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Investigating the Influence of Functional Units on the Life Cycle Assessment of Asphalt Pavements

Bruno G. Gouveia [1, 2*], Marina Donato [2, 3], Filipe A. Corrêa do Nascimento [2, 4], Marcelino A. V. da Silva [2]

[1] *Department of Civil Construction and Transportation, Rio de Janeiro State University, Rio de Janeiro, Brazil.*

[2] *Postgraduate Program in Transportation Engineering, Alberto Luiz Coimbra Institute for Postgraduate Studies and Engineering Research, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil.*

[3] *Department of Technology in Civil Engineering, Computing, Automation, Telematics and Humanities, Federal University of São João del Rei, Campus Alto Paraopeba, Ouro Branco, Brazil.*

[4] *Science and Technology Department, Military Engineering Institute, Rio de Janeiro, Brazil.*

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Abstract

The Life Cycle Assessment (LCA) of asphalt pavements is an essential tool for reducing environmental impacts. The definition of the functional unit (FU) within LCA can significantly influence the results, affecting the assessment of greenhouse gas (GHG) emissions and, consequently, the selection of asphalt mixtures. In this context, this study aims to analyze the impact of different functional units on the selection of asphalt mixtures for road pavements, considering the phases of raw material extraction, material production, mixing, and construction. To this end, the mechanical behavior of two distinct asphalt mixtures was evaluated under two different loading conditions, and their contributions to climate change were assessed using three functional units: t CO_2 eq/km of roadway, kg CO_2 eq/t of HMA, and kg CO_2 eq/m³ of HMA. The results indicated that asphalt mixtures with a higher resilient modulus require thinner pavement layers, leading to lower GHG emissions. However, when asphalt mixtures are analyzed individually and compared, no clear pattern in GHG emissions is observed, reflecting the specific characteristics of each production process. Additionally, it was found that the environmental impact varied according to the adopted functional unit, demonstrating that this choice can significantly influence decision-making regarding the selection of asphalt mixtures in terms of their contributions to climate change. It was concluded that the selection of the FU in pavement LCA should be aligned with the study's objective and the context of the analysis, as an inadequate choice may compromise the selection of asphalt mixtures.

Keywords: Life Cycle Assessment (LCA); Functional Unit (FU); Pavement.

1. Introduction

Considering that the density of the Brazilian road network is around 25.1 km per 1000 km² of paved area, the country has significant potential to expand its road infrastructure. Thus, compared to other countries such as China (477 km per 1000 km²), the USA (437.8 km per 1000 km²), Australia (94 km per 1000 km²), Mexico (89.4 km per 1000 km²), Russia (54.3 km per 1000 km²), Uruguay (43.9 km per 1000 km²), Argentina (42.3 km per 1000 km²), Canada (41.6 km per 1000 km²) and Ecuador (31.4 km per 1000 km²), the figures are higher than those recorded in Brazil. In addition, the Brazilian road system is responsible for transporting 65% of goods and 95% of passengers in the country, with a notable environmental impact, as it accounts for 22.9% of carbon dioxide (CO_2) emissions [1].

* Corresponding author: bruno.gouveia@eng.uerj.br

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Greenhouse gas (GHG) emissions from human activities are associated with climate change, which in turn can lead to an imbalance in terrestrial and aquatic ecosystems [2]. Given the limited capacity of the planet's natural systems to meet growing demands and mitigate the impacts of human activities, the concept of sustainable development has gained relevance. This concept highlights the importance of considering the economic, environmental and social impacts of current activities, with a view to the well-being of present and future generations [3]. It is therefore important to check the environmental implications of implementing these infrastructures. According to Crawford [4], there are numerous methods for assessing the environmental impacts of a given product or service. In this context, Life Cycle Assessment (LCA) has emerged as a management methodology aimed at identifying and quantifying the main environmental impacts throughout the life cycle (LC) of a production chain, by evaluating the system's inputs and emissions. In this way, the use of LCA makes it possible to draw up indicators that highlight critical points in product, service or process chains, which can be used to select alternatives or to promote actions to mitigate and reduce impacts [5-8].

In the specific case of road pavements, the LC can contain the following stages: (1) Exploration of virgin inputs; (2) Transportation of inputs; (3) Machining of materials; (4) Transportation of pavement materials; (5) Construction of the pavement; (6) Conservation and Maintenance; (7) Use; (8) Recycling; (9) Demolition; (10) Reconstruction [9-14]. Within each stage of the LC, there is a set of processes. In the process units, different types of energy and materials are put in, mixed and modified, and the output is a product of interest and undesirable emissions of substances that can affect the soil, water and air [15, 16]. Various investigations have been carried out using the LCA methodology to assess the effects of variations in the properties of the materials that make up asphalt surfacing on environmental impacts [5, 17, 18]. Moins et al. [19] emphasize the importance of combining Environmental Product Declarations (EPDs) for pavement construction materials with LCA, aligning them with the environmental impacts they generate. Although EPDs can provide independent, reliable, and quantified information, several inconsistencies must be addressed, such as the standardization of functional units (FU), the environmental impact categories to be assessed, the defined scope of the study, and the methods adopted. These inconsistencies often make direct comparisons between studies impractical.

