

Comparative Life Cycle Assessment for Asphalt Mixtures with SBS-Modified Binders

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Road construction and rehabilitation are energy-intensive activities with considerable environmental impacts. This study presents a comparative Life Cycle Assessment (LCA) of asphalt pavement wearing courses manufactured with SBS-modified bitumen (PMB) and highly loaded bitumen (HPLA). Conventional unmodified bitumen was used as the reference scenario, whereas mixtures incorporating different contents of styrene-butadiene-styrene (SBS) block copolymer (modified and highly modified bitumen) were evaluated as alternatives. Three mixture types were analyzed to determine the most environmentally efficient option based on mechanical performance and service life.

The results demonstrate that SBS-modified binders significantly reduce the carbon footprint of asphalt mixtures when durability is considered. Their enhanced mechanical properties enable longer service life and allow for structurally optimized designs, reducing both material consumption and maintenance frequency. Depending on the scenario, the use of modified binders leads to a carbon footprint reduction of 10-47%.

These findings underscore the importance of durability as a key factor in evaluating the life cycle of bituminous mixtures. SBS-modified binders emerge as a viable strategy for reducing greenhouse gas emissions and extending pavement lifespan, aligning with the decarbonization objectives of the transport sector.

Keywords: SBS modified binders, highly loaded bitumen, Life Cycle Assessment, Durability, Carbon Footprint.

1. INTRODUCTION

There is a growing interest in the investigation of new materials that can reduce the overall maintenance costs of pavements, while simultaneously maximizing their durability, minimizing greenhouse gas emissions to the atmosphere, and reducing the consumption of non-renewable resources. Since more than 90% of roads worldwide are paved with asphalt mixtures, the development of high-performance, sustainable materials plays a fundamental role in the decarbonization of road infrastructure and in achieving the targets set by the European Green Deal and the United Nations 2030 Agen-

da [1], which include reducing the carbon footprint of construction and pavement maintenance activities by at least 55% by 2030, and achieving net-zero emissions by 2050.

One of the most common solutions to achieve high performance in the design of asphalt mixtures is the use of modified binders. The incorporation of polymers enhances the mechanical response of these materials, extending their service life and providing significant benefits to users in terms of safety, as well as to administrations in terms of maintenance investment. Among the various polymers employed for bitumen modification, styrene-butadiene-styrene (SBS) block copoly-

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mers [2] are the most widely used due to their excellent elastomeric properties, compatibility with bitumen, and ability to significantly enhance the mechanical performance and thermal stability of asphalt mixtures [3]. SBS modified binders can help optimize the use of materials during pavement construction, thereby contributing to the reduction of its carbon footprint. However, it is essential to objectively quantify the extent of the potential environmental benefits associated with the reduced material consumption required throughout the pavement layer's life cycle because of improved, in comparison to the impacts generated during production due to the increased consumption of bitumen or polymers.

To understand, identify, and quantify the potential improvements in carbon footprint associated with the use of modified binders, it is necessary to use the Life Cycle Assessment (LCA) methodology [4]. LCA is a systematic evaluation tool that enables the study, identification, measurement, and quantification of the potential environmental impacts of asphalt mixtures throughout their complete life cycle: from raw material extraction, production, and distribution, to use and end-of-life. This methodology quantifies the resources consumed throughout the life cycle to define strategies for impact reduction by identifying areas for improvement and eliminating or minimizing environmental deficiencies.

The main scopes of the different life cycle assessment types are as follows:

- Cradle-to-gate: A partial life cycle that covers processes from raw material extraction (cradle) to the factory gate, excluding the use and end-of-life phases.
- Cradle-to-grave: A comprehensive life cycle assessment that includes all stages, from raw material extraction to final disposal.
- Cradle-to-cradle: A closed-loop approach in which recycled materials and construction residues are reintegrated into the raw material processing stage, promoting circularity.

Many tools applied to bituminous mixtures perform a "cradle-to-gate" [5] LCA, focusing solely on product

manufacturing (raw material extraction, transport to the plant, and mix production), while excluding impacts from transport to site, placement (e.g., workability, equipment efficiency), and service life (e.g., mechanical performance and durability). Under such conditions, high-performance mixtures, such as those with higher binder content or modified binders, are environmentally penalized.

