



## Article

# Comparative Environmental Assessment of Rigid, Flexible, and Perpetual Pavements: A Case Study of Texas

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**Abstract:** Unlike conventional pavements with a service life of 20–30 years, perpetual pavements (PPs) are designed to have a 50-year service life without requiring major maintenance and rehabilitation (M&R) activities. In this way, PPs are more cost-effective than conventional rigid pavements (CRPs) and conventional flexible pavements (CFPs). Nonetheless, even though the economic and mechanical aspects of PPs have been widely studied and well documented, the literature is limited regarding the environmental assessment of PPs. Consequently, this research estimated the environmental burden associated with five pavement structures (one CRP, one CFP, and three PP structures) through the life-cycle assessment (LCA) methodology. Notably, the PaLATE computational tool was used to carry out the LCAs. The results indicated that for CFP, most of the environmental impacts are generated by the M&R activities. Otherwise, for CRP and PP structures, the most impact occurred during the initial construction stage. The study results also revealed that materials production is the sub-stage that most contributed to the generation of environmental detriments. Overall, this comparative case study concluded that the pavement alternative with the slightest environmental damage is the PP structure.

**Keywords:** environmental efficiency; life-cycle assessment; PaLATE; perpetual pavements



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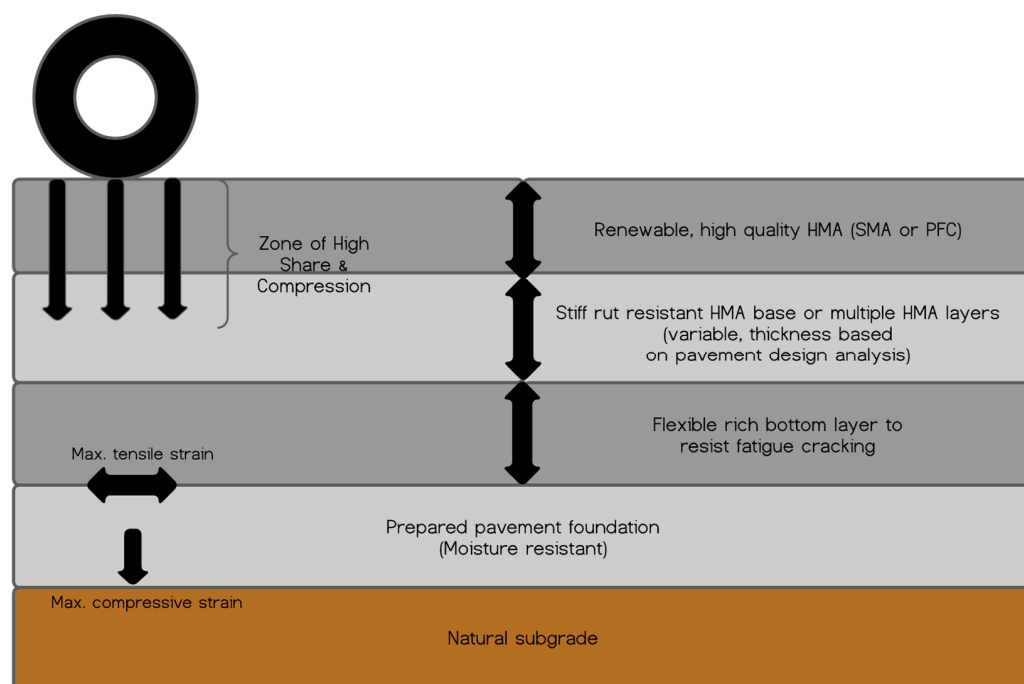


