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HOW SUSTAINABLE ARE INNOVATIVE NOISE MITIGATION ROAD PAVEMENTS? AN LCA APPROACH

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ABSTRACT

The use of innovative materials is being experimented in asphalt mixtures to improve acoustic performance of road pavements with the aim of mitigating noise as one of the impacts generated by road infrastructures. However, further investigation is required to evaluate their sustainability.
To this end, as part of the LIFE SILENT project- aimed at developing innovative and sustainable solutions for mitigating road and railway noise- a comparative Life Cycle Assessment (LCA) has been conducted to assess the environmental impacts of asphalt mixtures incorporating recycled and innovative components.
The LCA has considered multiple processes involved in the application of asphalt mixtures, from raw material extraction and transportation to manufacturing and laying, as each of these contributes to the overall impact. The study compares 8 alternatives of asphalt mixtures, that differ from each other for the presence of traditional or innovative materials, such as crumb rubber. The latter enhances the acoustic performance of the paved surface and could provide environmental benefits, being a secondary raw material.
This approach enables standardized assessments at system level, offering the opportunity to compare the impacts of either different flows within the same process or different product alternatives, to identify and promote more sustainable practices.

Keywords: *life cycle assessment, asphalt mixtures, environmental impacts, acoustic performance*

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1. INTRODUCTION

Asphalt mixtures are essential materials in modern infrastructures, widely used in the construction of roads and other surfaces. These mixtures are composed of a variety of materials, including aggregates, bitumen, and, increasingly, recycled and innovative components, such as the ones used for the road pavements developed in the LIFE SILENT project that are the focus of this paper.
The production and application of asphalt mixtures involves multiple and various processes, from raw material extraction and transportation to manufacturing and construction. Each of these stages contributes to the overall impact of asphalt, making its environmental life cycle assessment (LCA) a highly complex task.
A comprehensive LCA is based on extensive and detailed data collection and analysis and often requires the definition of assumptions for calculations; therefore, changes in material composition and processes for asphalt mixture production involve significant variability in LCA outcomes. Therefore, a life cycle thinking (LCT) method represents a powerful tool to compare product alternatives and have a detailed understanding of generated impacts.

2. THEORETICAL FRAMEWORK AND RESEARCH GOAL

Sustainability assessment methodologies in road infrastructure design and construction have been extensively addressed and rated by the scientific literature [1-3], highlighting their capacity to innovate existing procedures and approaches. While the importance of sustainability is nowadays recognized in all aspects of life [4], the significant weight of road infrastructures in destabilizing the environment has stimulated strategic and proactive approaches towards the adoption of low-emissions and energy saving

solutions starting from the phases of infrastructures design [5-7]. In particular, the application of a life cycle assessment (LCA) to road pavement industry has been receiving considerable attention by practitioners and policy makers for the recognised ability of this methodology to assess the performance of materials and products throughout their life cycle [8-10], considering both their technical and environmental characteristics.
In this context, this work contributes to the existing studies focused on the potential of innovative materials in asphalt mixtures to help alleviating the environmental burden of road pavements [11-13]. The comparison of multiple additives through the LCA approach has been helpful to assess the consequences and to highlight the hotspots of incorporating innovative solutions into asphalt mix production, contributing in particular to the assessment of the use of crumb rubber in asphalt mixtures [14-18].
Crumb rubber is a recycled material obtained from end-of-life tires (ELT) through mechanical shredding and grinding processes. It can be used as an additive in asphalt mixtures to enhance performance characteristics such as durability, flexibility, and above all noise reduction. By incorporating crumb rubber into asphalt, the material, besides improving the mechanical properties of road surfaces, contributes to the overall asphalt's sustainability, by reducing tire waste and minimizing the demand for virgin raw materials. The LCA approach inquires further in the environmental impacts of its production, including the energy-intensive chipping process, to fully assess its benefits.
Against this framework, the goal of the paper is to assess the sustainability of innovative and low-noise road solutions developed in the LIFE SILENT project through an LCA study. In particular, the paper aims to contribute to the assessment of environmental impacts, paying attention to the analysis of hotspots generated by incorporating innovative solutions into asphalt mix production.