If material durability is not considered in the LCA, mixtures using modified binders, regardless of type, will appear environmentally less favorable due to the impacts associated with polymer production. However, since these modified binder mixtures provided improved mechanical properties and/or more efficient structural design, the LCA methodology applied in this study is based on the comprehensive collection and evaluation of environmental impact inputs and outputs throughout the life cycle of bituminous mixtures. This includes estimating durability using laboratory tests. Durability, understood as the service life of the functional unit, is one of the most critical parameters in cradle-to-grave life cycle assessments (LCA) of bituminous mixtures [6]. It depends on a wide range of factors, including volumetric composition, aggregate and binder properties, structural performance, construction quality, and in-service conditions such as climate and traffic loads. Since durability directly influences the environmental impact of a mixture, reduced maintenance needs or lower material consumption becomes essential when comparing different mixture types.

2. MATERIALS

Table 1 summarizes the main characteristics of the asphalt mixtures studied. To avoid introducing a greater number of variables into the study, the mineral skeletons used in the production of the different types of mixtures were the same. In the case of AC 22 mixtures, the mineral skeleton consisted of limestone aggregates both in the gravel and sand fractions, using calcium carbonate as filler.

Meanwhile, the mineral fraction of the BBTM 11B mixtures was composed of trachyte aggregates in the gravel fraction and limestone aggregates in the sand

Table 1. Properties of the mixtures under study.

Nomenclature	Type of Mixture	Type of Binder	Origin	Manufacturing Temperature [°C]
AC 22 B	AC 22	B 50/70	Refinery	160
AC 22 PMB		PMB 45/80-65	Refinery	165
AC 22 HPLA		HPLA 45/80-80	LabI.C.UGR	165
BBTM 11B B	BBTM 11B	B 50/70	Refinery	160
BBTM 11B PMB		PMB 45/80-65	Refinery	165
BBTM 11B HPLA		HPLA 45/80-80	LabI.C.UGR	165

fraction, also using calcium carbonate as filler.

The polymer modified bitumen (PMB) used in the study was type 45/80-65 with a SBS content of $\approx 4\%$, while the highly polymer loaded bitumen (HPLA) was type 45/80-80, with a SBS content of 8%. The SBS used to produce polymer-modified bitumen typically contains 30 - 35% styrene by weight, with a vinyl content of 10 - 15% relative to butadiene. In contrast, SBS grades designed for highly loaded bitumen formulations contain 35 - 40% styrene by weight and exhibit a vinyl content ranging from 40 - 60% relative to butadiene. These compositions help balance rigidity and elasticity, impro-

ving both bitumen compatibility and performance in varying temperatures. These SBS are generally found in either linear or radial block forms, and their viscosity in 25% by weight in toluene at 25°C typically falls between 4,000–20,000 cP.

The compositions of AC22 and BBTM 11B mixtures for the various scenarios under consideration are presented in Tables 2 and 3 below.

Table 2. Composition of AC 22 mixtures.

Component	Scenario		
	AC 22 B [kg/T]	AC 22 PMB [kg/T]	AC 22 HPLA [kg/T]
Limestone sand (0/6 mm)	468		
Limestone gravel (6/12 mm)	143		
Limestone gravel (12/18 mm)	153		
Limestone gravel (18/25 mm)	143		
Added filler (carbonate)	48		
Bitumen B50/70	45	-	-
Bitumen PMB 45/80-65	-	45	-
Bitumen HPLA	-	-	45
Manufacture Temperature [°C]	160	165	165

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Table 3. Composition of BBTM 11B mixtures.