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## 1. Introduction

Perpetual pavements (PPs) are a type of asphalt pavement designed under a long-durability philosophy, i.e., the designs encounter robust enough structural packages that do not require major maintenance and/or rehabilitation (M&R) activities throughout their design life (around 50 years), only demanding surface treatments to guarantee users comfort [1,2]. The durability of PP is associated with the design method of the multi-layer structure: the upper surface layer is designed to resist wear and top-down cracking, the intermediate asphalt layer is designed to resist rutting and fatigue, and the lower asphalt layer is designed to resist bottom-up cracking [3,4]. Consequently, the PP uses a mechanized design that guarantees high rigidity to the upper layers of the pavement to reduce the incidence of the rutting phenomenon while proffering elevated flexibility to the lower layers to prevent bottom-up fatigue cracking [5,6]. The preceding is achieved by limiting the horizontal tensile strain at the bottom of the asphalt layers ( $\leq 70 \mu\epsilon$ ) and the vertical compressive strain on the top of the subgrade layer ( $\leq 200 \mu\epsilon$ ) [6–9].

In addition to the strain criteria, other aspects considered in the PP design are traffic (vehicle counts, loads, and speeds), climate conditions, and the availability of materials and construction processes [4,10,11]. According to the Asphalt Pavement Alliance [1,2], a typical PP structure is formed by: (i) a high-quality hot-mix asphalt (HMA), preferably stone matrix asphalt (SMA) or permeable friction course (PFC); (ii) at least one layer of stiff rut resistant HMA; (iii) fatigue-cracking-resistant HMA layer; and finally, (iv) a stabilized granular layer (base or subbase). Figure 1 illustrates the generalized PP design. Moreover, Table 1 exemplifies the PP structures reviewed in the literature.



**Figure 1.** Generalized PP design. Adapted from [1,2].

Previous studies by [5,6,9,12] optimized the Texas PP design method from mechanistic and economic perspectives. In these studies, it was demonstrated that for an analysis period of 50 years, the PP structures generated lower life-cycle costs (i.e., higher cost-effectiveness) than both conventional flexible pavements (CFP) and conventional rigid pavements (CRP), respectively. This cost-effectiveness was mainly attributed to the superior mechanical performance of the PP structures, which inherently reduces the required M&R activities. Thus, it ultimately reduces the long-term user and agency costs.

On the other hand, the studies listed in Table 2 suggest that the lower requirements in terms of M&R activities could potentially lead to PPs generating less environmental impacts than conventional pavements [13–15]. With this background, this research was conducted to comparatively assess the environmental burden of PPs against conventional flexible and rigid pavement structures. For these purposes, the Texas (USA) pavement structures were used as a case study, as documented by [6,9,12,16,17]. Consequently, the life-cycle assessment (LCA) was used to comparatively evaluate, analyze, and quantify the environmental damage produced by these pavement structures. The study's second objective was to bridge the knowledge gap and contribute to the literature enrichment by proving the potential sustainability benefits of using PP structures.

**Table 1.** Summary listing of PP structures found in the literature.

References	Design Traffic (MESALs *)	Analysis Period (Years)	HMA Thickness (cm)	Granular Layer Thickness (cm)
[3]	80	40	40	15
[4]	-	70	42	75
[11]	120	30–40	45	36
[18]	200	50	36	20
[19]	-	40	36	51
[20]	-	-	33	40
[21]	80	40	20	70
[22]	663	50	25	40
[23]	80–100	30	30	15–65
[24]	165	50	25	15
[25]	-	50	50	30

\* MESALs = million equivalent single axle loads.

