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Life Cycle Assessment (LCA) of Alternative Pavement Rehabilitation Solutions: A Case Study

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Abstract: In the context of sustainability, the pavement construction industry is taking a more holistic approach to environmental, economic, and social issues. In particular, pavements are believed to be responsible for up to 24% of total greenhouse gas emissions over the last century. Therefore, it is critical to include a tool to assess the environmental and health impacts of pavement construction or rehabilitation in the related design studies. This tool is called Life Cycle Assessment (LCA). With this in mind, this case study examines two alternative solutions for the rehabilitation of an existing highway pavement: one using conventional materials and processes and one using conventional recycled materials and recycling processes. These two alternatives are ecologically evaluated using an LCA method to increase the importance of quantifying environmental and health impacts. By comparing the corresponding results, this study aims to quantitatively demonstrate how recycled materials and recycling processes contribute to the sustainability of pavements. As a final result, it is shown that the environmental and human health benefits are significant, even though the use of recycled materials and processes for pavements may be limited.

Keywords: pavement sustainability; LCA; recycling materials; RAP

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1. Introduction

In the context of sustainability, the road construction industry is taking a more holistic approach to environmental, economic, and social issues. In terms of the environment, natural resource depletion, greenhouse gas (GHG) emissions, chemical pollution, and ecosystem loss are of paramount importance and must be quantified to assess the environmental impact of road projects. In particular, road pavements were the largest contributor to the carbon footprint in the last century, accounting for 24% of total GHG emissions [1]. In addition, the construction sector consumes 3 billion tons of natural aggregates annually, 20% of which are contained in all pavement layers [2], a common practice that leads to the depletion of these natural sources. In addition, construction waste accounts for more than one-third of the total waste generated worldwide that ends up in landfills [3]. Based on these considerations, road pavement treatment should take into account such sustainable criteria, as road infrastructure contributes to economic growth and development of countries and facilitates access to employment, social, health, and education services [4].

Because the environmental impact of human activities—in this case, pavement construction—is important to the way construction is approached, it is critical to include a tool in construction studies that can estimate environmental impact. This tool is called Life Cycle Assessment (LCA) and is a methodology that allows decision makers to thoroughly identify and assess the environmental impacts and their influence on social aspects of infrastructure pavement systems throughout their life cycle [5]. The LCA methodology is described by the specifications of the standard ISO 14040 [6] and consists mainly of four steps. The first step concerns the definition of the objective and scope, i.e., the reason for conducting the study, and provides a description of the product system or structure (e.g., building, pavement) in terms of its boundaries and functional unit. The second step is the Life Cycle Inventory (LCI), which records and quantifies the inputs and outputs of the product or structure under study during its life cycle phases or for the phases included in the boundary system. The third step is the assessment of the environmental impacts caused by the resource use and emissions identified in the inventory, including a prior compilation of impact categories and indicators. The last step is the interpretation, where the results of the previous phases are analyzed in terms of significance, variability, quality, etc. The interpretation also includes the conclusions and recommendations for the improvement or modification of a process/product, taking into account the objective and scope of the assessment.

It is worth mentioning that the idea of LCA was first taken up around 1970 [4,7]. After that, the studies of LCA were mainly conducted to analyze consumer products or materials and components of daily life [4]. However, over time, LCA has evolved to assess the environmental impacts of more complex systems such as building [4], tunneling and underground constructions [8,9], or pavement structures [10]. In the case of road pavements, the impact on the environment and human health is significant because large quantities of materials are required for construction and rehabilitation, while the temperature required for asphalt mixtures can cause large amounts of energy, exhaust gases, particulate matter, sulfur dioxide, nitrogen oxides, carbon monoxide, and carbon dioxide [11–13]. Therefore, continuous research is considered essential to limit the environmental footprint of pavements. Previous research [14–18] has shown that recycled materials and processes can reduce the environmental footprint of pavement construction and rehabilitation. In addition, the importance of material quality has also been pointed out to ensure the required performance of the pavement. With this in mind, this study demonstrates the importance of the LCA method in pavement projects by estimating the values of the different loading categories for two alternative scenarios of a rehabilitation project. Specifically, this study examines two rehabilitation alternatives for an existing highway pavement: one using conventional materials and processes and one using both conventional and recycled materials and recycling processes. These two alternatives will be ecologically evaluated using the LCA method to increase the importance of quantifying environmental impacts. By comparing these two scenarios, this study aims to quantitatively demonstrate how recycled materials and processes contribute to pavement sustainability.

