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A comparative life cycle-based decision-making framework for road pavement structures incorporating recycled and artificial aggregates.

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Abstract

Recent years have witnessed a significant rise in pavement life cycle assessment studies in response to the escalating focus on sustainable development in the construction sector. The traditional decision-making methods for investments in infrastructure usually consider technical and economic criteria, without taking into account the sustainability of the project. This underscores the critical need to integrate life cycle assessment with technical feasibility when evaluating and selecting road pavement structures. This research aims to bridge the gap between conventional investment considerations and the increasing importance of sustainability in infrastructure development, particularly within the urban contexts. The objective is to characterize, in terms of durability and environmental impact, two different road pavement structures for urban applications. The first is a conventional flexible pavement produced with virgin aggregates, with a porous asphalt concrete serving as the wearing course. In contrast, the second road structure incorporates an elevated proportion of recycled materials in every layer, and its surface course is a porous asphalt mixture with a high content of artificial and recycled aggregates. The experimental program is divided in two phases: in the first one, the durability of the pavements is predicted and evaluated using a professional software for the mechanical analysis and design of pavement structures; then the second step involves the comparison of the environmental performance of the two road structures, adopting a cradle-to-cradle approach. The life cycle assessment (LCA) analysis is conducted using the SimaPro software. The outcomes of the study highlighted the necessity to integrate LCA analysis into the decision-making process for the design and maintenance of urban roads.

Keywords: Life cycle assessment, recycled aggregates, artificial aggregates, porous asphalt, urban environment

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1. Introduction

In recent years, the integration of Life Cycle Assessment (LCA) into road infrastructure decision-making processes has gained significant importance, thanks to the growing awareness of the environmental footprint of road system (Gschösser et al., 2012; Negishi et al., 2022). Currently, LCA offers a holistic approach for assessing the environmental impacts associated with road infrastructure across their entire life cycle. By considering the full life cycle of roads, from cradle-to-cradle, stakeholders can identify the proper alternative to minimize waste generation, environmental burdens and maximize resource efficiency (Giunta et al., 2020; Hoxha et al., 2021). Considering the pursuit of sustainable infrastructure development, the incorporation of recycled materials and alternative aggregates has gained significant attention in the last decades (Abdalla et al., 2022; Hoxha et al., 2020). As traditional road construction practices heavily rely on virgin aggregates, which entail high environmental burdens connected with their extraction, transportation and processing, there is an urgent need to explore innovative materials that minimize the impacts and promote the circular economy (Lima et al., 2020; Polo-Mendoza et al., 2022). Many studies demonstrated that various type of recycled aggregates can be used to produced asphalt mixtures, considering for example reclaimed asphalt pavement (RAP), construction and demolition waste and industrial by-products. The inclusion of recycled materials and by-product can further enhance the environmental valence of asphalt mixtures, transforming a by-product into a valuable resource (De Pascale et al., 2023; Pasetto et al., 2017). Particularly, porous asphalt pavement results to be the proper solution in the realm of sustainable road infrastructure. Porous asphalt (PA) consists in a particular type of bituminous mixture characterized by the presence of high interconnected voids and a coarse granular skeleton (Zhang et al., 2020). The main properties of porous asphalt concrete are their capacity of infiltrate runoff waters, to improve surface safety and to enhanced environmental quality (Jasni et al., 2021). However, the higher percentage of air voids of PA, creates some challenges in terms of durability of the material. Performance-based assessments are essential to ensure that the structural integrity, durability and functional characteristics of porous asphalt pavement meet the engineering requirements and performance standards (Rodríguez-Fernández et al., 2020). The aim of the present research is to compare two pavement structures: a traditional road structures composed of layers with virgin aggregates and a porous asphalt mixture as wearing course, and a sustainable alternative with recycled materials also in the superficial porous asphalt (20% of electric arc furnace (EAF) steel slags and 30% of RAP). The two designs are compared in terms environmental impacts, considering their entire life cycle, with a cradle-to-cradle approach. In order to consider the use phase of the pavements, a durability assessment is developed trough the ALIZE software. The environmental feasibility of the recycled design is evaluated trough a life cycle assessment method. By conducting comparative LCA of these two scenarios, utilizing recycled and artificial aggregates, stakeholders can gain insights into the environmental implications of their choices, including factors such as energy consumption, greenhouse gas emissions, air and water pollution, and resource depletion.