**Table 2.** Summary listing of LCA studies of PPs found in the literature.

Features	References		
	[13]	[14]	[15]
Tool	PaLATE	Not specified	PaLATE
Service life	50 years	60 years	50 years
Design traffic	5 million ESALs (reference axis of 13 tons).	Average daily traffic of 12,000 vehicles, of which 10% are trucks.	30 million ESALs (reference axis of 8.2 tons).
Conventional pavement structure (mm (in))	In this paper, a PP was not evaluated against a conventional pavement. Two HMA structures were evaluated, one being conventional, while the other was modified with the addition of lime.	51 mm (2 in) surface HMA + 51 mm (2 in) intermediate HMA + 140 mm (5.5 in) upper base HMA + 394 (15.5 in) granular subbase	40 mm (1.6 in) surface HMA + 120 mm (4.7 in) intermediate HMA + 150 mm (5.9 in) granular base + 450 mm (17.7 in) granular subbase
PP structure (mm (in))		51 mm (2 in) surface HMA + 51 mm (2 in) intermediate HMA + 140 mm (5.5 in) upper base HMA + 7.6 mm (3 in) lower base HMA + 394 mm (15.5 in) granular subbase	40 mm (1.6 in) surface HMA + 120 mm (4.7 in) intermediate HMA + 80 mm (3.1 in) base HMA + 150 mm (5.9 in) granular base + 390 mm (17.7 in) granular subbase
M&R activities	Overlays.	Mill and fill, overlay, micro-surfacing, and cold in-place recycling.	Mill and overlays.
LCA approach	Cradle-to-grave (from the extraction of raw materials to end of life of the road).	Pavement construction and maintenance.	Pavement construction and maintenance.
Results	The modified HMA structure generated the following effects compared to the control case: 23% lower greenhouse emissions, 44% decrease in acidification, and 45% lower eutrophication.	The PP showed an approximate decrease of 20% (compared to the conventional alternative) in the following impact categories: ozone depletion, global warming, smog, ecotoxicity, fossil fuel depletion, and water resource depletion.	PP had a lower impact on the environment than conventional pavement in terms of use of materials, energy consumption, and greenhouse gas emissions (CO <sub>2</sub> , NO <sub>x</sub> , PM10, and SO <sub>2</sub> emission).

## 2. Background: LCA Concepts and Related Tools

LCA is a standardized methodology that allows determining and classifying the potential environmental impacts generated by activities, systems, or projects throughout the stages of their life cycle [26,27]. For instance, in the case of pavements, the stages of extraction and processing of raw materials, production of mixtures, transportation, construction process, and end of useful life are typically used [13,28–32]. The international standards associated with LCA are the ISO-14040 and ISO-14044, respectively [26,27]. The ISO-14040 establishes the principles and framework. Meanwhile, the ISO-14044 details the requirements and guidelines. According to these standards, LCA must be executed in four phases, as follows:

- Goal and scope definition phase: include the system boundary and level of detail. The depth and the breadth of LCA can differ depending on the goals of a case.
- Life-cycle inventory (LCI) analysis phase: this is an inventory of input/output data associated with the studied system. It involves the collection of the data necessary to meet the goals.
- Life-cycle impact assessment (LCIA) phase: the environmental category indicators, also called impact categories, are used to condense and explain the LCI results.
- Interpretation phase: LCI and LCIA results are summarized and discussed as the basis for drawing conclusions, recommendations, and decision making.

On the other hand, it is common to employ specialized software to implement the LCA methodology. SimaPro and GaBi are the leading software tools used for LCA [33–35]. However, in the field of road infrastructure, it is common to use various pavement-specific LCA tools, including but not limited to the following: ROAD-RES, PaLATE, UK asphalt pavement LCA model, ROAD-RES, CMS RIPT, CFET, ECORCE-M, DuboCalc, CO2NSTRUCT, Greencalc+, Ecosoft, VTTI/UC asphalt pavement LCA model, and Athena Impact Estimator for Highways [36–39].

Due to the wide variety of environmental outputs, simplicity, and customization potential to the project goals, PaLATE stands out from the other LCA tools considering that it was explicitly developed for pavements [40]. PaLATE is a free Microsoft Excel add-on tool created by the Consortium on Green Design and the University of California (Berkeley). It evaluates the life-cycle costs and environmental impacts by employing a hybrid life-cycle analysis of various pavement alternatives [41]. This tool has a vast trajectory in the study of road infrastructure projects. In the literature, it is found that it has been successfully used as follows: as a carbon footprint estimator [42], as a decision-making technique [43,44], as a quantifier of environmental benefits caused by recycled materials [45–47], as a green highway rating system [48,49], and as a preservation treatment comparator [50], among other applications. On this basis, PaLATE was selected for use in this study.