Various investigations have been carried out using LCA to assess the potential environmental impacts associated with the life cycle of processes related to the study of the properties of the materials that make up both the pavement structure and the asphalt layer [5, 17, 18]. In this context, considering the evolution of research into the materials that make up the asphalt surfacing layer, it is important to study and verify the differences in the environmental impact generated by determining the functional unit, whether depending on the asphalt mixtures or the asphalt pavements.

De Simone Souza et al. [20] highlights the fundamental importance of the functional unit in LCA studies, pointing out that the ISO 14040 [21] and ISO 14044 [22] standards only offer general guidelines on its definition. The ISO (International Organization for Standardization) series of standards for LCA establish that the FU must be coherent with the objective and scope of the research, as well as being clearly defined and measurable. In addition, when comparing two systems with multiple functions, it is essential to ensure that the functional units adopted represent the same number of functions. However, the ISO standards act as a reference framework, without providing detailed guidelines for functional unit selection in specific LCA studies. Due to the nature of these studies, which depend on specific geographical, technological and temporal contexts, the choice of functional unit must reflect these aspects, which makes ISO's generic guidelines sometimes insufficient. In this sense, DeMarco & Fortier [23] point out that the lack of standardization in functional units' compromises comparability between LCA studies, limiting the applicability of the results for decision-making. It is therefore necessary to establish a consolidated benchmark for the definition of the functional unit, allowing for more consistent and comparable analyses, as well as contributing to the efficiency of the system and the mitigation of the environmental impacts of transport infrastructures. In this context, it is essential to develop new studies that explore the application of LCA to transport infrastructure, integrating advances in pavements mechanics and improving the definition of functional units.

Therefore, when it comes to asphalt surfaces, it is essential to understand the materials used in their layers, with the asphalt binder and mineral aggregates being the main components. Aggregates play a fundamental role in supporting and transmitting the mechanical loads generated by vehicles, as well as resisting wear and tear resulting from stress. In turn, among other functions, the asphalt binder has the role of binding the aggregates and making the coating impermeable [24, 25]. As can be seen, the road infrastructure sector consumes considerable amounts of natural resources, especially during the construction and maintenance phases [10, 26].

The aim of this study is to evaluate how the choice of functional unit can influence the selection of asphalt mixtures for pavements, considering greenhouse gas emissions in the stages of extraction of inputs, manufacture of materials, machining and construction. To this end, three different functional units are used, analyzing their effects on the decision on asphalt mixtures. The article is structured in five main sections. Section 2 shows the main bibliographical references on the subject. Section 3 describes the materials and methods used. Section 4 presents and discusses the results obtained by applying the proposed procedure, including projections of environmental impacts and analysis of the results.

2. Functional Unit (FU) Applied to Road Pavements

According to Gouveia [27], one of the important elements of an LCA is the functional unit used to evaluate alternatives. The FU defines the system that will be studied and acts as a reference for calculating the input and output data in any of the product or service's LC phases. It also aims to ensure equivalence between the alternatives that will be compared and to reduce interference in the analysis. The FU should be described according to: (1) the purpose, which will determine the characteristics of the components; (2) the location of the study, which will influence the collection and applicability of the data, the selection of the impact category and the interpretation of the results; (3) the physical boundaries of the FU, which define the portions of the pavement structure to be considered as part of the pavement system to be evaluated. The physical dimensions make it possible to determine volumes, masses, surface areas and other quantities needed to carry out the LCA [28, 29]. Some of the FU adopted in LCA applied to pavements can therefore be highlighted: 1.0 km of built-up lane [30]; 1.0 km of built-up lane with a width of 13 m and a thickness of 0.08 m [31]; 1.0 km of built-up lane with a width of 9 m [32]; 1.0 km of built-up lane with a width of 3.5 m [18]; m² of built-up pavement [33].

In agreement to Inyim et al. [34], the most used functional unit is the km (kilometer) of roadway. The authors evaluated several paving articles that used LCA, and found that 12 articles, out of the 32 analyzed (37.50%), used kilometers (km) built, or miles (mi), as the functional unit. They also noted that some studies used lengths, such as 5 km and 10 km, as the functional unit, since the authors analyzed the project. Another FU used was the square meter (m²), when the scope of the analysis focused on pavement surfacing materials. The authors Jiang & Wu [35] evaluated 94 articles dealing with the LCA of road paving and found that 68 (72.3%) of the articles analyzed adopted the length of the road in kilometers (km) or miles (mi) as the functional unit. In addition, 11 articles (11.7%) adopted an evaluation area that considered the surface and the analysis of pavement degradation and was therefore expressed in square meters (m²). Aryan et al. [36] evaluated 67 articles dealing with flexible and rigid pavements, 24 of which were carried out in the USA, 23 in the European Union, 2 in Canada, 1 in Australia and 17 in Asia. According to the researchers, 54 of the 67 studies used length (in km or mi) as the functional unit, while the remaining studies used m².

Liljenström et al. [37] analyzed 84 articles on road infrastructure, most of which were about comparing different construction materials. The authors highlighted the importance of defining the infrastructure's service life, as it is a key factor in defining the functional unit of the LCA, i.e. the unit by which the environmental impacts of different design alternatives or materials will be compared. In this way, the researchers found that in 30% of the articles evaluated, the service life was the same as the service life of the project, i.e. the intended service life of the infrastructure.