2. Background

Several studies have studied the environmental impacts of pavement construction and maintenance and the factors under comparison are LCA method, recycling method, recycling materials, inventory data, and impact categories. Researchers such as Chiu et al. [19] and Chan et al. [14] performed an environmental impact assessment following different LCA methods, cradle-to-grave LCA and cradle-to-lay LCA, respectively, which are related to the included life cycle stages of pavement. Other studies [20–22] followed an LCA methodology by focusing on the different materials used for the pavement construction, such as Reclaimed Asphalt Pavement—RAP, asphalt rubber, fly ash, and glass waste. The recycling methods, such as Hot In-place Recycling and Cold In-place Recycling, are also considered in an LCA process [15,23,24]. As for the inventory data, they could be obtained from the literature review, laboratory and field findings, and datasets [23,24]. Finally, the impact categories considered are energy and water consumption, air and water emissions (CO_2, SO_2, PM10, Hg, Pb), hazardous waste, acidification potential and several toxicity potentials, eutrophication, cancerous human toxicity potential (HTP), and non-cancerous HTP [20,25].

In more recent research, Vidal et al. [16] conducted an LCA analysis on four asphalt pavements; two Hot Mix Asphalt (HMA) pavements containing 0% or 15% RAP and two zeolite-based Warm Mix Asphalt (WMA) pavements containing 0% or 15% RAP. The analysis was related to all the life cycle stages of pavements, from the extraction and production of the pavement materials to the end-of-life phase. The estimated environmental impacts were mainly connected to the energy consumption and the emissions to the atmosphere, as well as other impacts connected to all life phases of pavement, but all impacts were assessed based on their damage to human health, ecosystem, and materials availability. The authors observed that, for the same RAP content, the total environmental impacts are almost the same for the WMA and HMA pavement. Although, in the stage of materials production, the impacts of WMA were 14–15% lower than the impacts of HMA, due to the lower temperature used for the asphalt production. Furthermore, the addition of RAP caused a significant reduction of the total environmental impacts; up to 13% for human health and ecosystem, respectively, and up to 14% for materials availability. Finally, they concluded that the reduction of the environmental impacts for an asphalt pavement can be reached by using WMA instead of HMA and adding a large quantity of RAP to WMA.

Araújo et al. [26] focused on the use phase of pavements. They developed a new LCA methodology, which included all life cycle stages of pavement, and the goal of their research was to investigate the influence of the utilization of sustainable pavements or/and different materials for the surface layer, which mostly affect skid resistance and, consequently, the interaction between pavement and vehicles, during the use phase. They conducted their LCA analysis on four different pavements regarding the used materials in asphalt layers. For the asphalt base course and wearing course, two types of materials were used: conventional materials and materials consisting of 50% RAP. For the surface layer, two types of materials were also used: conventional materials and materials consisting of Polymer-Modified Asphalt (PMA). The thicknesses of all four structures were adjusted, so that all pavements could support the same loads. Their findings showed that the use of recycled materials in asphalt layers could significantly reduce the gas emissions and the energy consumption and they concluded that the sustainability in pavement construction can be greatly improved by incorporating recycled materials into pavements.

Aurangzeb and Al-Qadi [27] carried out an LCA analysis on four different asphalt mixtures: one with conventional materials and three with RAP (30%, 40%, and 50%). The LCA was related to the phases of materials production, construction, and maintenance. They observed that the greenhouse gas emissions and energy consumption are reduced up to 28% when asphalt mixtures with RAP are used. In their conclusions, they pointed out that, although a large quantity of recycled materials can reduce significantly the environmental impacts, it is important to consider the mechanical performance of the recycled materials, the traffic loads, and the material costs in order to reach the optimal solution. Additionally, Willis [17] used the LCA methodology for the asphalt layers with recycled materials of the experimental pavement sectors prepared by the National Center for Asphalt Technology (NCAT) in Auburn, Alabama, and compared their results with an asphalt mixture containing conventional materials. The LCA was applied for the materials production and construction phase. There were four examined pavement sectors and they differed with regard to the composition of asphalt layers; (i) mid-to-high RAP content in lower asphalt layers and WMA in surface layer, (ii) high RAP content, (iii) Reclaimed Asphalt Shingles (RAS) and RAP, and (iv) Ground Rubber Tire (GRT) and RAP, while the comparison asphalt mixture was an HMA mixture. Finally, they concluded that the usage of recycled materials improves their environmental footprint, as each of samples' energy consumption and CO_2 emissions were reduced up to 29%.