### 3. LCA and Results

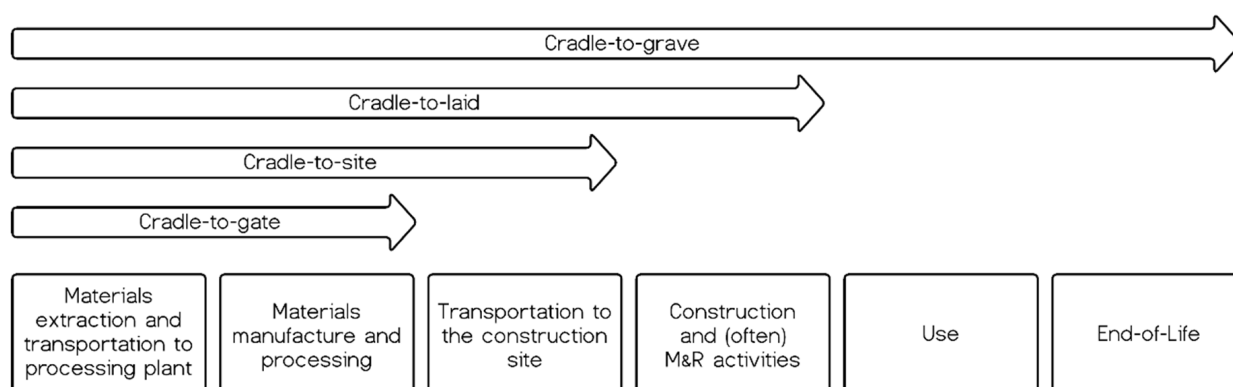
#### 3.1. Goal and Scope Definition Phase

##### 3.1.1. Goal

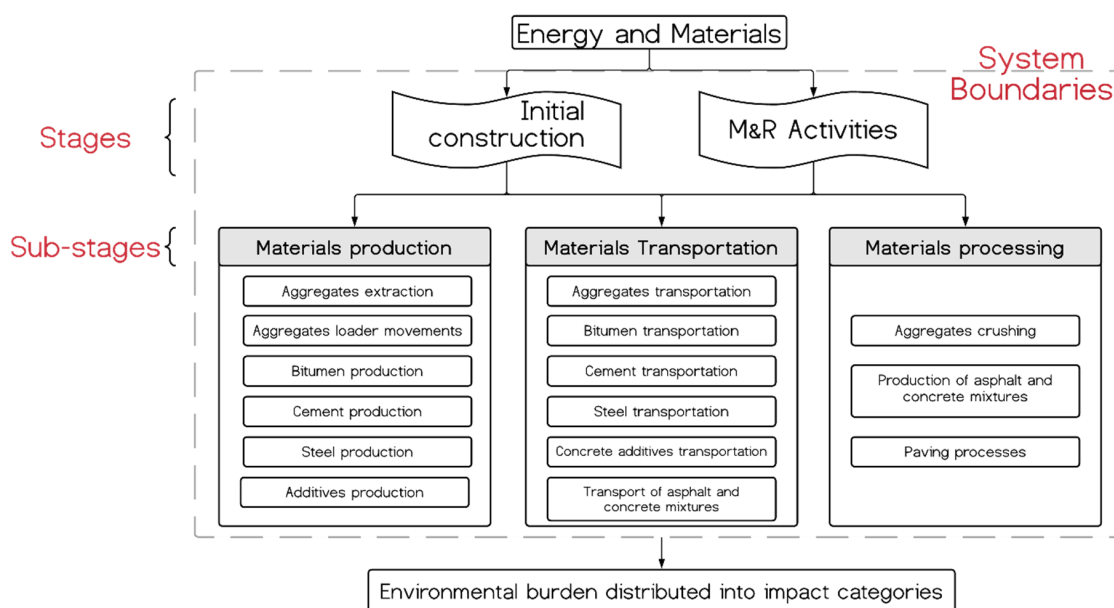
As previously mentioned, this study aimed to determine the potential environmental benefits of using PP structures. For this purpose, existing PP structures and several conventional pavement alternatives (CFP and CRP) from the state of Texas (USA) were comparatively assessed. In this way, the present research intends to enrich the state of the knowledge by providing an environmental assessment of PP structures to provide agencies, pavement designers, and other stakeholders with a complete picture of PP implementation's performance, cost, sustainability, and environmental benefits.