3. METHODOLOGICAL APPROACH

For the purposes of this study, the LCA work breakdown structure of the analysis conducted, aligned with international sectorial standards, consists in the following steps:

A) Scope definition;
B) Base assumption and Inventory analysis (LCI);
C) Selection of impact categories and Impact assessment for the selected impacts (LCIA);
D) Results interpretation.

A) <u>SCOPE</u>

Comparative LCA analysis constitutes a useful and adaptable tool for identifying and promoting more sustainable practices; this applies also to asphalt mixture design and production as required by CAM Strade - the ministerial decree nr. 279/2024 indicating the Minimum Environmental Criteria for the design, construction, and maintenance of road infrastructures. The scope of the LCA analysis reported in this paper is to present and compare LCA results for 8 alternatives of closed asphalt mixtures, which are listed and described in the table below.

Table 1. Description of the 8 asphalt mixture alternatives.

Type	Description
A	This traditional asphalt type, developed by ANAS and used as a reference scenario in the LIFE SILENT project, includes bitumen and stone aggregates. Its composition contains a slightly higher percentage of bitumen and a lower percentage of aggregates in comparison to type B.
B	This traditional asphalt type, developed according to regulatory standards in the LIFE SILENT project, includes bitumen and stone aggregates, and is used as a reference scenario together with type A.
2	This new asphalt type, developed within the LIFE SILENT project, includes bitumen, stone aggregates, crumb rubber, warm mix asphalt additives, and treated cellulose fibre. Its composition contains the highest percentage of warm mix asphalt additives, compared to all other new types.
4	This new asphalt type, developed within the LIFE SILENT project, includes bitumen, stone aggregates, crumb rubber, additives for warm mix asphalt and cellulose fibre. Its composition contains the same percentage of additives for warm mix asphalt as types 5 and 6, and lower percentage compared to types 2, 7 and 8.

5	This new asphalt type, developed within the LIFE SILENT project, includes bitumen, stone aggregates, crumb rubber and additives for warm mix asphalt. Its composition contains the same percentage of additives for warm mix asphalt as types 4 and 6, and a lower percentage compared to types 2, 7 and 8.
6	This new asphalt type, developed in the LIFE SILENT project, includes bitumen, stone aggregates, crumb rubber, hot asphalt additives and treated cellulose fibre. Its composition contains the same percentage of additives for warm mix asphalt as types 4 and 5, and a lower percentage compared to types 2, 7 and 8.
7	This new asphalt type, developed in the LIFE SILENT project, includes bitumen, stone aggregates, crumb rubber, hot asphalt additives and treated cellulose fibre. Its composition contains a higher percentage of hot asphalt additives compared to types 4, 5 and 6, but a lower percentage compared to type 2. Also, the amount of treated cellulose fibre is lower than in mixtures 2 and 6.
8	This new asphalt type, developed in the LIFE SILENT project, includes bitumen, stone aggregates, crumb rubber, hot asphalt additives and treated cellulose fibre. Its composition contains a higher percentage of hot asphalt additives compared to types 4, 5 and 6, but a lower percentage compared to type 2. In addition, the amount of treated cellulose fibre is lower than in types 2 and 6. It differs from all other new types by the lower amount of crumb rubber.

B) BASE ASSUMPTION AND INVENTORY ANALYSIS

Determining raw material inputs, energy requirements, and other fundamental data is a critical step in conducting comprehensive and close-to-reality LCA studies.
The baseline assumptions and the inventory analysis are described in the following:
The *declared unit* is one square meter of pavement.

The *system boundary* is *"Cradle-to-Gate"* with declared modules of life stages A1 to A5 (see table below). The setting of calculation follows the Allocation Cut Off System model in line with regulatory standards [19-21] and PCRs [22-23], and meets the requirements set by EN 15804+A2:2019 in compliance with the end-of-waste criteria [24].

Table 2. Life cycle stages [22].