Zhu et al. [28] also investigated the environmental impacts of asphalt layers by using the LCA methodology, regarding the recycling technologies and the WMA method for producing asphalt mixtures. Their findings showed that the Cold In-place Recycling (CIR) technology was the most beneficial to the environment as for energy consumption and GHG emissions. They also noticed that, in the case of Hot Mix Asphalt Recycling (HMAR)—the worst-case scenario between technologies—the addition of 30% and 50% RAP reduced the environmental indices. Bloom et al. [29] carried out LCAs on recycled materials used for the reconstruction of a highway, converting the HMA to rigid pavement. These materials were fly ash, steel slag, RCA, RAS, and RAP. According to their results, the incorporation of recycled materials into pavement decreases the impacts of most environmental indices. Especially, the energy consumption and the CO_2 emissions reduced 15–25% and 17–24%, respectively. Similarly, Del Ponte et al. [30] assessed the data of the quantities of recycled materials (RAP, RAS, RCA, fly ash) used in six states of USA in 2013 by using LCA methodology. They concluded that the use of recycled materials can significantly reduce the environmental footprint of pavement construction, but they noticed that the total outcome was affected by the quality and type of these materials.

Santos et al. [31] analyzed and compared six different pavement sections for the following life cycle stages: materials extraction and mixtures production, construction, use phase, maintenance and rehabilitation, and end-of-life phase. Each pavement section had a different composition of asphalt layers. The asphalt layers of reference pavement were composed of HMA without RAP content and they were compared to five alternative structures with equal geometry. In each of these five structures, the wearing course was made of HMA with RAP content, WMA produced according to two different technologies (foaming asphalt and additives) and with and without RAP content. In their conclusions, they stated that the alternative scenario of foamed WMA with 50% RAP is the most ecofriendly one among all the solutions, if the performance of each used asphalt mixture is assumed to be the same. Furthermore, they observed that the materials extraction and mixtures production phases have the biggest impact on the environmental performance of pavement sections. In this context, they also noticed that the replacement of fuel in asphalt plants is environmentally equal to the dismantling and recycling of the pavement structure, while this replacement can originate more expressive environmental benefits than those arising from using both recycling and WMA technologies. Finally, regarding the pavement performance, if the alternative pavement sections are inferior to conventional ones, then their use causes an increase in the environmental burdens due to the higher frequency of maintenance activities.

Praticò et al. [11] evaluated the energy and environmental performance of several bituminous mixtures for pavements by means of a life cycle method that complies with European standardization and refers to all life cycle stages except the use phase. They analyzed five different scenarios of pavement sections (surface layer, asphalt base layer, and unbound base layer) consisting of common paving materials and recycled materials. Their findings showed that using a WMA technology is an environmentally friendly solution, since it reduces the environmental impacts. Additionally, when it is combined with the addition of RAP, the consumption of virgin bitumen and aggregates is decreased, which lowers the raw material requirement and produces a further reduction in primary energy consumption. These statements drive to the conclusion that the scenario of WMA technology and a 45% RAP addition to all pavement layers was the best environmental solution. In addition, Bressi et al. [18] carried out an LCA analysis for eleven asphalt mixtures, one conventional mixture and ten alternative mixtures with recycled materials (GRT, RAP) in different proportions, referring to the materials production and construction phase. They observed that the mixtures consisting of GRT had higher scores for all environmental impacts, while the mixtures containing 40% RAP decreased these scores. Finally, the authors pointed out the importance of aged binder reactivation in the reduction of the environmental impacts.

Overall, there are several studies that regularly suggest that recycled materials and processes could reduce the environmental footprint of pavement construction and rehabilitation. At the same time, they point out the importance of material quality to ensure the required pavement performance. In this study, the importance of an LCA method in pavement projects is demonstrated by estimating the values of the different loading categories for two alternative rehabilitation solutions using conventional and non-conventional (recycled) materials.

3. Methodology

3.1. General Description

In this study, the research methodology follows the LCA method based on ISO 14044 [6]. The four steps of this method are shown in the flowchart in Figure 1.