Finally, according to Donato [38], the data collected for the inventory makes it possible to outline the scope and limits of the study, as well as defining the purpose and perspective of the analysis, ensuring the relevance and comparability of the results. The definition of the functional unit is essential in this context, as it guarantees consistency in conducting the LCA and the appropriate interpretation of the results obtained.

3. Materials and Methods

In accordance with the objectives of this research, the methodological procedure was structured to summarize the steps involved in preparing and analyzing the behavior of the functional unit in the Life Cycle Assessment of road pavements. Thus, the study was organized into six parts, covering:

- Determination of the objective and scope of the Life Cycle Assessment (LCA);
- Determination of pavement layer materials;
- Physical and mechanical characterization of materials;
- Mechanistic-empirical pavement design;
- Determination of the Life Cycle Inventory (LCI);
- Determination of the Life Cycle Impact Assessment (LCIA)

3.1. Determination of the Objective and the Scope of the Life Cycle Assessment

In this stage of the LCA, the objectives of the analysis are first defined, as well as the scenarios for comparing different paving projects. Next, the stages of the pavements life cycle to be considered are established, as well as the evaluation period. In addition, it is essential to define the functional unit, as this serves as a reference for the development and interpretation of the LCA. However, there is still no consensus on the most appropriate functional unit for LCA studies on pavements, which highlights the need for well-founded criteria for this choice.

Thus, for this research, several functional units were created for comparison purposes, such as: (a) emissions of tons of CO_2 equivalent per kilometer built; (b) emissions of kilograms of CO_2 equivalent per ton of hot-mix asphalt (HMA), and (c) emissions of kilograms of CO_2 equivalent per cubic meter of HMA

3.2. Determination of Pavement Layer Materials

As of 2021, the National Department of Transportation Infrastructure (DNIT) began the transition from the mechanistic-empirical method to the National Pavement Design Method (MeDiNa). This process was formalized through the new Service Instruction (IS-247), which establishes guidelines for the preparation and implementation of projects based on the new flexible pavement design method. IS-247 also highlights the need for significant adaptations to the proposed LCA method [39].

According to the DNIT [40], paving materials in the MeDiNa method are classified into two groups: (1) asphalt materials and (2) granular materials. For each group, there are different physical and mechanical characterization tests, which must be carried out in accordance with Brazilian technical standards.

In the case of HMA, the minimum mechanical characterizations required are as follows:

(a) Resilience Modulus [41];

(b) Diametral Compression Fatigue [42];

(c) Permanent deformation [43].

For granular materials, the minimum requirements include:

(a) Resilience Modulus [44];

(b) Permanent Deformation [45].

3.3. Mechanistic-Empirical Pavement Design

With regard to the application of the MeDiNa method for the design of the pavements evaluated in this study, the following steps can be specified: (1) selection of the materials for the pavement layers; (2) definition of the evaluation period; (3) determination of the traffic demand; (4) definition of the layer thicknesses; (5) calculation of the performance of each pavement, considering the failure criteria; (6) verification of the conformity of the layer arrangements (materials and thicknesses) with the failure criteria established for the analysis period.

3.4. Determining the Life Cycle Inventory (LCI)

This phase of the procedure aims to identify and quantify all the services and processes that take place throughout the pavement's life cycle. In the context of this study, the stages analyzed include: (a) extraction of inputs and raw materials; (b) processing of materials; (c) construction of pavement layers; (d) transportation of inputs and materials.

In order to guarantee a standardized and verifiable approach, it is proposed to use the Construction Reference Cost System (SICRO) [46] from Brazil, which provides methodologies and criteria for calculating the unit costs of the inputs and services required for the construction, restoration, signaling and conservation of highways. SICRO is based on the definition of cost compositions, which model the execution of services to price them. The information required for this includes: (1) type of machinery; (2) production of mechanical teams; (3) specifications and consumption of inputs; (4) equipment utilization rates; (5) loading, unloading and maneuvering times; and (6) transportation times [47].

Once the materials and thickness of the pavement layers have been defined, the functional unit is considered to create an inventory of services and processes, detailing the quantities of inputs and the construction techniques required at each stage of the pavement's life cycle.

3.5. Determining the Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) aims to convert the data obtained in the Life Cycle Inventory (LCI) of pavements, with a focus on environmental impacts, and classify them into indicators that can be considered as intermediate or final impacts. This stage aims to translate the results of the pavement life cycle processes into quantifiable information, allowing the environmental effects to be analyzed over the entire service life of the infrastructure [46].

For this, it is recommended to use software that meets the following requirements [8-20-30-38]:

- It has an interface capable of modeling the system's output based on the information from the previous stages;
- Include in your internal library an equation or allow the implementation of the equations of the LCA methods;
- Have calculation tools to determine the environmental impacts of the processes modeled in the databases, applying life cycle impact analysis methods;
- Offer resources for analyzing and interpreting the results obtained.

3.6. Case Study

3.6.1. Data Exposure

In this work, four scenarios have been designed. All the scenarios have in common: the base and sub-base thicknesses, 15 cm for both layers; the base and sub-base materials, graded gravel and soil-gravel mix, respectively; priming service; two 3.6 m wide rolling lanes with no shoulder; 1 km in length; a 10-year design period; the annual traffic volume growth rate of 0%; the type of road adopted for design in the MeDiNa software was the primary arterial system of a new pavement. The parameters that changed between the scenarios were: the types of HMA for the overlays; AADT, 1,350 ($N=4.93\times10^6$) and AADT 2,700 ($N=9.86\times10^6$); the thicknesses of each overlay layer, relative to the design processes. Figure 1 shows the pavements used in the scenarios in this work.