Component	Scenario		
	BBTM 11B B [kg/T]	BBTM 11B PMB [kg/T]	BBTM 11B HPLA [kg/T]
Limestone sand (0/6 mm)	242		
Trachyte gravel (6/12 mm)	662		
Added filler (carbonate)	48		
Bitumen B50/70	48	-	-
Bitumen PMB 45/80-65	-	48	-
Bitumen HPLA	-	-	48
Manufacture Temperature [°C]	160	165	165

3. METHODOLOGY

3.1 Goal and Scope definition

The objective of this research is to evaluate the sustainability of SBS modified and highly loaded bitumen in the production of asphalt mixtures through LCA methodology, by determining the carbon footprint (CF) of asphalt mixtures produced with binders of different modification grades, compared to an asphalt mixture produced with a conventional bitumen under the same conditions. This evaluation is based on actual data obtained from laboratory testing and from the construction and service life of roads and highways, as well as from globally recognized databases and inventories (Ecoinvent [7], Asphalt Institute, Eurobitume, Ministry for Ecological Transition and the Demographic Challenge of the Government of Spain and EPDs). This study was carried out in accordance with the UNE-EN ISO 14040:2006, UNE-EN ISO 14044:2006/A1:2018, UNE-EN ISO 14067:2019, UNE-EN ISO 14025:2010, and UNE-EN 15804:2012+A2:2020/AC:2021 standards, which provide specific modeling rules for construction products, including asphalt mixtures.

This study evaluates the potential environmental impacts associated with the complete life cycle of asphalt pavement wearing courses composed of bituminous mixtures incorporating SBS-modified (PMB), SBS-highly loaded (HPLA) and conventional bitumen. The analysis

considers three mixture types: AC 22 and BBTM 11B, under three reference scenarios using unmodified bitumen (AC 22 B and BBTM 11B B), two alternative scenarios with SBS-modified bitumen (AC 22 PMB and BBTM 11B PMB), and two additional scenarios with SBS-highly loaded bitumen (AC 22 PMB and BBTM 11B PMB). The bitumen concentration in AC22 mixtures is 4.5%, and in BBTM 11B is 4.8%.

The reference scenarios are derived from standard pavement reinforcement procedures:

- Asphalt concrete pavement (AC 22 scenario): Milling and replacement on a single carriageway of a conventional road (6 cm thickness, 9 m width, and 3,000 m length), totaling approximately 27,000 m² of hot-mix asphalt using conventional B 50/70 bitumen.
- Thin asphalt concrete mixtures (BBTM 11B scenario): Milling and replacement on a dual carriageway of a highway (3 cm thickness, 10.5 m width, and 6,000 m length), totaling approximately 126,000 m² of hot-mix asphalt using conventional B 50/70 bitumen.

3.2 Description of the system boundaries

The system boundaries define the process units considered in the life cycle assessment (LCA), which are established based on the different stages of the life cycle of the studied bituminous mixture layers. These stages are modeled through individual yet interconnected modules. To standardize Environmental Product Declara-

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dary closes at (C2), in the point of transport to a nearby asphalt plant for reuse. To limit the number of processes to be considered in the study, a 2% cutoff threshold was applied, excluding processes contributing less than this value to the impact categories as residual. A schematic illustration of the system boundaries is shown in Figure 2.

Durability is a complex parameter influenced by multiple factors, including volumetric properties, aggregate and binder characteristics, structural strength and capacity of the mixture, construction quality, and service conditions. Due to the uncertainty associated with the durability of a pavement mixture under specific construction and service conditions, a durability coefficient has been introduced to integrate material performance during the use phase (B1). This coefficient, developed by LabIC.UGR, is based on the mechanical properties of the material, assessed through laboratory tests focused on structural response and resistance to deterioration under traffic loads, climatic agents, and aging. These properties are compared with those of reference asphalt mixtures with known service life on Andalusian roads. The coefficient is calculated using functions calibrated against traditional mixtures of the same typology with documented durability under defined traffic conditions.

3.3 Functional unit

The functional unit is defined as the layer subjected to equivalent traffic and environmental conditions throughout its service life. It is based on geometry (thickness), traffic loads, environmental exposure, and durability. For this study, the functional unit is one square meter of wearing course. However, due to differences in mechanical performance, this unit may vary in thickness or durability across mixtures.