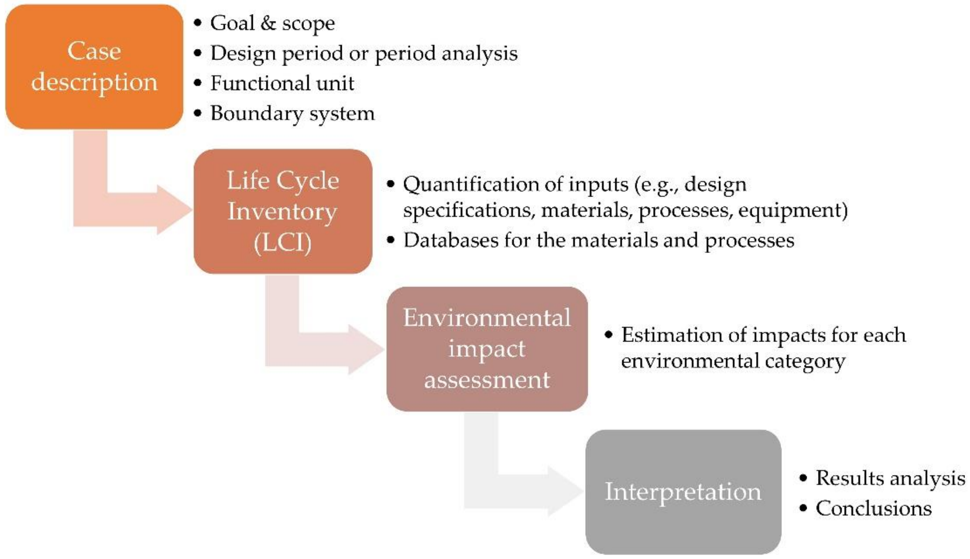

Figure 1. Research methodology.

"Case description" describes the framework of this study: case study, planning period, functional unit, and boundary system. "LCI" selects the data used for the current LCA: LCA program, design specifications, materials, processes, and databases, e.g., on material properties, paving process, and equipment. Quantities are then estimated for each impact category. The impact categories analyzed in this study are energy and water consumption, gas emissions (CO_2, CO), SO_2, and NO_X, which are responsible for acidification and eutrophication, respectively. Particulate matter with an aerodynamic diameter of less than 10 mm (PM-10), hazardous wastes, and carcinogenic and non-carcinogenic HTPs that are harmful to human health are also included in the impact categories. The results are then analyzed and the final conclusions are drawn.

3.2. Case Description

3.2.1. Goal and Scope

The goal of this study is to demonstrate the potential environmental and health impacts of using recycled material—RAP—versus conventional material in pavement rehabilitation in a case study on a highway. As part of the highway project, the centerline of this road was to be raised to a higher level because the road design had changed and now had to withstand heavier loads than originally required. Therefore, two different approaches to pavement rehabilitation and evaluation of the results from LCA were developed to provide decision makers with valuable insight into important sustainability issues.

3.2.2. Functional Unit

The functional unit is a length of one kilometer of the highway under study. It is a four-lane segment, two lanes per direction with a width of 3.50 m, and shoulders with a width of 2.30 m each. The existing pavement section comprises a 170 mm asphalt layer and a 250 mm unbound layer (base/subbase) in both directions and it is shown in Figure 2.

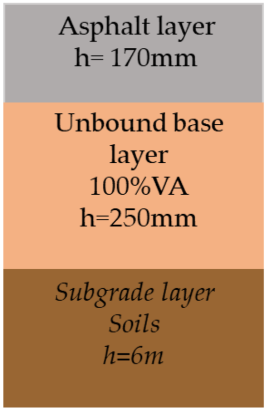

Figure 2. Existing pavement section.

Furthermore, transporting materials based on the local conditions and available suppliers in the area were considered. Therefore, aggregate transport distance was considered as 30 km and asphalt transport distance was 55 km, all in one traveling direction. As for the RAP transport distance, it was considered to be 0 km, as the used recycling process was Cold In-place Recycling (CIR), which means that the RAP material was used immediately in the field. Regarding the design period, it should be mentioned that the estimation of design and maintenance periods for road pavements is not a general aspect, but is linked to the technical specifications established by the Road Authority. Therefore, according to the technical specifications of this project, the design period for the rehabilitated pavement was set at 24 years, and the start of the period was set at the first design period. The first time period for the maintenance of the rehabilitated pavement section is estimated after the first 12 years (2nd design period), while the second time period for its maintenance is estimated after a total of 24 years (3rd design period). The two alternatives are described thoroughly in Section 3.3.2.

3.2.3. System Boundary

This project consisted of reconstructing the existing pavement based on two different approaches regarding the used materials, conventional and recycled. Production of materials, initial construction, transport, and maintenance/rehabilitation techniques were considered in the LCA. In addition, environmental impacts due to the use of RAP were evaluated. A comparison was also carried out between the two approaches, as an attempt to evaluate the traditional materials compared to the recycled materials.