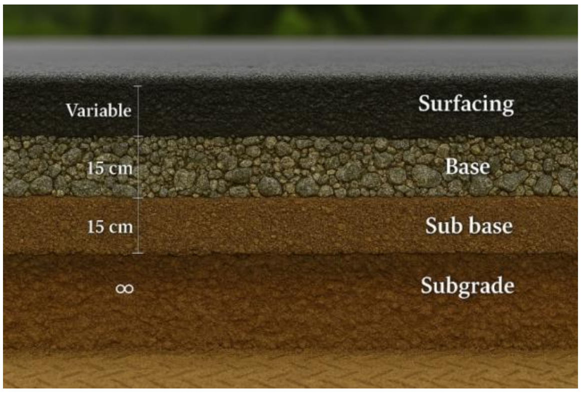


Figure 1. Illustration of the longitudinal section of the road pavement for the scenarios

The materials for the scenarios considered in this study were sourced from different regions of Brazil. Those for the base, sub-base, and subgrade layers were selected using the MeDiNa software [48]. In the case of HMA, compositions from studies by Flôra [49] and CCR [50] were considered. Table 1 shows the materials used in the coatings and the traffic volumes considered for each scenario. In addition, Table 2 shows the mechanical properties of the materials used in the pavement, which are essential for sizing the scenarios analyzed.

Table 1. Description of scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
AADT	1350	1350	2700	2700
Surfacing	PAC 30/45	PAC 50/70	PAC 30/45	PAC50/70

Note: AADT - Annual Average Daily Traffic; PAC - Petroleum Asphalt Concrete.

Table 2. Mechanical properties of materials (adapted from MeDiNa [48], Flôra [49] and CCR [50])

Layer	Hot mix asphalt		Base	Sub base	Subgrade
Material	PAC 30/45	PAC 50/70	Gnaisse C5	Clay Soil LG'1	Sandy Soil NA
RM (MPa)	17521.0	11583.0	-	-	-
k_1	-	-	1149.0	446.5	785.8
k_2	-	-	0.530	0.262	0.340
k_3	-	-	-0.180	-0.086	0,000
Tensile strength (MPa)	2.67	1,7	-	-	-
Fatigue classes	3.0	1	-	-	-
FFM (100µ a 250µ)	0.7	0.67	-	-	-
FN (cycles)	345.0	-	-	-	-
DBD (g/cm³)	2.620	2.447	2.223	1.665	1.820
OMC (%)	-	-	5.0	24.0	10.0
Poisson's ratio	-	-	0.35	0.45	0.45
Compaction energy	-	-	Modified	Standard	Intermediate
LAA (%)	-	-	43.0	-	-
psi_1 (PD)	-	-	0.0868	0.206	0.097
psi_2 (PD)	-	-	-0.2801	-0.240	-1.600
psi_3 (PD)	-	-	0.8929	1.340	1.900
psi_4 (PD)	-	-	0.0961	0.038	0.063

Note: RM – Resilient Modulus; k1, k2, k3 – parameters of the RM; FFM – Fatigue Factor of the Mixture; FN – Flow Number; DBD – dry bulk density; OMC – Optimum Moisture Content; LAA – Los Angeles Abrasion; PD – Permanent Deformation; psi1, psi2, psi3, psi4 – parameters of the PD.

The Life Cycle (LC) stages analyzed in this work are restricted to the phases of extraction, manufacture and transport of inputs; asphalt plant processes; and construction of the pavements themselves. The characterization of the processes and services required to carry out the pavements LC phases was based on the Construction Reference Cost System (SICRO) [46] from Brazil, as shown in Table 3.

Table 3. List of materials used to prepare the scenarios according to SICRO

Layer	Description	SICRO
Surfacing	Asphalt concrete - Track C - commercial sand and gravel (adapted)	4011463
Priming	Printing with asphalt diluted petroleum (ADP)	4011351
Base	Graded gravel base or sub-base made with a paver (vehicle) - commercial gravel	4011549
Sub-base	Sub-base of granulometrically stabilized soil without mixing with quarry material	4011227

Figure 2 illustrates the activities of the defined scope, covering the phases of extraction and production of inputs, manufacture and machining of materials, transportation of the inputs required for each stage and, finally, construction, which includes the operation of engineering equipment.