##### 3.1.2. System Description and Boundaries

This investigation was accomplished by applying the LCA in adherence to the current international regulations (namely ISO-14040 and ISO-14044) and the Federal Highway Administration's Pavement LCA Framework [51]. Figure 2 shows the graphic description of the primary approach for system boundaries used in the road infrastructure industry for LCA execution, namely cradle-to-grave, cradle-to-laid, cradle-to-side, and cradle-to-gate. The cradle-to-laid approach was chosen as the most convenient method to align with previous PP studies [6,9,12]. Thus, the initial construction process and M&R activities are considered in the LCAs [51,52]. Materials production, materials transportation, and materials processing (equipment) were examined for both stages. In this way, Figure 3 presents the system boundaries and processes considered in the study.



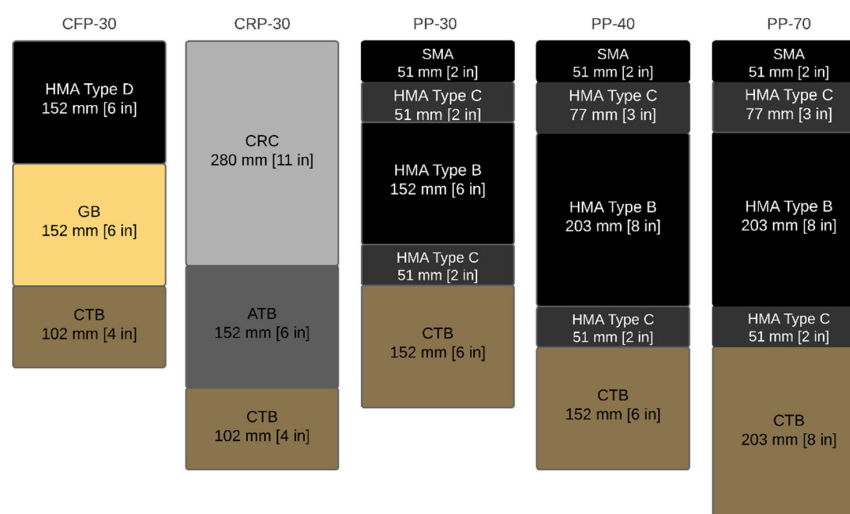
**Figure 2.** Main system boundaries employed to develop the LCA on road infrastructure. Adapted from [51,52].



**Figure 3.** System boundaries adopted for the development of LCAs.

### 3.1.3. Functional Unit

The pavement alternatives were analyzed considering a service life of 50 years, 30 million equivalent single axle loads (MESALs), and a typical Texas climate for the Fort Worth area (TX, USA). The structural packages for the PP, CFP, and CRP designed under these conditions were designated as PP-30, CFP-30, and CRP-30, respectively. It was also desired to evaluate the PPs' environmental impacts on traffic loading sensitivity. Therefore, the PP structures were assessed for 40 and 70 MESALs traffic loading, denoted as PP-40 and PP-70, respectively [6]. For all the cases, the function unit has deemed a width of 24 ft (7.3 m) and a length of 1 mile (1609 m). Following the previous studies that supported this research [6,9], the pavement alternatives were designed using the flexible pavement design system (FPS), Texas mechanistic-empirical flexible pavement design system (TxME), and AASHTOWare® Pavement M-E Design software. Figure 4 shows these structures. In addition, the subgrade properties (gradation, Atterberg limits, specific gravity, moisture-density curves, Texas triaxial, shear strength, and unconfined compressive strength) employed in the design process can be found in the Texas PP database [6,9,53].



**Figure 4.** Pavement structures used for LCA. Acronyms: GB—granular base; CTB—cement-treated base; CRC—continuously reinforced concrete; ATB—asphalt-treated base.