Due to the variability in traffic and climate conditions, and considering that the LCA is comparative, it is assumed that all mixtures will perform under comparable conditions to those of reference wearing courses within the Andalusia region of Spain. The reference analysis period is set at 8 years for BBTM mixtures and 10 years for AC mixtures, based on average service lives observed in

conventional pavements. In alternative scenarios using polymer-modified bitumen (PMB), the analysis period may vary depending on whether the durability coefficient is applied.

3.4 Inventory analysis

Primary and secondary data were collected to develop the life cycle inventory. Primary data were obtained from pavement construction/reinforcement projects conducted in the south of Spain over the past five years. These included: laboratory tests on bituminous mixtures and core samples, direct emission and temperature monitoring during production and worker surveys.

To estimate the environmental impacts associated with the use of the materials studied throughout their service life, a series of laboratory tests were conducted to evaluate and compare their mechanical properties and durability. The following tests were conducted:

- Water sensitivity (UNE-EN 12697-12).
- Wheel tracking at 60 °C (UNE-EN 12697-22).
- Cracking due to thermal contraction (UNE-EN 12697-46).
- Structural strength and fatigue cracking resistance (UGR-FACT) (UNE 41210).

A durability coefficient, based on the laboratory tests results, has been calculated using a set of functions calibrated against reference mixtures of the same type with known service lives under specific traffic conditions. By inputting the mechanical performance data of the studied mixtures, two types of equivalence coefficients can be derived: (i) an equivalent heavy vehicle coefficient for a fixed layer thickness (VhP-eq.), and (ii) an equivalent layer thickness coefficient for a fixed traffic load (e-eq.).

The secondary data used relates to the production of raw materials, such as bituminous binders and additives, obtained from reports of similar studies or from consistent and up-to-date databases. The life cycle inventory data associated with the production of asphalt binders and modified asphalt binders were modeled based on information provided by leading international associations of manufacturers of these materials ([9-10]), as well as recent literature from similar LCA studies and more localized EPDs).

3.5 Impact assessment

To ensure maximum accuracy, this study considers only the classification and characterization phases.

Consequently, impacts related to the rest of the pavement structure or to other processes and materials involved in activities preceding or following the application of the surface layer, such as tack coats, road markings, vertical signage, delineation, lighting, etc., have not been considered. These processes are assumed to be identical across scenarios and therefore do not introduce relevant variations for the study's objectives.

4. RESULTS AND DISCUSSION

Based on the experiments performed in the laboratory, as well as the density values of each of the mixtures studied, the required quantities of AC 22 and BBTM 11B mixtures for pavement reinforcement have been calculated, considering both equal design thickness and structural. At equal thickness, AC 22 mixtures with modified bitumen require 2% less material due to lower density,

while BBTM 11B mixtures show no change. When accounting for structural equivalence, material reductions reach 13% (AC 22 with modified bitumen), and 37% for BBTM 11B mixtures.

Using the quantities of raw materials and the associated impacts of their procurement, the carbon footprint corresponding to each module was calculated for each of the scenarios considered.

Figure 3 shows the global carbon footprint (calculated as the sum of all LCA modules) of the functional units for each mixture studied across the different scenarios, excluding their mechanical properties (durability, module B1). The results show that, when durability is not accounted for, mixtures produced with conventional bitumen exhibit slightly lower environmental impacts compared to those with modified or highly loaded bitumen. The incorporation of modified bitumen results in an approximate increase of 2.6% in carbon footprint for AC 22 scenarios and 5.5% for BBTM 11B scenarios, while for highly loaded bitumen is 6.2% and 10.6% respectively.