3.3. Life Cycle Inventory (LCI)

3.3.1. Program Selection

The Pavement Life-cycle Assessment Tool for Environmental and Economic Effects—PaLATE 2.0 [32]—was used for inventory analysis and as a component of the impact assessment. PaLATE 2.0 is a spreadsheet model that tracks the flow of materials and energy and outflow of emissions and their costs in the design, construction, and maintenance of a pavement segment. Required inputs are construction specifications (design period and layer thicknesses), information on materials (material type and density), energy consumption data of construction and maintenance machines, and transportation distance. PaLATE 2.0 also provides user-defined databases for materials and processes that can be modified and updated by the user based on local conditions. No changes were required for this study, and the databases provided were used for the inventory analysis.

3.3.2. Pavement Design Alternatives

As mentioned above, the centerline of the road will be raised by 130 mm as part of the rehabilitation project to upgrade the pavement. For this purpose, the existing asphalt layer will be milled off at a certain depth and new pavement layers will be constructed above the milled asphalt layer. These new pavement layers are asphalt layers and an unbound layer (base/subbase), while the layers of the existing pavement are considered as the pavement subgrade. Based on this, two scenarios are considered as alternative solutions for pavement rehabilitation, including milling and construction of new pavement layers to achieve the project goal of raising the road centerline. The milling depth depends on the degree of damage to the existing asphalt layer, as does the thickness of the new layers relative to the required bearing capacity of the rehabilitated pavement. In the first scenario, the milling depth is 120 mm. The unbound layer has a thickness of 100 mm and the asphalt layers have a total thickness of 150 mm. In the second scenario, the milling depth is 100 mm. The unbound layer has a thickness of 100 mm and the asphalt layers have a total thickness of 130 mm. In this case, the milled asphalt (RAP) is used for the construction of the unbound layer of the added pavement and its proportion is thought to be 40% along with 60% of VA, while the asphalt layers are made of conventional materials. Finally, two periods of future maintenance and rehabilitation works are considered for both alternatives. In the 2nd design period, the asphalt layers are milled to a depth of 100 mm and new asphalt layers are constructed. Their thicknesses are 100 mm for each scenario. In the 3rd design period, the construction of a new surface layer with a thickness of 30 mm is considered.

All of the above are shown graphically in Figure 3, while Table 1 contains the inputs for the software used (inventory data).

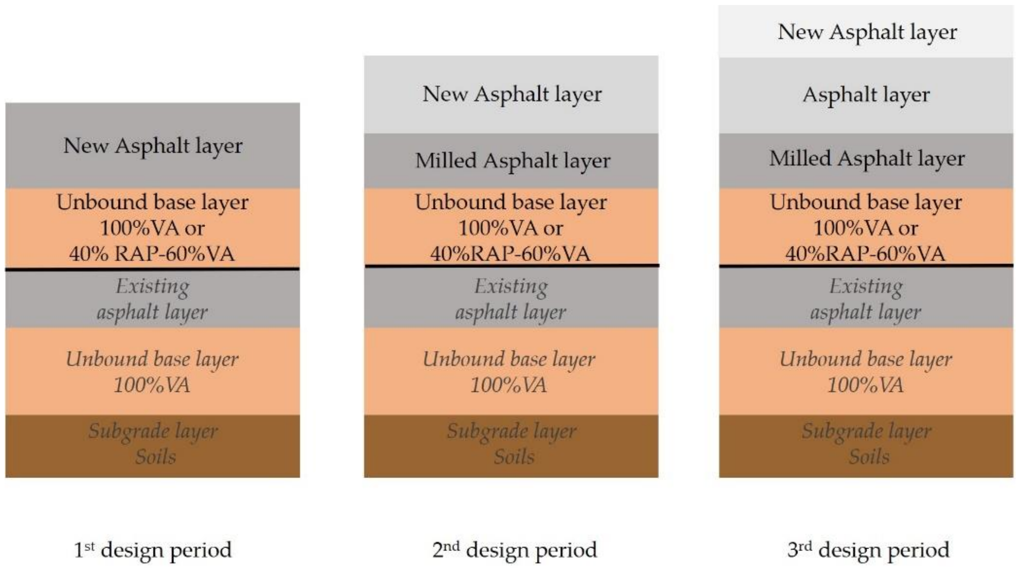

Figure 3. Outline of pavement design.

Table 1. Inventory data.