Figure 4 shows that all the PP structures under evaluation have SMA as the surface layer. SMAs are a type of HMA developed to provide maximum resistance to rutting, cracking, noise reduction, high skid resistance, and better wet visibility [54,55]. Nevertheless, due to the mineral skeleton (gap-graded conformed by two parts of coarse aggregate) of the SMAs, it is required to incorporate a stabilizer additive to prevent the drain-down phenomena [56,57]. The inclusion of the stabilizing agent can cause SMA to generate a higher environmental burden than conventional HMA mixtures [58]. In this study, crumb rubber was used as the stabilizing additive. The literature demonstrates that this material provides excellent mechanical performance [59–63].

### 3.1.4. Data Source

The studies and literature publications by [5,6,9,12,16,17,53] served as the primary data source for the work contained in this paper. For LCA analysis, the PaLATE tool was used. This tool includes a detailed database built on the literature review, which comprises the environmental impact of several materials and processes commonly used in pavement construction [64,65]. PaLATE considers the user inputs for the design, initial construction, maintenance, equipment used, and costs for a roadway and provides the outputs for the life-cycle environmental impacts and associated costs [66,67]. PaLATE was selected because it is specially designed for pavement evaluation, presents an extensive record of use in the literature, incorporates a transparent programming code, and the user interface allows for flexibility in updating the inventory database [68,69].

### 3.2. LCI Analysis Phase

PaLATE implements its LCI according to the project specifications, i.e., required materials, transport distances, and equipment. Based on the pavement structures, the M&R activities planned for the alternatives (Figure 5), the composition of the pavement layers (Table 3), and the required volume of materials (Table 4) were determined. The M&R activities were adapted from previous research [6]. For the PP alternatives, an asphalt overlay will be placed every 12 years. Regarding the CFP-30 alternative, an asphalt overlay will be placed every 4 years, and the asphalt layer will be rebuilt every 20 years. In all the cases, the asphalt overlay was 2 in (50.8 mm) thick. Likewise, the road surface was not previously milled in any case of asphalt overlay. For its part, the CRP-30 alternative only contemplates a full-depth repair 30 years after the initial construction. Further, the transport distances considered for the materials are listed in Table 5. These distances are representative of the state of Texas, USA. Otherwise, different types of construction equipment can strongly influence the calculated environmental impacts due to the differences in efficiency and fuel consumption. Therefore, it was decided to use the equipment database suggested in PaLATE as representatives of the USA construction practices. Accordingly, Table 6 shows the LCI employed in this study.

**Table 3.** Pavement layer material composition (mass).

Layer	Aggregate (%)	Bitumen (%)	Cement (%)	Water (%)	Additive (%)	Steel (%)	Gmb	Gmm
SMA	93.7	6.0	-	-	0.3 *	-	2.350	2.446
HMA Type B	95.5	4.5	-	-	-	-	2.381	2.480
HMA Type C	94.7	5.3	-	-	-	-	2.396	2.496
HMA Type D	95.0	5.0	-	-	-	-	2.401	2.476
ATB	95.5	4.5	-	-	-	-	2.259	2.353
CTB	97.0	-	3.0	-	-	-	-	-
CRC	77.0	-	14.0	5.9	0.1 **	3.0	-	-

\* Crumb rubber; \*\* concrete additive.