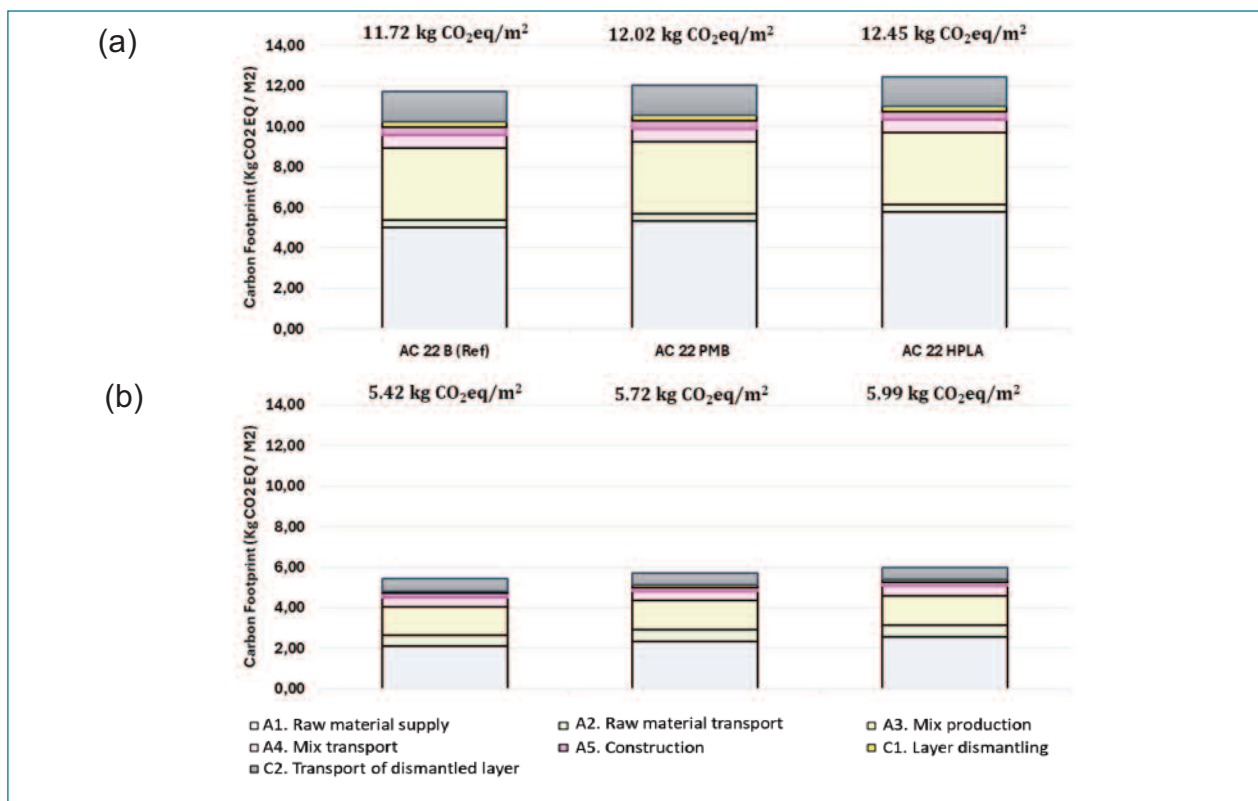


Figure 3. Environmental impacts assessed in the LCA of the different (a) AC 22 and (b) BBTM 11B scenarios, assuming equal layer thickness and without considering mixture durability.

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It is common for the accuracy of LCA calculations to vary between 10% and 20% for individual scores, and around 10% for characterized results. Therefore, LCA outcomes that do not account for the mechanical properties of the mixtures should be considered comparable, i.e., under the evaluated scenarios, no significant differences are observed between the use of conventional or modified bitumen when performing a cradle-to-grave LCA without considering durability. Conversely, when the durability of each mixture type (module B1 in Figure 2) is included in the LCA across the different scenarios (Figures 4 and 5), the differences become significant. In

scenarios with varying layer thicknesses but equivalent durability between mixtures (e-eq., Figure 4), the use of modified bitumen enables carbon footprint reductions of 9.4% for AC 22 mixtures and 29.4% for BBTM 11B mixtures; and for highly loaded bitumen the reductions reach 20.4 % for AC 22 and 26 % for BBTM 11B. Furthermore, in scenarios with equal layer thickness but accounting for the durability of each mixture type (VhP-eq., Figure 5), the use of modified bitumen results in carbon footprint reductions of 35.6% for AC 22 and 39.7% for BBTM 11B mixtures; and for highly loaded bitumen 46.9 % and 36.8 % respectively.