Material Inputs	
Material	**Density (kg/m^3)**
Asphalt mixture	1609
Virgin aggregates	1635
Bitumen	1099
RAP	2420
Gravel	1766
Sand	1635
Soil	2132

Table 1. *Cont.*

Density regarding used processes (kg/m^3)							
Cold In-place Recycling (CIR)	2394						
Milling process	2394						
Inputs for vehicle types used for transportation							
Vehicle type	**Fuel Efficiency (L/km)**	**Energy (MJ/L)**	**CO_2 (g/L)**	**Nox (g/Mg-km)**	**PM-10 (g/Mg-km)**	**SO_2 (g/Mg-km)**	**CO (g/Mg-km)**
Dump truck	0.4	35.8	2679.0	3.0	0.6	0.2	0.25
Tanker truck	0.4	35.8	2679.0	3.0	0.2	0.2	0.25

Inputs for equipment used in construction/rehabilitation			
Equipment per process		**Productivity (tons/h)**	**Fuel Efficiency (L/h)**
Milling machine		1100	156.2
Asphalt mixer		226.8	-
Asphalt paving	Paver	2400	49.1
	Pneumatic roller	668	26.1
	Tandem roller	285	32.7
Excavation, placing, and compaction	Excavator	315	34.2
	Vibratory soil compactor	1832	27.6
CIR	CIR recycler	1713	150.0
	Pneumatic roller	884	25.1
	Tandem roller	285	32.7

It is worth noting that the differences between the two scenarios can be seen only in the first design period.

4. Results and Discussion

The two pavement design alternatives were run through the PaLATE 2.0 model. In Table 2, a summary of the output from simulation runs including the inventory outputs and impact categories for both scenarios in the first design period is presented. As it is shown, all impact variables have higher values, as the phase of materials production is considered. For the other two phases, materials transportation and processes, the values of impact categories are much lower. This means that the crucial phase for environment as well as human health (Hg, Pb, cancerous and non-cancerous HTP) is the materials production phase, especially the asphalt production (materials extraction and asphalt mixtures).

Table 2. Quantities of each impact category for first design period.

		Impact Categories—Scenario 1											
		Energy ($\times 10^4$ MJ)	**Water (kg)**	**CO_2 (tons)**	**NO_x (kg)**	**PM-10 (kg)**	**SO_2 (kg)**	**CO (kg)**	**Hg (g)**	**Pb (g)**	**Hazardous Waste (tons)**	**HTP Cancer (kg)**	**HTP Non-Cancer (tons)**
Materials Production	Asphalt layers	301.6	855.4	154	1108.6	747.6	41332.1	497.4	3.3	164.0	33.2	562.9	767.0
	Base/Subbase layers	29	40.3	20.5	41.7	293.8	20.2	27.1	0.0	6.0	0.3	21.7	185.8
Materials Transportation	Asphalt layers	8.8	15.1	6.6	352.1	66.8	21.1	29.3	0.1	3.0	0.6		
	Base/Subbase layers	4.0	6.8	3.0	158.7	30.9	9.5	13.2	0.0	1.3	0.2		
Processes	Paving HMA	1.5	2.6	1.1	26.5	15.8	1.8	5.7	0.0	0.5	0.1		
	Compaction	0.9	1.5	0.6	14.0	1.7	0.9	3.0	0.0	0.3	0.1		
	Milling	0.5	0.0	0.4	10.0	0.7	0.7	2.1	0.0	0.2	0.0		

Table 2. *Cont.*

		Impact categories—Scenario 2											
		Energy (× 10^4 MJ)	Water (kg)	CO_2 (tons)	NO_x (kg)	PM-10 (kg)	SO_2 (kg)	CO (kg)	Hg (g)	Pb (g)	Hazardous Waste (tons)	HTP Cancer (kg)	HTP Non-Cancer (tons)
Materials Production	Asphalt layers	260.6	738.8	133	958	646.4	35738.2	429.6	2.8	142.0	28.6	486.2	663.4
	Base/Subbase layers	16.9	23.6	12	24.4	171.7	11.8	15.8	0.0	3.5	0.2	12.7	108.8
Materials Transportation	Asphalt layers	7.6	13	5.7	304.5	57.7	18.3	25.4	0.1	2.6	0.6		
	Base/Subbase layers	0.4	4.0	1.7	92.4	18.0	5.5	7.7	0.0	0.8	0.2		
Processes	Paving HMA	1.3	2.2	1	22.9	13.7	1.5	4.9	0.0	0.4	0.1		
	CIR	0.9	1.5	0.7	15.2	1.1	1.0	3.3	0.0	0.3	0.1		
	Compaction	0.5	0.9	0.4	8.2	1.0	0.5	1.8	0.0	0.2	0.0		