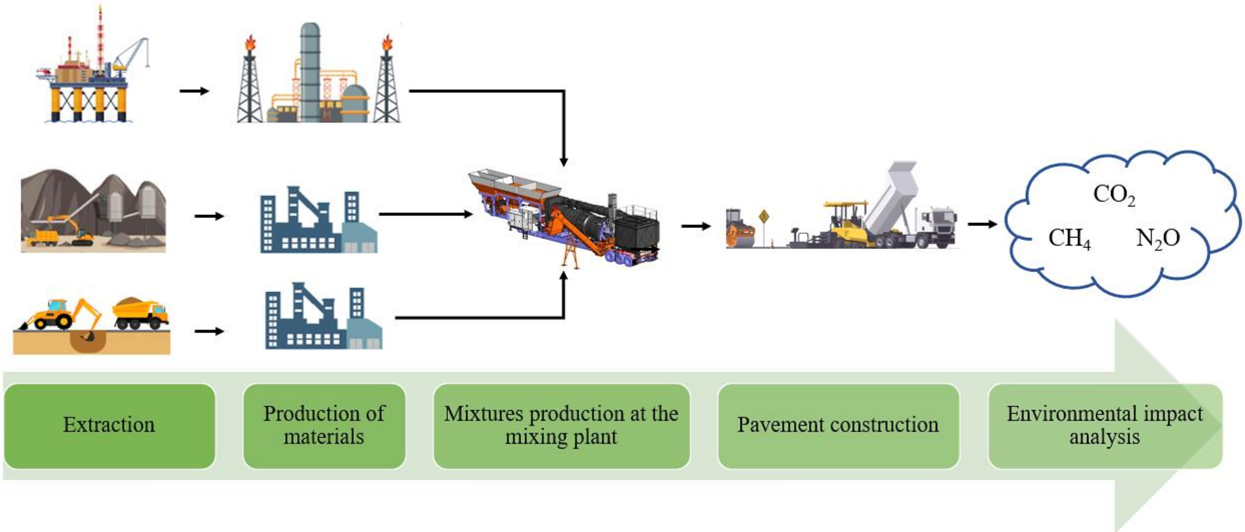


Figure 2. Illustration of the stages in the scope of this research

The average transportation distances (ATD) varied according to the type of material and its processing stage. It should be noted that some of the processes listed, as well as the respective ATDs, were taken from the Ecoinvent database. Therefore, in the case of crushed aggregates (gravel 0, gravel 1, gravel 2, crushed stone and stone dust), the ATD between the production and use sites was 23.8 km. For sand from dredging, the distance was 10 km, while hydrated lime had an ATD of 20 km. All these materials are extracted and transported to the asphalt plant, which is their final destination. Regarding bitumen, the logistics involved initial transportation of petroleum of 300 km to the refinery, followed by an additional 70 km to the asphalt plant. For the asphalt used in priming, an ATD of 50 km was used from the refinery to the asphalt plant. An ATD of 10 km was considered for the transportation of materials that make up the surface and priming layer, from the plant to the highway construction site. In the case of the base, the ATD from the extraction of the gravel to the soil plant was 23.8 km, while the distance from the plant to the pavement construction site was 25 km. Finally, for the sub-base made up of borrow, the ATD from the excavation site to the construction site was just 1.5 km.

Based on the compositions shown in Table 3 and the ATDs established, a detailed analysis was carried out to identify the inputs corresponding to each stage of the scope. The volumes of material per layer were associated with the SICRO compositions, which enables the precise quantification of inputs and services. The data extracted from SICRO was then processed using "90 Compor®" software and systematically organized. This information was then made compatible with the SimaPro® software, using the Ecoinvent® library. This process required matching and adjusting the units of measurement between the SICRO databases and the Ecoinvent® inventory categories.

Thus, Tables 4 to 7 together show the sum of the amount of material, in tons, for each kilometer of road built, establishing one of the study's functional units, expressed in tons per kilometer built (t/km). From Table 4, the necessary conversions were made to obtain other metrics, such as tons of HMA and cubic meters of HMA. It should be noted that Tables 5 to 7 show the same amount of material for all the scenarios analyzed, since the thicknesses of the layers of primer, base and sub-base were kept constant.

Table 4. Quantity of materials from the extraction, manufacturing, machining, construction and operation stages for building the cladding layer: (Scenario 1, Scenario 2, Scenario 3, and Scenario 4)

Stage	Description in the Ecoinvent database	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Unity
1. Surfacing		Quantity	Quantity	Quantity	Quantity	
1.1 Extraction, manufacture and transportation to the asphalt plant	Gravel, crushed {BR}| market for gravel, crushed | APOS, U	126177.00	172807.00	216303.00	258924.00	kg
	Gravel, crushed {BR}| market for gravel, crushed | APOS, U	126177.00	172807.00	216303.00	258924.00	kg
	Gravel, crushed {BR}| market for gravel, crushed | APOS, U	277580.00	380164.00	475852.00	569615.00	kg
	Limestone, crushed, washed {RoW}| market for limestone, crushed, washed | APOS, U	75695.00	130669.00	129763.00	155332.00	kg
1.2 Extraction and manufacture of inputs	Sand {BR}| sand quarry operation, open pit mine | APOS, U	656110.00	898584.00	1124761.00	1346386.00	kg
	Bitumen adhesive compound, hot {GLO}| market for | APOS, U	85164.00	174762.00	145995.00	174762.00	kg
1.3 Transportation to the asphalt plant	Transport, freight, lorry 7.5-16 metric ton, EURO3 {BR}| transport, freight, lorry 7.5-16 metric ton, EURO3 | APOS, U	6561.10	8985.84	11247.60	13463.90	tkm
	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {BR}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | APOS, U	5961.48	8164.59	10219.70	12233.30	tkm
1.4 Asphalt plant	Heat, district or industrial, other than natural gas {RoW}| heat production, heavy fuel oil, at industrial furnace 1MW | APOS, U	336601.42	436730.45	577031.00	654370.96	MJ
	Diesel, burned in building machine {GLO}| market for | APOS, U	13.52	1877.82	2350.40	2813.54	MJ
	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	13.52	18.52	23.18	27.75	h
	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	10.82	14.89	18.55	22.20	h
1.5 Transportation from the asphalt plant to the construction site	Transport, freight, lorry 7.5-16 metric ton, EURO3 {BR}| transport, freight, lorry 7.5-16 metric ton, EURO3 | APOS, U	13468.90	18446.50	23089.50	27639.14	tkm
1.6 Layer construction	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	9.413	12.89	16.14	19.32	h
	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	10.87	14.89	18.64	22.31	h
	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	13.26	18.16	22.73	27.21	h
Total quantity of material for the construction of the surfacing layer		**1346.89**	**1844.65**	**2308.95**	**2763.91**	**t**