Product Stage			Construction process stage		Use Stage	End of life Stage	Benefits and loads beyond the system boundary
A1	A2	A3	A4	A5	B1-B7	C1-C4	D
Raw materials supply	Transport	Manufacturing	Transport	Construction-Installation	Modules not declared		

Geographical aspects were considered those as representative as possible of the life cycle processes of the mixtures analysed.
Data Quality is assured using the most recent available datasets and internationally recognized database. The software employed for the assessment is OpenLCA, which allows for a detailed evaluation of the environmental impacts associated with asphalt mixture production and installation through the use of Ecoinvent 3.10 and other specifically selected datasets.
Necessary data from the production, transportation and installation processes are collected using the best available datasets, including both primary and secondary data collection, such as:

- consultations and data exchange with industry specialists: for material and other input selection and *quantity estimation*;
- sectorial scientific literature: utilized when direct access to experts' data was not available;
- official database "Ecoinvent 3.10 – 15804 Unit process Cut-off", and publicly available LCA studies: for supplementary data and validation.

Besides, the baseline assumptions on material inputs are established for LCA calculations. While specific input

quantities are not detailed in this paragraph, the association of calculation inputs with relevant environmental datasets is provided to introduce the assumptions of the analysis.
The following table summarizes the inputs considered in the model along with their corresponding data sources used later for the impact assessment.

Table 3. Datasets used for each life cycle stage.

Life Cycle Stage	Data source
A1	LCI by Eurobitume, 2012 [25] LCI by Ortega et al., 2023 [26] Ecoinvent 3.10 [27]
A2	Ecoinvent 3.10 [27]
A3	
A4	
A5	

Additionally, assumptions regarding energy consumption and transportation distances are made based on the best available data sources. The energy consumption associated with the manufacturing of asphalt mixture production process is derived from technical plant sheets provided by LIFE SILENT partners.
Similarly, transportation distances for materials and finished products were estimated based on discussions with sector experts, aiming to the most realistic representation of logistics and supply and transport chain.

C) SELECTION OF IMPACT CATEGORIES AND IMPACT ASSESSMENT

The methodology adopted for identifying the environmental Impact Categories, and relative KPIs, consists of a literature review carried out as a joint work of the project partners and consolidated in specific meetings. For the literature review were considered, among others, European and international standards, scientific journals and research projects' reports, as well as FS Group internal documents. The initial list of KPIs resulted from the literature review was further refined through desk analysis and validated in a workshop held with the project partners, in order to cover all the life cycle phases of the solutions developed in the project. This process has been critical to confirm the reliability of the methodology and refine its reproducibility.
Impact Categories and indicators used for this LCA study are listed in the following table. The choice of KPIs started from the EN 15804+A2 (EF v3.1) standard, which has a high relevance being among the main standards of the LCA and found to be recurring as a source also in other documents of the literature reviewed.
In addition to the 14 indicators of the most known 7 Environmental Impact Categories, the table lists also:
• 6 indicators for the 5 additional Environmental Categories;
• 5 indicators for the category Outgoing Flows;
• 10 indicators for the category Consumption of Resources;
• 3 indicators for the Waste category.
This makes a total of 15 impact categories and 38 indicators used for the LCA of the LIFE SILENT project asphalt mixtures.

Table 4. Impact Categories and KPIs used for LCA.

Impact category	Indicator (Acronym)	Unit of measure
Environmental		
Abiotic depletion potential	ADP - fossil resources (ADPF)	MJ
	ADP - non-fossil resources (mineral and metal) (ADPE)	kg Sb eq.
Acidification Potential	AP, Accumulated Exceedance (AP)	Mol H+ eq
Ozone depletion Potential	Depletion potential of the stratospheric ozone layer (ODP)	kg CFC 11 eq.
Eutrophication potential	EP – freshwater	kg P eq.
	EP - marine	kg N eq.
	EP - terrestrial	mol N eq.
Global Warming Potential	GWP - biogenic	kg CO2 eq.
	GWP - fossil fuels	kg CO2 eq.
	GWP - land use and land use change	kg CO2 eq.
	GWP - total	kg CO2 eq.
	GWP except emissions and uptake of biogenic carbon (GWP-GHG)	kg CO2 eq.
Photochemical Ozone Creation Potential	POCP	kg NMVOC eq.
Water Depletion potential	Water (user) deprivation potential (WDP)	m3 world eq. deprived
Ecosystem Potential Toxicity	Potential Comparative Toxic Unit for ecosystems (freshwater) (ETP-fw)	CTUe
Additional environmental impacts		
Human Toxicity Potential	Potential Comparative Toxic Unit for humans - cancer effects (HTP-c)	CTUh
	Potential Comparative Toxic Unit for humans - non-cancer effects (HTP-nc)	CTUh
Ionizing radiation	Potential Human exposure efficiency relative to U235 (IRP)	kBq U235 eq.
Particulate Matter emissions	Potential incidence of disease due to PM emissions (PM)	Disease Incidence
Soil Quality Potential	Potential Soil quality index (SQP)	Adimensional
Outgoing flow (energy and other materials)		
Outgoing Flows	Components for re-use (CRU)	kg

