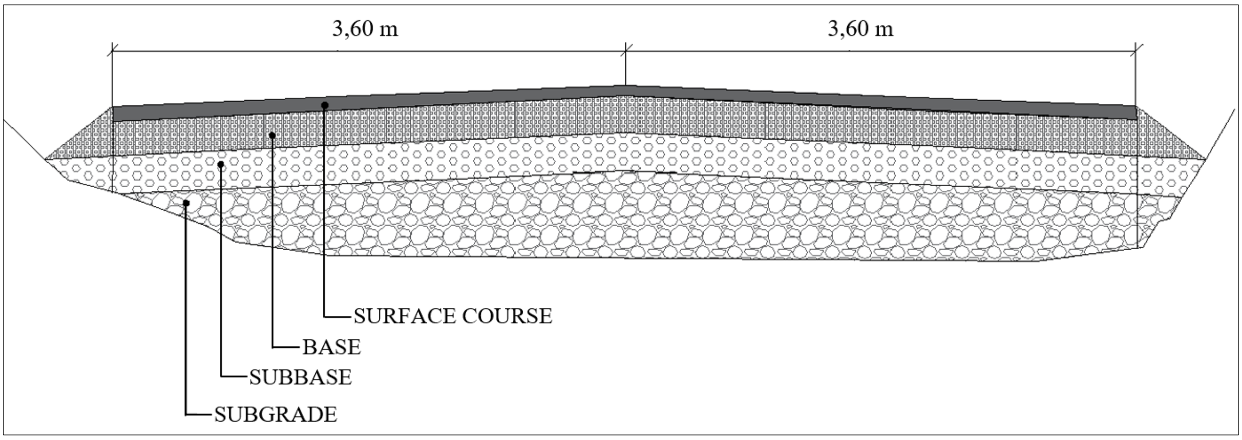


Figure 3. Flexible pavement platform

Finally, there is vehicle factor (VF), from this value the program can, together with the ADV, automatically calculate the "Equivalent Number of Passages of the Road Standard Axle (N)", it was considered a VF equal to 1, being this a single axle configuration of double wheel with a load of 8.20 tons. The MeDiNa software has several types of axle configurations and their specified characteristics, all these values are already predetermined by the program itself when initialized. Furthermore, 100% of the vehicles are in the design traffic lane, due to the fact that the number of two lanes on the road is not exceeded, so the traffic does not split to other lanes. Therefore, for a 10-year design period, the total number of passes (Total N) will be the ADV multiplied by VF, equal to N of 5.48 x 10^6 standard axles.

Regarding the resilient modulus analysis, it was considered linear elastic 9000 MPa material for asphalt layer. As for the other layers, it was considered nonlinear elastic, i.e., the resilient modulus is variable within the thickness of the layer itself. It was not considered permanent deformation behaviour of the materials applied in the subgrade layer. However, these parameters are necessary for the design of the pavement using the MeDiNa method, as stated in the User Guide of the MeDiNa program [59].

At the research criteria, different types of thicknesses were tested for the asphalt layer, rounded off from half to half cm, in order to meet the values of 20%, 25%, 30%, 35% and 40% of cracked area (%CA). For each scenario, the software returns in the Results tab a detailed report about the monthly damage evolution for that analysis, making it possible to evaluate the pavement service life related to the type of subgrade used and the value of the dimensioned thickness. Mechanical parameters of each soil were inserted in the Brazilian design software (MeDiNa), which have different attributes, bringing to the research a wider range of possibilities in order to demonstrate the differences in thickness, cracked area, and service life.

Once the layer thicknesses were determined, the SICRO 3 table for the State of Rio de Janeiro was used for July 2021 (Table 7). The SICRO 3 table is consulted through the analysis of the materials used in the project and the inventory survey. From layer thicknesses established by pavements design, environmental impacts were calculated with Simapro® software and Ecoinvent® database, as well as the work of Stripple (2001) [68], Nascimento et al. (2020) [11], and Gouveia et al. (2021) [12]. It should be noted that material and energy consumption were considered in three stages of the pavement life cycle: exploration of natural inputs, machining and construction.