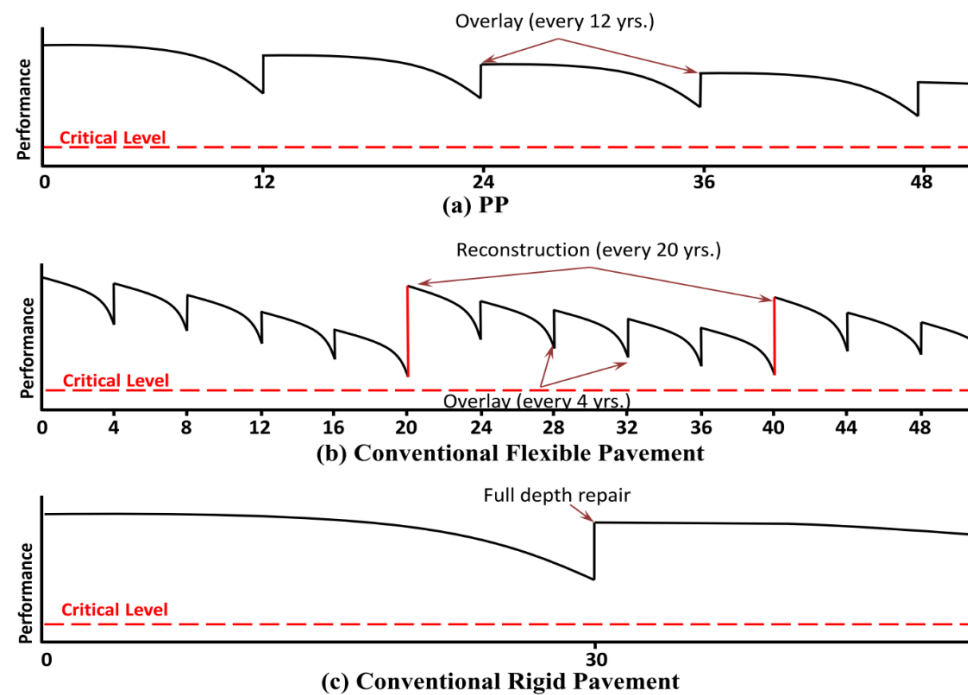


Figure 5. Pavement M&R activities. Adapted from [6].

Table 4. Material quantity (volume).

Materials	Initial Construction (m <sup>3</sup> )					M&R Activities (m <sup>3</sup> )				
	CFP-30	CRP-30	PP-30	PP-40	PP-70	CFP-30	CRP-30	PP-30	PP-40	PP-70
Aggregates	4375.2	4856.5	4721.2	5488.1	6044.7	8211.9	2287.0	1981.9	1981.9	1981.9
Bitumen	210.5	178.3	418.8	518.6	518.6	1122.9	-	329.7	329.7	329.7
Cement	29.4	384.9	44.1	44.1	58.9	-	355.5	-	-	-
Concrete additive	-	7.9	-	-	-	-	7.9	-	-	-
Crumb rubber	-	-	3.7	3.7	3.7	-	-	14.6	14.6	14.6
Steel	-	30.1	-	-	-	-	30.1	-	-	-
Water	-	464.4	-	-	-	-	464.4	-	-	-

Table 5. Distances considered for LCA.

Route	One-Way Trip Distance (km (mile))
From the aggregates supply to production plant	48.3 (30)
From the bitumen supply to production plant	160.9 (100)
From the cement supply to production plant	160.9 (100)
From the concrete additives supply to production plant	80.5 (50)
From the crumb rubber supply to production plant	80.5 (50)
From the steel reinforcement supply to production plant	321.9 (200)
From the production plant to the paving area	16.1 (10)

Table 6. LCI employed in this study. Source: PaLATE.

Activity	Equipment	Brand/Model	Capacity	Productivity	Fuel Consumption	Energy
Transportation mode	Dump truck	-	20 ton	-	0.42 lt/km	35.83 MJ/lt
	Tanker truck	-	20 ton	-	0.42 lt/km	35.83 MJ/lt
	Rail	-	1 ton	-	0.7 lt/km	35.83 MJ/lt
	Barge	-	1 ton	-	1.03 lt/km	35.83 MJ/lt
	Cement truck	-	23 ton	-	0.42 lt/km	35.83 MJ/lt
Concrete paving	Slipform paver	Wirtgen SP 250	106 hp	564 ton/h	19.7 lt/h	-
	Texture curing machine	Gomaco T/C 400	70 hp	187 ton/h	20.2 lt/h	-

Table 6. Cont.