Note: *Unid: Unity

Table 5. Quantity of materials from the extraction, manufacturing, construction and operation stages of the machinery for carrying out the priming service (All scenarios)

Stage	Description of the Ecoinvent database	Quant.*	Un.**
2. Priming			
2.1 Extraction and manufacture of inputs	Bitumen adhesive compound, hot {GLO}| market for | APOS, U	4320.00	kg
	Kerosene {BR}| market for kerosene | APOS, U	4320.00	Kg
2.2 Transportation to the building site	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {BR}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO3 | APOS, U	432.00	tkm
2.3 Execution of the service	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	12.80	h
	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	6.40	h
Total quantity of material for the priming service		**7200.00**	**m²**

Note: *Quant.: Quantity; **UN.: Unity

Table 6. Quantity of materials from the extraction, machining, construction and operation stages for building the base layer (All scenarios)

Stage 3. Base	Description of the Ecoinvent database	Quant.*	Un.**
3.1 Extraction, manufacture of inputs and transportation to the soil plant	Gravel, crushed {BR}| market for gravel, crushed | APOS, U	859831.00	**kg**
	Gravel, crushed {BR}| market for gravel, crushed | APOS, U	238140.00	**kg**
	Gravel, crushed {BR}| market for gravel, crushed | APOS, U	422172.00	**kg**
	Gravel, crushed {BR}| market for gravel, crushed | APOS, U	855835.00	**kg**
3.2 Manufacturing in the soil plant	Transport, freight, lorry 7.5-16 metric ton, EURO3 {BR}| transport, freight, lorry 7.5-16 metric ton, EURO3 | APOS, U	9.54	**h**
	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	10.88	**h**
3.3 Transportation to the building site	Transport, freight, lorry 7.5-16 metric ton, EURO3 {BR}| transport, freight, lorry 7.5-16 metric ton, EURO3 | APOS, U	59400.00	**tkm**
4.3 Layer construction	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	10.88	**h**
	Diesel, burned in building machine {GLO}| market for | APOS, U	222.65	**MJ**
	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	4.96	**h**
	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	9.54	**h**
	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	3.24	**h**
Total quantity of material for building the base layer		**1080.00**	**m³**

Note: *Quant.: Quantity; **UN.: Unity

Table 7. Quantity of materials from the extraction, construction and operation stages for building the sub-base layer (All scenarios)

Stage 4. Sub-base	Description of the Ecoinvent database	Quant.*	Un.**
4.1 Extraction and manufacture of inputs	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	5.16	h
4.2 Transportation to the building site	Transport, freight, lorry 7.5-16 metric ton, EURO3 {BR}| transport, freight, lorry 7.5-16 metric ton, EURO3 | APOS, U	3341.25	tkm
4.3 Layer construction	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	4.77	h
	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	4.62	h
	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	4.82	h
	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	3.32	h
	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | APOS, U	5.97	h
Total quantity of material for the construction of the sub-base layer		**1080.0**	**m³**

Note: *Quant.: Quantity; **UN.: Unity

To reiterate, LCIA consists of transforming the results from the LCI processes of pavement infrastructures to assess their environmental impacts. These impacts are then categorized into intermediate impact indicators. The SimaPro software was used to integrate the database and the ReCiPe (H) LCIA method, version 1.07, into the LCA processes. The SICRO processes were translated into SimaPro using the Ecoinvent® database. It should be noted that by loading the layer characterizations for each scenario into the SimaPro software, it was possible to determine the contributions of each pavement to climate change. The codes selected from the Ecoinvent database, used to represent SICRO processes and services, followed the APOS methodology and the UNIT "U" type. Regarding considering the transportation required at each stage, we opted to use processes with the MARKET subtype, which already incorporates the transportation service. When it was not possible to use this type of process, i.e. when the processes belonged to the TRANSFORMATION subtype, transportation was considered separately.

4. Results and Discussion

This section presents the results of the application of the proposed methodological procedure.

4.1. Mechanistic Empirical Design

The mechanical properties of the materials, especially the resilient modulus, have a direct influence on the calculation of pavement thickness, as they represent the material's ability to support and distribute traffic loads. In general, asphalt mixtures with a higher resilient modulus tend to require a thinner structure to support the same load, while mixtures with a lower resilient modulus require a greater thickness to ensure the desired structural performance and service life. Table 8 shows the design results.