Table 7. Materials of each layer: adopted from [69]

LAYER	DESCRIPTION	SICRO 3
Surface	Asphalt concrete - type C - commercial sand and gravel - CAP 30/45.	4011463
Base	Granulometrically stabilized base with a gravel soil mixture (70% - 30%) on the track with quarried material and commercial gravel.	4011256
Subbase	Granulometrically stabilized soil subbase without mixing with quarry material.	4011227

To ascertain the atmospheric potential impacts from execution of asphalt pavements, four indicators were selected that establish a more complete picture of emissions: gross energy consumed (MJ), carbon dioxide (kg), nitrogen dioxide (kg) and methane (kg) emissions. The gas emissions were then converted into CO_2 equivalent. Thus, it was possible to calculate ratios between their predicted emissions, energy consumption, and service lives.

For LCIA stage, primary energy and greenhouse gas emissions data were computed with Simapro® software and Ecoinvent® database, as well as the work of Stripple (2001) [68]. Table 8 summarizes all these manufacturing data for the inputs used in the paving services in this case study. The only exception is due to the Diesel oil input, which is related to the consumption of the engineering equipment in the construction phase, whose energy quantity characteristics and GHG emissions are published in Edwards et al. (2019) [70].

Table 8. Quantity of Energy (QE) and Greenhouse Gases (CO_2, N_2O e CH_4) necessary for the manufacture of the inputs

INSUMPTION	QE (MJ/t)	CO_2 (kg/t)	N_2O (kg/t)	CH_4 (kg/t)
Fuel oil 1A	0.1	4.31E+02	9.35E-03	1.57E+00
Asphalt cement CAP 30/45	682	3.99E+02	2.73E-03	1.71E-01
Medium sand	96	1.13E+01	3.31E-04	1.46E-02
Hydrated lime	5161	9.53E+02	7.01E-03	2.73E-01
Gravel	96	1.69E+01	5.25E-04	3.05E-02
Diesel oil consumption	42087	4.95E+02	9.34E-03	1.59E+00

5. Result and Discussion

5.1. Mechanistic-Empirical Dimensioning

After the preparation of the 13 design simulations, the asphalt pavement thickness values were obtained for each subgrade material and meeting their respective predetermined percentages of cracked area within the design time of 10 years. Then, the 3 scenarios were built, as explained in topic 3, from the average thicknesses (e) of the asphalt pavement and the service life (SL) to reach 30% of cracked area for each pavement-type were calculated and are shown in Table 9. It can be observed that the need for greater thicknesses of the coating as the design criterion becomes more stringent (smaller cracked area at the end of service life).

Table 9. Surfacing thickness and service life of each pavement (PAV) for each design criterion and subgrade type

% Cracked area	PAV 1		PAV 2		PAV 3	
	e (cm)	SL Wot (meses)	e (cm)	SL Wot (meses)	e (cm)	SL Wot (meses)
20%	12.5	166	12.5	167	13.5	164
25%	11.5	143	11.0	138	12.5	141
30%	10.5	123	10.0	123	11.5	126
35%	10,0	111	9.5	112	10.5	110
40%	9.5	102	8.5	104	9.5	100

Notations: (1) SL: Service Life; (2) Wot: Optima Moisture Content;