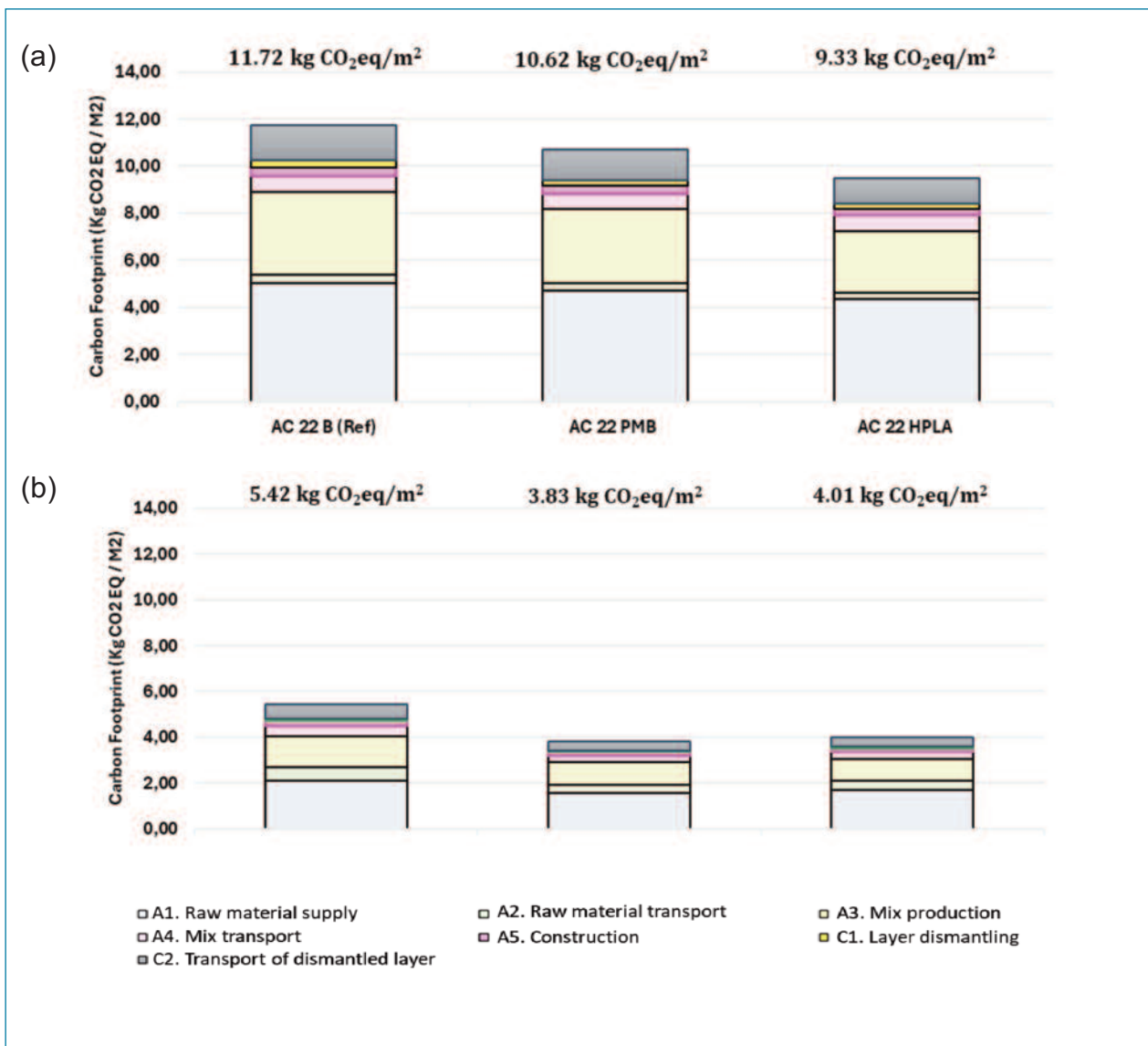


Figure 4. Environmental impacts obtained in the Life Cycle Assessment (LCA) of the different AC 22 (a) and BBTM 11B (b) scenarios under varying layer thicknesses..