2. Materials and Methodology

2.1 Materials

The pavement structures analyzed in the present study were a structure made with conventional mixtures with natural aggregates, named PAV-T, and a sustainable road structure, composed by 30% of RAP in the binder and base layers, and 30% of RAP with 20% of EAF steel slags in the porous asphalt for the wearing course, named PAV-R. For each structure the same granular subbase and subgrade soil layers were considered. The Poisson coefficient used in the durability evaluation was maintained equal to 0,35 for all the layers.

The mechanical performances of the mixtures composing the two structures were previously analyzed in laboratory, and the results in terms of stiffens modulus (ITSM, Indirect Tensile Stiffness Modulus, EN 12697-26 at 20 °C) are reported in the Table 1 .

Table 1. Stiffness modulus of the three layers of the designed structures.

	PAV-R			PAV-T		
Pavement type	Surface layer	Binder layer	Base layer	Surface layer	Binder layer	Base layer
Stiffness modulus [MPa]	5200	8000	5500	3300	8500	6000
Thickness [cm]	5	7	13	5	7	13

The stiffens modulus are used in the implementation of the durability computation in the ALIZE software as developed by different studies (Ingrassia et al., 2023; Rodríguez-Fernández et al., 2020).

2.2 Durability assessment

The rational calculation method for pavement design enables the validation of calculation assumptions, which are based on the chosen design pavement structure. This method validates the quality of the design choice by assessing the mechanical response, specifically focusing on the stresses and deformations within the analyzed pavement structure. The purpose of the analysis is to evaluate the deformations, and thus the stresses, in a point within the pavement structure resulting from the application of a static load. Since the magnitude of the applied load is lower than the materials' failure load, the individual deformation is reasonably considered reversible, hence it can be deemed elastic. The choice of an elastic constitutive model is therefore justified by the magnitude of the deformations. The calculation software ALIZE, developed by the LCPC (French Public Institute for Infrastructure Research), is based on the theory of elastic multilayer.

Fatigue cracking is one of the primary causes of deterioration in flexible pavement. The phenomenon initially manifests as degradation in the bituminous layers, progressing to damage the entire pavement structure. These fractures form at the bottom of the bituminous layers and propagate towards the surface under repeated loading. To assess the fatigue durability of the asphalt concrete mixtures, the fatigue law proposed by the Asphalt Institute was utilized, as reported in Equation 1.

$$N_f = 0.0796\varepsilon^{-3.291}E^{-0.854} \tag{1}$$

This law, based on the elastic modulus E of the asphalt concrete layer and the tensile strain ε_t at its base, determines the permissible number of load cycles that lead to pavement failure due to fatigue. Applying the formula of the fatigue law, the number of equivalent standard axle passes (ESALs) of 120 kN has been calculated.

To assess the durability of the pavements, and make assumption in terms of maintenance operation, the Average Annual Daily Traffic (AADT) equal to 14793, of an urban major road in Bologna, Italy has been used.

2.3 Life Cycle Assessment

The LCA methodology, as outlined in the ISO 14040 and 14044, comprises four interactive stages: (i) defining goals and scope; (ii) conducting the life cycle inventory (LCI); (iii) performing life cycle impact assessment (LCIA); and (iv) interpretation of the results obtained. During the goal and scope definition phase, the purpose of the study, the intended application and the target audience are delineated, along with defining the system boundaries and functional unit. The LCI stage compiles resources inputs and emission outputs throughout the product's lifecycle correlated to the functional unit chosen. The LCIA links the system with the potential human and environmental impacts. Lastly, the interpretation phase assesses the findings against the goal and scope of the study to identify conclusions, and provide recommendations, ultimately supporting the decision-making process.

2.3.1 Goal and scope definition

The goal of this Life Cycle Assessment study is to compare the environmental impacts of two pavement structures within an urban environment, aiming to support decision-making processes for sustainable infrastructure development. The two pavement structures compared are described in section 2.1.

The functional unit for this study is defined as 1 m^2 of road pavement over a lifetime of 30 years, in the urban area of Bologna, Italy. This unit will serve as the basis for comparing the environmental impacts of the pavement structures. The system boundaries encompass a cradle-to-cradle approach, considering all life cycle phases of the pavements, including material extraction, transportation, manufacturing, construction in site, maintenance and end-of-life phase. Therefore, it is assumed that 100% of RAP materials obtained from the demolition process at the end-of-life stage, were recycled within the same system chain and reused in the manufacturing of new asphalt concretes.

Figure 1 shows the system boundaries of the analysis, using the terminology described in the EN 15804-2018 standard.

Figure 1. System boundaries of the LCA analysis

Based on the durability results, the maintenance strategies for each layer of the two pavements will be assumed, and the use phase will be consequently designed.