5.2. Life Cycle Impact Assessment (LCIA)

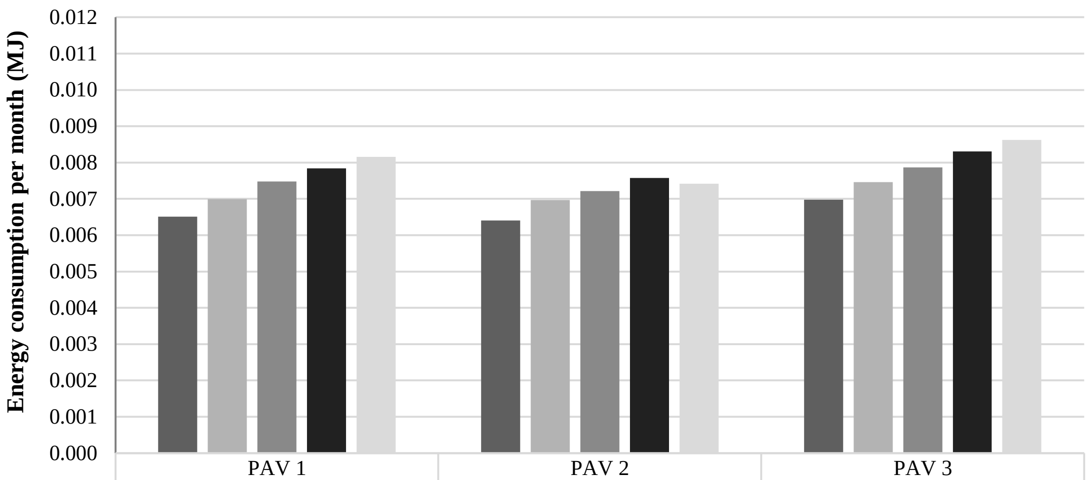
According to section 4, data presented in Table 10 was obtained referring to thicknesses, shown in Table 8, and materials of the design performed with the optimum moisture. Thus, it can be observed that soil 3 requires greater amounts of energy for the same length of track constructed in all design criteria. In addition, it is noted that soil 2 is the one that demands the least energy under the same conditions. Similarly, it can be seen that, going through Table 9 which presents the environmental footprint that would generate CO_2, N_2O and CH_4 for each pavement, from the lowest percentage of cracked area to the highest, the consumption of soil 2 with respect to that of soil 3 tends to decrease. However, it is observed that the performance of soil 1 approaches that of soil 3. This phenomenon can be explained by the fact that the difference between the thicknesses is decreasing as the strictness regarding the limit of cracked area is relaxed.

Figure 4 shows the ratio of energy consumed by the months of service life of each pavement for the life cycle stages addressed in the study. It can be observed that, in general, as the tolerance for pavement deterioration increases, represented by the percentage of cracked area, energy efficiency is reduced, since the values of the ratios present in columns rise. Moreover, it is noted that the increase in ratios evidenced for PAV 1, PAV 2 and PAV 3 within the range of cracked area considerate was 26%, 16% and 23%, respectively. Thus, it can be seen that the energy efficiency of PAV 2 is less susceptible to the design criteria adopted in this study. Finally, it is noted that PAV 3 is the one that presents the highest energy consumption per month.

At Figure 5, similarly to what is exposed in Table 10, one can observe the contribution that each pavement would exert with respect to global warming calculated from Table 4. It can be observed that all pavements intensify their environmental impacts as the tolerance to surface deterioration increases, i.e., the percentage of cracked area increases. It can be seen that PAV 3 has the greatest potential to contribute to global warming.

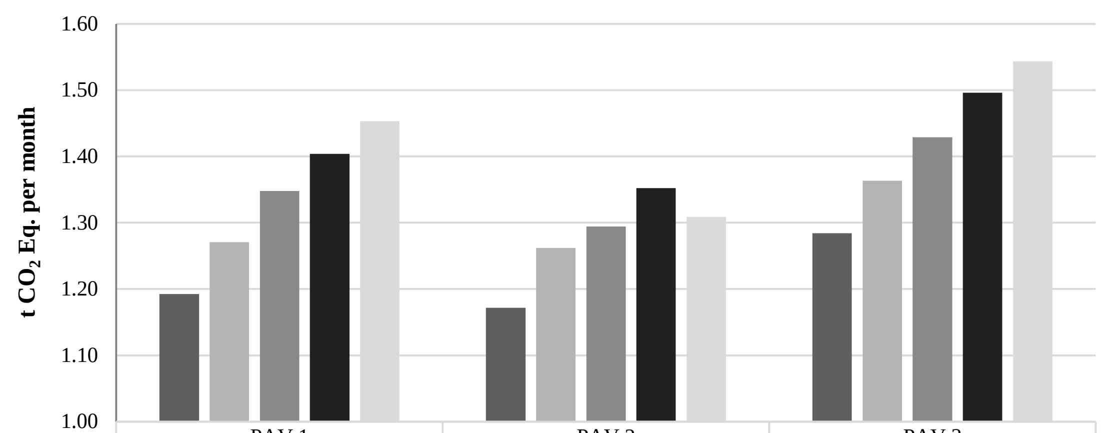
Table 10. Amount of energy consumed and greenhouse gases emitted in the manufacture of inputs and in the operation of engineering equipment in construction per kilometer of track built