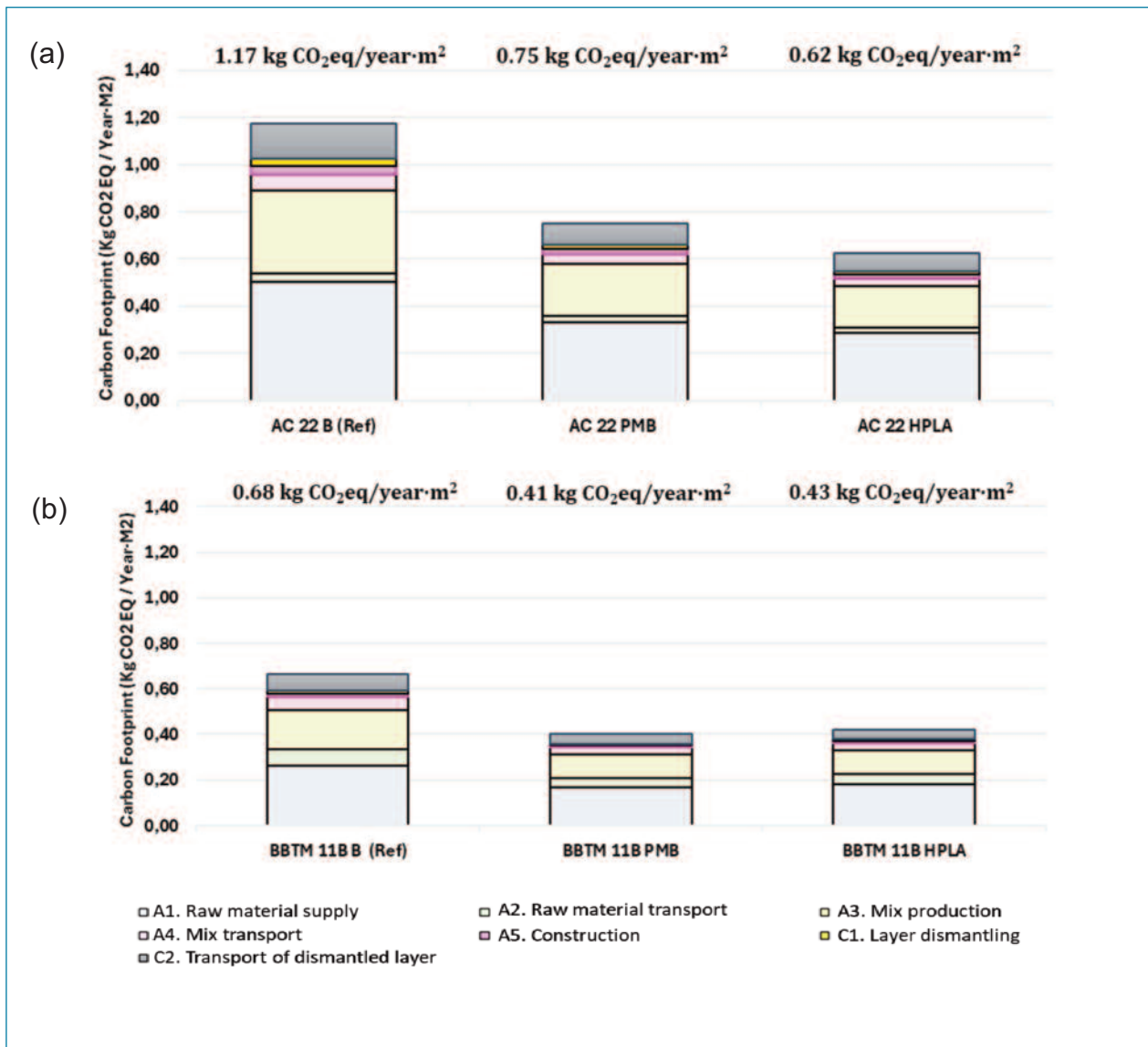


Figure 5. Environmental impacts obtained in the Life Cycle Assessment (LCA) of the different AC 22 (a) and BBTM 11B (b) scenarios under equal layer thickness, considering the durability of the mixtures.

These results show that considering durability, modified bitumen significantly reduce carbon footprint due to improved mechanical performance and extended service life. They also enable thinner, structurally efficient designs, reducing material consumption for equivalent performance.