Particularly, for both scenarios, CO_2 and SO_2 emissions were produced in extremely large quantities, higher than 130 tons, while the non-cancerous HTP was also produced almost up to 1000 tons. Therefore, it seems that a pavement project enhances the greenhouse effect and the air acidification to a great extent, while it could harm human health. Moreover, the quantities of the rest of the impact categories vary from 0.3 to 1 ton. The only exceptions are the emissions of Hg and Pb, which had a magnitude of lower than 4 and 170 gr, respectively. In addition, for the first scenario, energy and water consumption were up to 3.5 million MJ and 0.85 tons, respectively. For the second scenario, the values of these impact categories are 2.9 MJ and 0.73 tons, respectively, indicating a reduction compared to the first scenario. However, in both cases, these quantities are thought to be high, considering that an energy crisis is apparent and the whole planet is in search of potable water, as water sources are now limited.

Considering the materials transportation, since smaller quantities of materials are required in the second scenario, the values of all impact categories are correspondingly lower. On the contrary, as far as the processes used for pavement rehabilitation are concerned, the values of all impact categories are almost equal for both scenarios.

Regarding the second and the third design periods, the used materials and the processes are the same for both scenarios. Similarly, the phase of materials production requires the highest value of energy consumption and produces the highest values of air and water emissions. In Table 3, the quantities for each impact category for the second and third category are presented accumulatively.

Table 3. Quantities of each impact category for second and third design period.

		Impact Categories											
		Energy (×10^4 MJ)	Water (kg)	CO_2 (tons)	NO_x (kg)	PM-10 (kg)	SO_2 (kg)	CO (kg)	Hg (g)	Pb (g)	Hazardous Waste (g)	HTP Cancer (kg)	HTP Non-Cancer (tons)
Materials Production	Asphalt layers	323	917.2	164.9	1186.9	799.0	44162.4	533.3	3.5	176.3	35580.3	486.2	663.4
Materials Transportation	Asphalt layers	9.4	16.1	7.0	376.2	71.3	22.6	31.4	0.1	3.2	680.6		
Processes	Paving HMA	1.6	2.7	1.2	28.3	4.8	1.9	6.1	0	0.6	116.5		
	Milling	0.4	0	0.3	8.3	0.6	0.5	1.8	0	0	0		

The difference between the cumulative values of each impact category for all design periods for the two scenarios is calculated as the percentage reduction in the values of the second scenario compared to the first one. Figure 4 shows this difference (%) for each impact category. It can be seen that the values of all impact variables have decreased in the second scenario. In particular, the required energy consumption is reduced by up to 17% when a percentage of 40% RAP is used for the construction of the unbound base/subbase layer, while a recycling process is applied. This reduction is also due to the fact that the asphalt layers in the second scenario have a thickness of 130 mm instead of 150 mm as in the first scenario. The values for the impact categories water consumption, CO_2, NO_X, and CO are also reduced by 15, 18, 17, and 16%, respectively, in the second scenario. The most significant reduction (22%) is observed in the quantity of PM-10 due to the limited extraction of VA in the second scenario, while the impact category of non-carcinogenic HTP also shows a significant reduction in its quantity (19%). Moreover, the amount of carcinogenic HTP is reduced by up to 14.7%, which is an important result for the protection of human health. The other influencing variables show a smaller reduction in their levels, ranging from 0.03 to 1.6%.