2.3.2 Life Cycle Inventory (LCI)

The primary data associated with the pavement designs and the production of asphalt mixtures were collected through questionnaires answered by the different company that produce the asphalt concrete. The transportation distances for both primary (268 km for aggregates, 3 km for bitumen and 114 km for sand) and secondary raw materials (121 km for slags and 114 km for RAP) were assessed with the asphalt plant as the ultimate destination point. The reclaimed asphalt pavement material, originating from the milling of a motorway needs to undergo specific treatment before being used in the final asphalt concrete. For this reason, the RAP has been considered as secondary raw material and not the end-of-life phase of the pavement. The environmental burden linked to treating the RAP is solely attributed to the mixtures containing it. Therefore, the cutoff point was established between transporting the milled waste material to the asphalt plant and processing the RAP into a secondary raw material. The relevant input and output data not provided by the producers were collected from the literature, together with the information regarding the construction and deconstruction processes (Siverio Lima et al., 2021). The extraction of the primary raw materials was modeled based on the dataset available on Ecoinvent v.3.8, except for the neat bitumen and polymer modified

bitumen, modelled with the Eurobitumen inventory (The Eurobitumen LCI, 2020). All the materials are transported from the origin to the asphalt plant by a five-axle lorry vehicle, EURO 6, that has a maximum load capacity of 26 tons. All the inputs and outputs were modeled using the Econinvent v.3.8 database and the software SimaPro 9.2.

2.3.3 Life Cycle Impact Assessment (LCIA)

The environmental burdens of the two different scenarios are evaluated with the GWP (kg CO_2 equivalent) indicator used in the Environmental Product Declaration (EPD 2018) method. To obtain a more fulfilling analysis and to avoid the burden shifting problem, the CML-IA methodology, developed by the Center of Environmental Science of Leiden University. The version used in the current study is update in 2016 and involves the following impact categories (SimaPro Database Manual, 2023):

- Depletion of abiotic resource (AD);
- Climate change (GWP);
- Stratospheric Ozone depletion (ODP);
- Human toxicity (HT);
- Freshwater ecotoxicity (FE);
- Marine ecotoxicity (ME);
- Terrestrial ecotoxicity (TE);
- Photo-oxidant formation (PO);
- Acidification (AC);
- Eutrophication (EU).

3. Results

3.1 Durability results

The durability analysis, developed through the Alize Software, gives the following results reported in Table 2.

Table 2. Results of the durability analysis in terms of number of cycles.

	N° of cycles		
Pavement type	Surface layer	Binder layer	Base layer
PAV-R	7.21×10^{10}	4.72×10^{11}	2.07×10^{9}
PAV-T	2.54×10^{10}	6.68×10^{10}	1.04×10^{9}

The number of fatigue cycles leading to failure for the materials within the project packages has been compared with the number of ESAL calculated for the road section with the specific AADT over the project lifespan of 30 years, totaling 4.98×10^{7}. Therefore, neither the traditional nor the recycled pavement designs are expected to fail within the project timeframe. Nonetheless, it is evident how the layers composing the sustainable road structure perform better compared to the traditional layers. Based on this knowledge, it is possible to assume a maintenance plane for each layer of the two pavement designs considering that PAV-R can withstand more cycles and, consequently, last longer. In the following

Table 3 is presented a possible maintenance strategy adopted for the present study.

Table 3. Maintenance strategies for each layer express in years.

	Lifetime [years]		
Pavement type	Surface layer	Binder layer	Base layer
PAV-R	6	15	30
PAV-T	5	10	25

In this way, over 30-years lifetime, the surface layer of the recycled pavement will undergo rehabilitation 5 times, twice for the binder layer, and once for the base layer. In comparison, the traditional road structure requires more maintenance, with the surface layer requiring rehabilitation 6 times, the binder layer 3 times, and hypothetically, the base layer 1.2 times.

From these results, the use phase of the studied pavement’s life cycle has been established.

3.2 LCA results

The environmental impacts in terms of Global Warming Potential (GWP) and CML baseline methods are investigated. In Table 4 the results in terms of kg of CO_2 are presented.

Table 4. GWP results of 1 m^2 of road pavement expressed in kg of CO_2 eq.

Impact category	Unit	PAV-R	PAV-T
Global Warming Potential	kg CO_2 eq	110	163

From these initial results, it is clear that the design developed with the recycled layers has a lower environmental impact respect to the traditional design. This improvement can be attributed to the presence of the RAP in all the three layers, which minimize the use of virgin aggregates and reduce the amount of virgin bitumen needed. Furthermore, the recycled pavement has higher durability and performance than the traditional one. Consequently, fewer maintenance works are needed during the 30 years lifespan for the recycled design, resulting in reduced environmental burdens throughout the life cycle. To deeper understand which of the three layers is the most beneficial one, the results in terms of Global warming potential (in percentage) are presented in Figure 2.