% Cracked area	Parameters	Type of subgrade		
		PAV 1	**PAV 2**	**PAV 3**
20	QE (MJ)	1.074	1.069	1.141
	CO_2 (kg)	196.645	195.654	210.023
	CH_4 (kg)	0.000149	0.000148	0.000158
	N_2O (kg)	0.0000025	0.0000025	0.0000026
25	QE (MJ)	0.992	0.957	1.052
	CO_2 (kg)	180.295	173.358	192.186
	CH_4 (kg)	0.000138	0.000133	0.000146
	N_2O (kg)	0.0000023	0.000022	0.0000024
30	QE (MJ)	0.918	0.883	0.985
	CO_2 (kg)	165.431	158.494	178.809
	CH_4 (kg)	0.000128	0.000123	0.000137
	N_2O (kg)	0.0000021	0.0000020	0.0000023
35	QE (MJ)	0.866	0.846	0.910
	CO_2 (kg)	155.026	151.062	163.945
	CH_4 (kg)	0.000121	0.000118	0.000127
	N_2O (kg)	0.0000020	0.0000020	0.0000021
40	QE (MJ)	0.829	0.772	0.858
	CO_2 (kg)	147.594	136.198	153.540
	CH_4 (kg)	0.000116	0.000108	0.000120
	N_2O (kg)	0.0000019	0.0000018	0.0000020



	PAV 1	PAV 2	PAV 3
20%	0.0065	0.0064	0.0070
25%	0.0070	0.0070	0.0075
30%	0.0075	0.0072	0.0079
35%	0.0078	0.0076	0.0083
40%	0.0082	0.0074	0.0086

Figure 4. Ratio of Energy Consumption (MJ) to Service Life per kilometer of road construction



	PAV 1	PAV 2	PAV 3
20%	1.193	1.172	1.284
25%	1.271	1.262	1.363
30%	1.348	1.295	1.429
35%	1.404	1.352	1.496
40%	1.453	1.309	1.543

Figure 5. Ratio between kg CO_2 Eq. emitted and Service Life per kilometer of road construction

6. Conclusion

The method proposed was used in order to evaluate the effect of mechanical behaviour of subgrades in Life Cycle Analyses (LCA) of flexible surfacing pavement infrastructures. For each simulation it was measured the variations of its service life, thickness of each layer and percentage of cracked area. The scope of this study encompassed the extraction and production phases of the inputs necessary for the implementation of the idealized road for each scenario, as well as the construction phase itself, taking into account the operation of the engineering equipment. The LCA narrows its focus on the emission of greenhouse gases (GHG) and the amount of primary energy covered by the phases mentioned.

It is concluded that the materials used in this study have similar mechanical behaviour, and therefore the results of the design of the thicknesses of the asphalt overlay were similar, resulting in similar energy consumption and greenhouse gas emissions. Furthermore, in general, as the tolerance for pavement deterioration increases, represented by the percentage of cracked area, energy efficiency is reduced. Moreover, it is noted that the energy efficiency of the pavements evaluated has different susceptibles to the design criteria adopted in this study. Regarding the contributions related to climate change, the pavements observed intensify their environmental impacts as the tolerance to surface deterioration increases. Finally, the proposal for future work would be to study greater variations of materials applied to the subgrade and verify their effect on the LCA.

7. Declarations

7.1. Author Contributions

Conceptualization, M.D. and B.G.G.; methodology, M.D. and B.G.G.; software, M.D. and B.G.G.; validation, M.D. and B.G.G.; formal analysis, M.D. and B.G.G.; investigation M.D.; B.G.G.; A.S.M. and M.A.V.S.; resources, M.D.; B.G.G.; A.S.M. and M.A.V.S.; data curation, M.D.; B.G.G.; A.S.M. and M.A.V.S.; writing—original draft preparation, M.D.; B.G.G.; A.S.M.; M.A.V.S. and S.O.; writing—review and editing, M.D.; B.G.G.; A.S.M.; M.A.V.S. and S.O.; visualization, M.A.V.S. and S.O.; supervision, M.A.V.S. and S.O.. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.3. Funding

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001 and Conselho Nacional de Desenvolvimento Científico e Tecnológico – Brasil (CNPq).

7.4. Conflicts of Interest

The authors declare no conflict of interest.

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