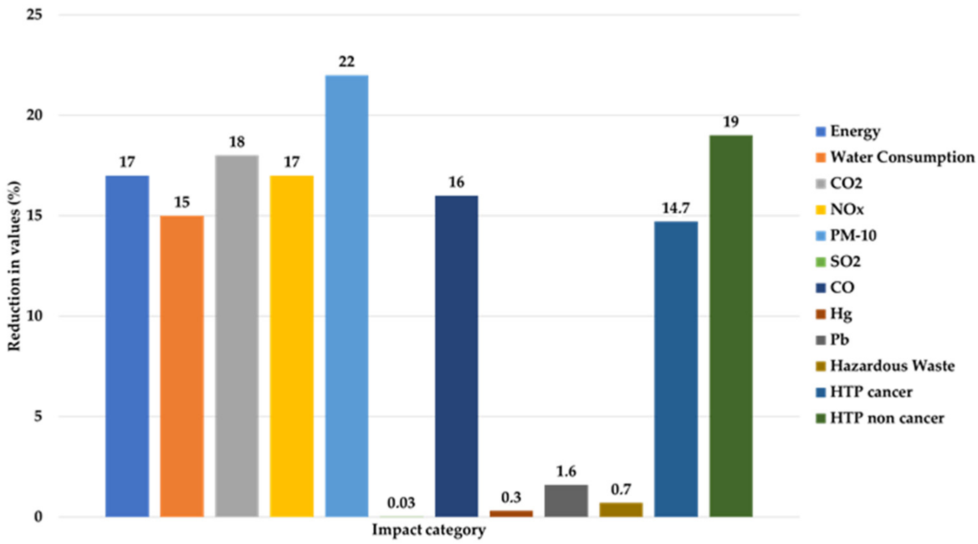

Figure 4. Reduction in values due to the application of Scenario 2.

More specifically, the main difference between the two scenarios is the formation of the unbound layer. In the second scenario, the unbound layer consists of RAP and VA. This means that 40% less VA is required to be extracted and used for the construction of the base/subbase layer. Therefore, the energy consumption decreases almost up to 40%, when compared with the alternative options, regarding the unbound layer. On the other hand, the total energy consumption does not decrease in a high rate, which means that the asphalt production requires higher amounts of energy than the VA extraction. Similarly, all the other impact variables have a similar tendency in the reduction rate. In addition, the thickness of asphalt layers is slightly lower in the second scenario, which contributes to a reduction in the values of all impact categories to a greater extent than VA for base/subbase layers.

Consequently, it is clear that even the inclusion of recycled materials in a satisfactory proportion could reduce the environmental footprint of a road project. Considering that the first scenario is a typical example of a conventional full rehabilitation to upgrade the existing pavement, it is clear that the existing techniques, i.e., the production of conventional materials, especially asphalt mixtures, as well as the conventional construction/rehabilitation methods need to be changed if the goal is to reduce emissions to air and water in order to slow down environmental phenomena such as global warming, the greenhouse effect, eutrophication, and acidification of air and water. In addition, other impact categories that affect human health are also important. In this regard, LCA for pavement construction and rehabilitation seems to be an important component of road projects to predict how the chosen solution might affect the environment and human health.

5. Conclusions

This study investigated the importance of quantifying environmental impacts and how an LCA method can contribute to the sustainability of pavements. To this end, the LCA method was used to evaluate two alternative rehabilitation options for a highway pavement in terms of environmental and human health. The difference between the two alternatives was in the materials and processes used. The first alternative used conventional materials and procedures, while the second alternative milled up the existing asphalt layers and reused them in the rehabilitation process. The following conclusions are drawn:

- It is a fact that pavement projects are highly responsible for aggravating environmental problems such as the greenhouse effect, eutrophication, acidification of air and water, and harm to human health.
- According to the results of LCA, it seems that among material production, transportation, and pavement processes in construction and maintenance, material production is the most important and has a greater impact on the environment and human health. This is particularly evident in asphalt production.
- The addition of 40% RAP in the unbound layer obviously reduces the amounts of all effect categories, since the reduction in the considered values due to the application of Scenario 2 ranges from 0.03 to 22%. The largest percentage changes are in the PM-10 and non-carcinogenic HTP effect categories, 22% and 19% reductions, respectively.
- Even a proportional amount of recycled material (in this case, 40% RAP in the unbound layer) can reduce the environmental footprint of a pavement construction or rehabilitation project.

Overall, this study proves the negative impact of the pavement construction and rehabilitation industry on the current global situation in terms of the environment and human health. Therefore, a tool to predict and quantify impact categories, namely an LCA study, is deemed necessary. In addition, the use of recycled materials and processes, even if limited, seems to go in the direction of protecting the environment and human health. In this context, it is assumed that the incorporation of recycled material in road sections produced by recycling processes will be a common practice in the future; therefore, further research in this scientific field is needed. Moreover, this study only refers to the environmental aspect of pavement construction or maintenance. Another important parameter for decision making between alternative applications is the life cycle cost analysis of pavements, i.e., Life Cycle Cost Analysis (LCCA), because the best option for the environment may also be the most expensive for the desired project. Therefore, an analysis that considers both the environmental and financial prospects of a project is required outside the scope of this study. In addition, this study is limited to the environmental assessment of the design, construction, and maintenance phases. The use phase and end-of-life phase are also important in estimating the environmental footprint of a pavement section. In this direction, an ultimate goal could be to capture the life cycle of a pavement to fully achieve the reuse and recycling of waste materials. Calibration of LCA programs to ensure accuracy of results for different use cases is also an important issue.

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