	Exported electrical energy (EEE)	MJ
	Exported thermal energy (EET)	MJ
	Materials for energy recovery (MER)	kg
	Materials for recycling (MFR)	kg
Consumption of resources		
Consumption of Resources	Total use of non-renewable primary energy resources (PENRT)	MJ
	Total use of renewable primary energy resources 8 PERT)	MJ
	Use of net fresh water (FW)	m3
	Use of non renewable primary energy resources used as energy carrier (PENRE)	MJ
	Use of non renewable primary energy resources used as raw materials (PENRM)	MJ
	Use of non renewable secondary fuels (NRSF)	MJ
	Use of renewable primary energy resources used as energy carrier (PERE)	MJ
	Use of renewable primary energy resources used as raw materials (PERM)	MJ
	Use of renewable secondary fuels (RSF)	MJ
	Use of secondary materials (SM)	kg
Waste		
Waste	Hazardous waste disposed (HWD)	kg
	Non hazardous waste disposed (NHWD)	kg
	Radioactive waste disposed (RWD)	kg

D) RESULTS INTERPRETATION

This paragraph summarizes the results of the comparative LCA of innovative and complex asphalt mixtures, evaluating their environmental performances against standard ones. Due to the extensive amount of data reported for each mixture, the complete set of results of the LCA study conducted with OpenLCA are available from the authors upon reasonable request.
A specific focus on Global Warming Potential (GWP-total) is provided here for a clearer understanding of the carbon footprint associated with the different alternatives. GWP is one of the most significant impact categories since all the indicators show similar trends, therefore it can be used as a key indicator for assessing the overall sustainability of asphalt mixtures.

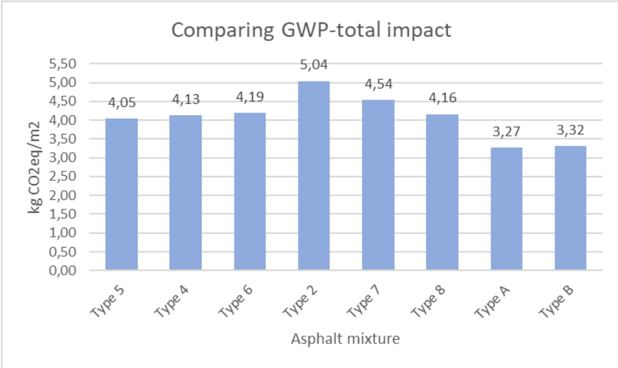

Figure 1. GWP-total for the 8 asphalt mixture alternatives.

The above graph shows the impact in terms of GWP-total. It highlights that the innovative LIFE SILENT mixtures could have higher carbon impact compared to traditional ones, with type 5 and 8 mixtures having the lower impact and type 2 the highest.
The higher impact of these mixtures may be attributed to the greater variety of materials and processes which leads to a higher number of assumptions, also increasing the level of uncertainty. It is worth noting that when the LCA for preliminary assessment was conducted, project data was not fully available therefore secondary data has been used as well [13].
Furthermore, the below graph illustrates the contribution of each life cycle phase to the total impact across the A1-A5 life stages, using average data. The results show consistent trends among all the mixtures.

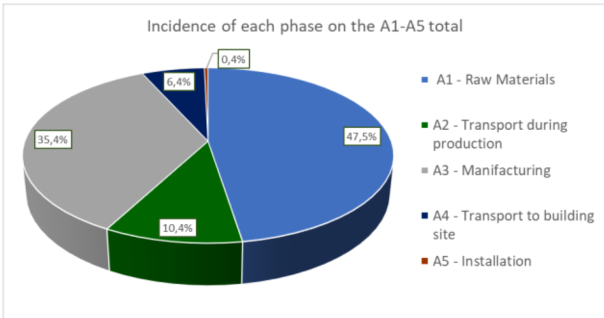

Figure 2. Contribution of each life cycle phase to the total impact.