Table 8. Surfacing for each design scenario

AADT	PAC 30/45			PAC 50/70		
1350	**Scenario 1**			**Scenario 2**		
	CA (%)	WTD (mm)	thick. (cm)	CA (%)	WTD (mm)	thick. (cm)
	28.2	9.6	7.0	29.3	7.1	10.0
2700	**Scenario 3**			**Scenario 4**		
	CA (%)	WTD (mm)	thick. (cm)	CA (%)	WTD (mm)	thick. (cm)
	29.0	4.5	12.0	29.1	4.1	15.0

Note: AADT - Annual Average Daily Traffic; PAC - Petroleum Asphalt Concrete. thick. – thicknesses; CA - Cracked Area; WTD - Wheel Track Depression.

For an AADT of 1,350, Scenario 1 (PAC 30/45 asphalt) had a coating thickness of 7.0 cm, while Scenario 2 (PAC 50/70) had a thickness of 10.0 cm. This shows an inverse relationship between the resilient modulus of the mixtures and the required thicknesses, i.e. the mixture with the lowest resilient modulus (PAC 50/70 asphalt) required the greatest thickness. For an AADT of 2,700, Scenario 3 (PAC 30/45 asphalt) had a thickness of 12.0 cm and Scenario 4 (PAC 50/70 asphalt) 15.0 cm. In this case, all the thickness was determined by the cracked area (CA) criterion, and it is no longer possible to verify a direct and clear relationship between the resilient modulus and the final thickness, as was the case for the lowest level of traffic. Finally, it should be noted that all thicknesses increased in relation to the VMD level of 1,350, reflecting the direct impact of the increase in traffic on the design of the coating.

4.2. Life Cycle Impact Assessment (LCIA)

The sum of the contributions to climate change of the coatings for the field HMA execution of each scenario is shown in Figure 3. For both types of loading, the emissions are directly proportional to the thicknesses. However, the different types of HMA reacted differently, i.e. the same increase in traffic demand generated increases of different intensities in their greenhouse gas emissions. It can be seen that for an increase of 5 centimetres in the thickness of each coating, the increase in GHG emissions between scenarios 1 and 2 was 71%, and between scenarios 3 and 4 was 50%, respectively.

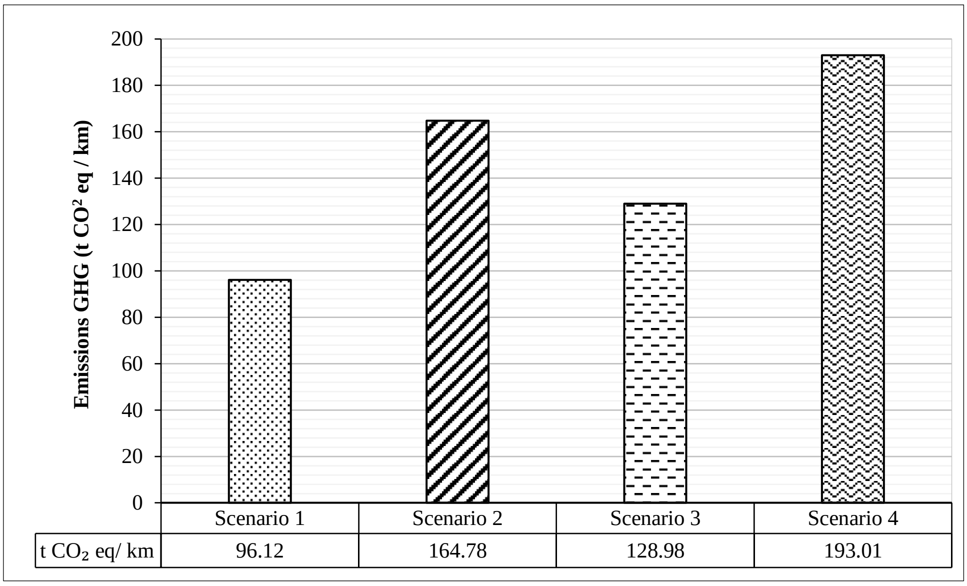
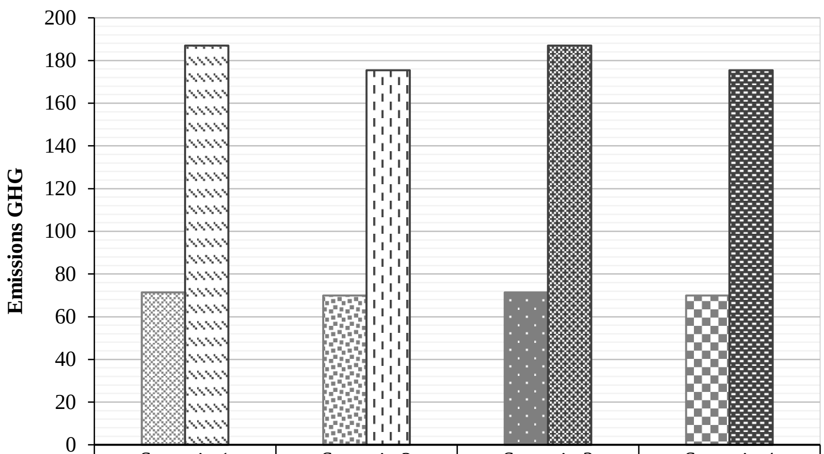


Figure 3. Amounts of CO_2 equivalent emitted by asphalt surfacing per kilometer built

This finding may indicate that, even if a HMA manages to pass the design process for a given loading situation, it does not necessarily mean that this HMA is the best choice from an environmental point of view for a wide range of traffic, given the uneven growth in emissions that each HMA can present, given the diversity of the processes that each HMA requires. The effects observed on emissions go far beyond a simple increase in the amount of material. It should be noted that each material has its own peculiarities in terms of the types and quantities of inputs and processes, each with their own impact on climate change.