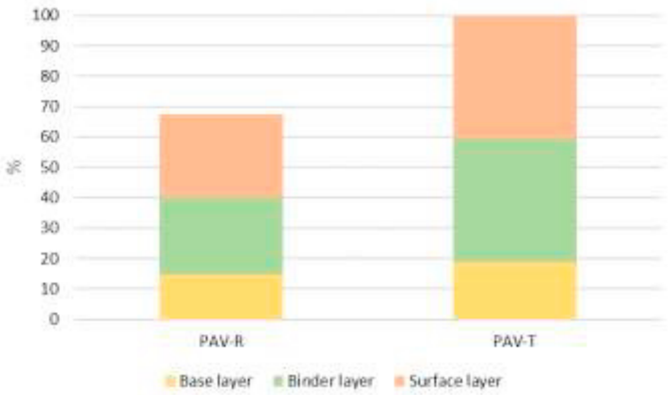

Figure 2. GWP impact of each layer of the analysed structures.

From the above results it evident that the surface layer experiences the highest decrease, attribute to the presence of two different recycled aggregates: RAP and EAF steel slags. Nonetheless, to gain a broader understanding of the influence of each phase and component, a sensitivity analysis should be developed. With that said, to avoid the mistake of burden shifting, it is of fundamental importance to analyze the environmental performances of the pavement design in different impacts categories.

Figure 3 reports the results of the impact categories using the CML-IA method.

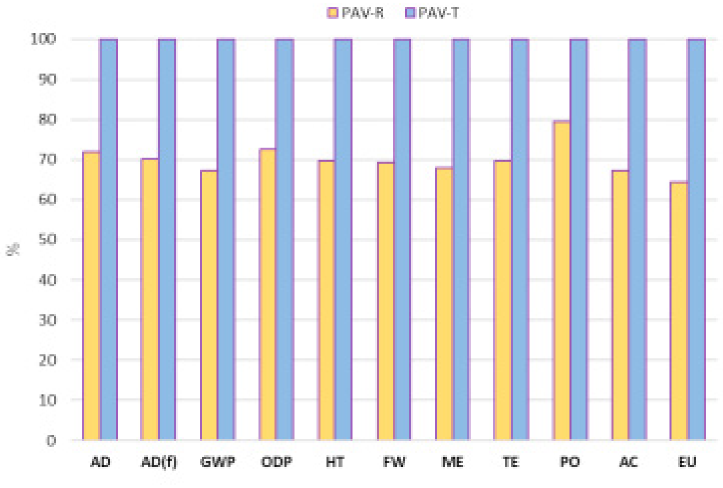

Figure 3. CML-IA results of 1 m^2 of the two pavement structures.

Upon examination of the results of the CML-IA baseline method, it is evident that the observed trend in the GWP results persists. The recycled pavement design has better environmental performance in all categories compared to the traditional design. The reduction observed in nearly every category is approximately 30% less than that the traditional counterpart.

4. Conclusions

This study aims to facilitate decision-making processes for enhancing environmental performance in urban road infrastructure by evaluating the life cycle of two types of urban pavements and their respective maintenance strategies over 30 years of lifetime. Based on the obtained results, the following statements can be made:

- The combination of layers containing the significative amount of recycled and artificial aggregates might reduce the environmental burdens in terms of global warming potential (GWP) and eutrophication (EU);
- The implementation of waste materials such inside asphalt pavement mixtures, is beneficial because it reduces the amount of raw aggregates need and decrease the amount of virgin bitumen, if RAP is used. An optimized mix design is fundamental in order to achieve specific performances for the final material.
- The higher performances and consequently durability of the designed pavement encompasses a lower environmental impact during the life cycle of the structure;
- Maintenance strategies can heavily influence the environmental performances of urban road. Hence, pavement design, mixture performances, service life and maintenance works need to be carefully studied.

This research is based on analyzing evidence that suggests the contrasting performance of the two pavement structures over the studied lifespan. This analysis was made possible by prior durability assessments conducted with specialized software. The evaluation of the durability of a pavement is a crucial step to define a maintenance intervention plan and consequently to perform a fulfilling LCA analysis considering a cradle-to-cradle approach. Although this study considers the lifespan of the design structures, it is crucial to consider other factors and components unique to urban road infrastructure during the use (i.e, fuel consumption, leaching materials, vehicle traffic).

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