4. CONCLUSIONS AND WAY FORWARD

The findings provide valuable insights into key impact areas and highlight opportunities for further improvements of the sustainability of the asphalt mixtures proposed within the LIFE SILENT project.

The incorporation of recycled materials, such as crumb rubber and cellulose fibres from recycled cardboard offers notable environmental and economic benefits, which adds to the aim of improved acoustic performance. By replacing virgin aggregates with the right amount of recycled materials, the demand for raw material extraction is reduced, leading to lower environmental impacts. Additionally, recycling minimizes waste generation and landfill disposal, contributing to a more circular and sustainable approach to asphalt production.

To improve the accuracy and reliability of LCA studies on the LIFE SILENT asphalt mixtures, future research should focus on refining critical parameters and assumptions, particularly by collecting more detailed and reliable data on:

- production temperature and its corresponding energy consumption;
- raw material transportation and packaging;
- Crumb rubber and cellulose fibres production, assessing its processing and potential optimizations;
- proportion of primary and secondary materials, including the presence and typology of chemical additives.

Along with the abovementioned points, a scenario comparison is presented to evaluate the potential impact of the LIFE SILENT mixtures production choices, again in terms of GWP-total.

The following graph illustrates how GHG emissions vary when reducing packaging (i.e., avoiding the use of big bags) and cutting off waste impact from the crumb rubber production. According to the LCA results this can lower GHG emission of about 10 % on average.

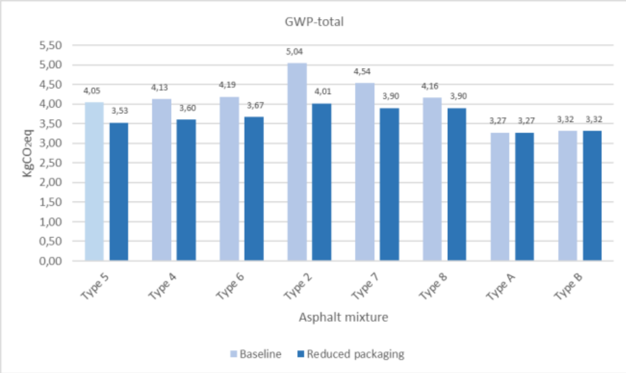

Figure 3. GWP-total in the scenario comparison.

Another graph shows the potential benefit of using higher amounts of crumb rubber by replacing virgin aggregates. The results illustrated in the graph below show that variations in crumb rubber content can improve the mixtures' impacts.

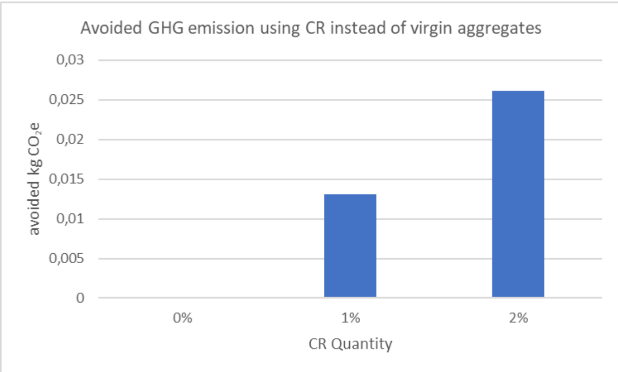

Figure 4. Avoided GHG emissions for different crumb rubber contents.

Additional sensitivity analyses can be conducted on materials' selection. For instance, bitumen, which represents another significant environmental impact, can be the subject of further analysis. While this study assumes the use of virgin bitumen (with SBS), incorporating recycled bitumen could significantly reduce resource depletion and environmental impacts, further contributing to the sustainability of the LIFE SILENT asphalt mixtures.

Together with bitumen, chemical additives also contribute to the overall impact of LIFE SILENT mixtures, despite being used to reduce production temperatures. In future studies, it will be crucial to assess the benefits of lower temperatures against the environmental impact of these chemical products.

Although the improvement opportunities identified in an LCA study can be numerous, the participation of other academia, industry and design experts is essential to identify additional optimization scenarios and to validate the abovementioned ones.

5. ACKNOWLEDGMENTS

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