Figure 4 shows the quantities of CO_2 equivalent emitted by all the processes required to obtain one ton and one cubic meter of HMA, machined and executed in the field, for each of the scenarios proposed in this work. It can be seen that, when presenting the results using the functional unit in Figure 4, the most efficient scenarios would be 3 and 4. However, determining the emissions per ton or per cubic meter of HMA does not express the real impact of the GHG emissions associated with the asphalt mixtures used in the construction of the stretches proposed in this study, since scenarios 1 and 2 have the most impactful tons for climate change, but have the best mechanical behavior and require lower thicknesses.



	Scenario 1	Scenario 2	Scenario 3	Scenario 4
kg CO_2 eq/ t HMA	71.37	69.92	71.37	69.92
kg CO_2 eq/ m³ HMA	186.98	175.43	186.98	175.43

Figure 4. Amounts of CO_2 equivalent emitted by asphalt coatings per ton and per m³ of hot-mix asphalt built

According to Vega et al. [18], who presented a compilation of studies comparing the environmental performance of HMA, the best functional unit for comparing the performance of asphalt mixtures is kg of CO_2 equivalent per cubic meter of HMA (kg CO_2 eq / m³ HMA). From the values presented in the work for HMA, emission rates are concentrated in the range of 100 to 200 kg CO_2 eq / m³ HMA. In her own research, she obtained an emission rate of 140 kg CO_2 eq / m³ HMA.

A joint analysis of Figures 3 and 4 highlights the importance of an integrated approach to HMA in the context of the pavement on which they will be applied. Otherwise, there is a risk of selecting coatings that, in isolation, perform better in terms of their contributions to climate change, but, together with the other pavement layers and underload simulations, do not adequately meet environmental criteria.

The simultaneous comparison of Table 8 and Figures 3 and 4, together with an understanding of the processes of extraction, manufacture, transportation of 0inputs, asphalt plant operations and construction of the layers, highlight the need to evaluate the coatings in the context of real loading. Firstly, the mechanical properties of coatings can directly influence the final thickness of the pavement, which has an impact on the amount of material required. Secondly, as already pointed out by Vega et al. [18], the differences between the life cycles of the mixtures, including the types and quantities of inputs, as well as variations in the manufacturing and construction processes, are determining factors for the environmental performance of the pavement.

4.3. Sensitivity Analysis

The sensitivity analysis was conducted considering the variation of the AADT, aiming to assess the impact of this variable on the structural characteristics of the pavement and the associated emissions. It was observed that the increase in AADT leads to an increase in the surfacing thickness for both types of binders, confirming the sensitivity due to different traffic load intensities. Moreover, even with similar resilient moduli, the combination of binder type and structural requirements results in significant differences in thickness, directly impacting greenhouse gas (GHG) emissions.

In the scenarios analyzed, the mixes made with PAC 30/45 asphalt showed greater sensitivity to variations in the average AADT, reflected in a more significant percentage increase in greenhouse gas (GHG) emissions. On the other hand, mixtures made with PAC 50/70 asphalt, although they require greater structural thickness to withstand high loads, show a less sensitive response in terms of emissions associated with increased traffic. This behavior indicates that, in the structural design of pavements, it is essential to consider not only the mechanical properties of the materials and the load demands, but also the analysis of environmental efficiency linked to different traffic intensities. In short, sensitivity to AADT is a determining factor in defining the structural layers of the sidewalk, showing that thicker solutions are needed for higher traffic volumes, regardless of the type of binder.

5. Conclusion

As highlighted, the functional unit is a quantitative reference standard adopted in an LCA to quantify the environmental impacts caused by each alternative evaluated, with the aim of ensuring fairness in the comparisons. To this end, the functional units considered the objectives, scope and physical characteristics of the alternatives to be evaluated. To highlight the importance of functional units in LCAs of asphalt pavements that evaluate asphalt mixtures, the study proposed an investigation into the effect of functional units in determining the environmental performance of asphalt pavements.

By applying the proposed procedure, it could be seen that the same mixtures would have different relative environmental performances, depending on the functional unit adopted to make the comparisons between the alternatives. In the case of paving, this choice of functional unit can end up excluding or including mechanical behavior, which is fundamental, given that the pavement is a structure that needs to resist the passage of traffic in a predictable way during its service life.

By analyzing the results obtained in this study and the literature review, it can be concluded that the selection of functional units can lead to an inadequate selection of asphalt mixtures if they are not evaluated together with the other constituent elements of the pavement under the expected design conditions. It is therefore proposed that LCAs should not be carried out on asphalt mixtures in isolation, but on asphalt pavement alternatives as a whole.

6. Declarations

6.1. Author Contributions

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

6.2. Data Availability Statement

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

6.3. Funding

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

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