BBTM 11B mixtures have about 15% higher carbon footprint per ton than AC 22, but their thinner application (3 cm vs. 5-8 cm) results in a 50-65% lower footprint per m².

The main contributors to carbon footprint are raw material supply (A1) and mixture production (A3), ac-

counting for over 70% in AC 22 and 65% in BBTM 11B scenarios. Transport stages (A2, A4 and C2) contribute ~20% and ~30%, respectively. Construction and demolition account for just 3-4% and about 2% of total emissions, respectively.

Within module A1, the most impactful stage, the bituminous binder is the primary contributor to the carbon footprint, accounting for over 40% of the environmental impacts in this module. Despite representing less than 5% of the mixture by weight (4.5% in AC 22 and 4.8% in BBTM 11B), its environmental burden is significantly higher than that of aggregates, which make up ~95%

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of the mixture but have a comparatively minor impact. This highlights the usefulness of the study's approach, which maintains the binder content and focuses solely on assessing the environmental effects of both traditional and modified binders.

The analysis shows that if material durability (B1 in Figure 2) is not considered, the inclusion of SBS in PMB increases the environmental impact due to their high associated emissions. However, in a full cradle-to-grave LCA, the increase is relatively modest, 2-5% for PMB, and 6-10 % for HPLA; compared to 4-9% and 7-13% in cradle-to-gate assessments. These differences are not substantial, suggesting that even without accounting for durability, the carbon footprint of mixtures with modified bitumen remains comparable to those with conventional ones.

Overall, this study provides an objective measurement of how modified binders can benefit the environment by showing that, although their production has a greater impact, this is balanced out by using less material and achieving better durability. In addition to their technical advantages, SBS-modified binders improve sustainability in road construction and rehabilitation through extended service life, decreased maintenance requirements, and improved safety for users.

In addition to binder type, the study identifies two other key contributors to carbon footprint reduction: mixture production (A3) and material transport (A2, A4 and C2). In module A3, energy consumption for aggregate heating and drying accounts for up to 70% of emissions. Consequently, reducing production temperatures, utilizing aggregates with lower moisture content, or transitioning to cleaner energy sources, such as substituting fuel oil, can substantially mitigate environmental impacts.

Transport distances also play a critical role. Using locally sourced materials, especially in the case of the aggregates, and applying mixtures near their production site can reduce emissions. Moreover, modified and highly loaded bitumen that enable thinner pavement structures are particularly beneficial when transport distances are long, as they reduce the volume of materials required.

5. CONCLUSIONS

This study assessed the environmental sustainability of using SBS-modified binders in the production of bituminous mixtures through Life Cycle Assessment (LCA). The analysis revealed that binder production, aggregate heating and drying, and material transportation are the main contributors to environmental impact, while the additional impacts associated with SBS modification or higher manufacturing temperatures are comparatively minor. Consequently, the carbon footprint of mixtures containing SBS-modified and highly loaded binders is comparable to that observed in mixtures utilizing conventional binders.

Beyond maintaining mechanical performance, the use of SBS-modified binders significantly enhances pavement durability and enables substantial reductions in carbon footprint. When the layer thickness is equal, SBS-modified bitumen enhances mechanical performance, leading to a longer service life and a reduction in emissions by about 35 to 40%, and 37-47% for highly loaded bitumen. Furthermore, utilizing these materials enables structurally optimized designs that maintain equivalent durability with decreased layer thickness, leading to an additional 10-30% reduction in carbon footprint for SBS-modified bitumen, and 20-26% for highly loaded bitumen. These benefits are particularly relevant when raw materials must be transported over long distances, as material savings amplify environmental gains.

The findings clearly demonstrate that SBS modification is a game changer for asphalt performance and sustainability. Mixtures with PMB, with SBS content ($\approx 4\%$), already deliver remarkable improvements over conventional bitumen, extending service life and reducing environmental impact. Going a step further, HPLA with its higher SBS content (8%), unlocks even greater potential, combining superior durability with significant carbon footprint reductions. These results position SBS-modified binders as a strategic solution for building longer-lasting, more sustainable pavements.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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