Activity	Equipment	Brand/Model	Capacity	Productivity	Fuel Consumption	Energy
Asphalt paving	Paver	Dynapac F30C	196 hp	2400 ton/h	49.1 lt/h	-
	Pneumatic roller	Dynapac CP132	100 hp	668 ton/h	26.1 lt/h	-
	Tandem roller	Ingersoll rand DD110	125 hp	285 ton/h	32.7 lt/h	-
Crushing plant	Excavator	John Deere 690E	131 hp	225 ton/h	34.2 lt/h	-
	Wheel loader	John Deere 624E	135 hp	225 ton/h	35.3 lt/h	-
	Dozer	Caterpillar D8N	282 hp	225 ton/h	71.4 lt/h	-
	Generator	Caterpillar 3406C TA	519 hp	225 ton/h	98.4 lt/h	-
Excavation, placing, and compaction	Excavator	John Deere 690E	131 hp	315 ton/h	34.2 lt/h	-
	Vibratory soil compactor	Dynapac CA 262D	174 hp	1832 ton/h	27.2 lt/h	-
HMA production	Asphalt mixer	Uncontrolled Batch-mix	-	226.8 ton/h	-	-
Concrete production	Ready-mixed concrete	-	-	-	-	536.13 MJ/ton 18.79 kWh/ton

### 3.3. LCIA Phase

PaLATE provides environmental effects into 12 impact categories, namely energy consumption (EC), water consumption (WC), carbon dioxide emissions (CO<sub>2</sub>), nitrogen oxide emissions (NO<sub>x</sub>), particle size less than 10 µm emissions (PM10), sulfur dioxide emissions (SO<sub>2</sub>), carbon monoxide emissions (CO), mercury emissions (Hg), lead emissions (Pb), hazardous waste generated (HWG), aldehydes generated (AG), and benzo[a]pyrene generated (BG) [70,71]. These impact categories can be grouped into three types: resource consumption (i.e., EC and WC), emissions to the atmosphere (i.e., CO<sub>2</sub>, NO<sub>x</sub>, PM10, SO<sub>2</sub>, and CO), and leachate information (i.e., Hg, Pb, HWG, AG, and BG). One of the PaLATE advantages over other tools to develop LCA is its clear distinction of leachates. Leachates are foul-smelling liquids (black or brown) produced by the percolation of moisture through non-containerized solid waste [72–74]. In addition, the PaLATE tool clarifies that the HWG refers to the resource conservation and recovery act (RCRA). Furthermore, it is stated that AG and BG represent human toxicity potential cancer (HTPc) and human toxicity potential non-cancer (HTPnc), respectively.

In environmental assessments, the contribution to climate change is one of the most studied aspects due to its significance in contemporary times [75–77]. Therefore, it is not surprising that CO<sub>2</sub> and NO<sub>x</sub> emissions are some of the most crucial impact categories of PaLATE. CO<sub>2</sub> is often used as a reference gas to quantify the global warming potential (GWP), a benchmark adopted to measure the contribution to climate change [78–80]. NO<sub>x</sub> is one of the major harmful emissions because it is a precursor of tropospheric ozone, i.e., a potent greenhouse gas [81,82]. NO<sub>x</sub> pollution is mainly formed during fossil fuel combustions at high temperatures [83,84]. Nitrogen oxide emissions are highly harmful to humans and even threaten their lives. This aspect has led to a growing interest in developing techniques and technologies for their reduction. Notably, this is one of the primary targets of the Clean Air Act [85–87].

### 3.4. Interpretation Phase

#### 3.4.1. Characterization Results

Considering the LCA methodology, the data provided, and the assumptions described above, the environmental impacts were determined. Table 7 shows the characterization results associated with the five pavement alternatives evaluated. The alternative that generates the highest and lowest environmental impact for each impact category is highlighted in red and green, respectively. For example, in Table 7, it is noted that: (i) the PP-30 alternative is the one that generates the least environmental impact in most of the impact categories (10 out of 12); (ii) CRP-30 is the most contaminating alternative (in 9 out of 12 criteria); (iii) the PP structures designed with considerably higher traffic (namely PP-40 and PP-70 with 40 and 70 MESALs, respectively) generated less environmental impacts than the conventional pavement alternatives.



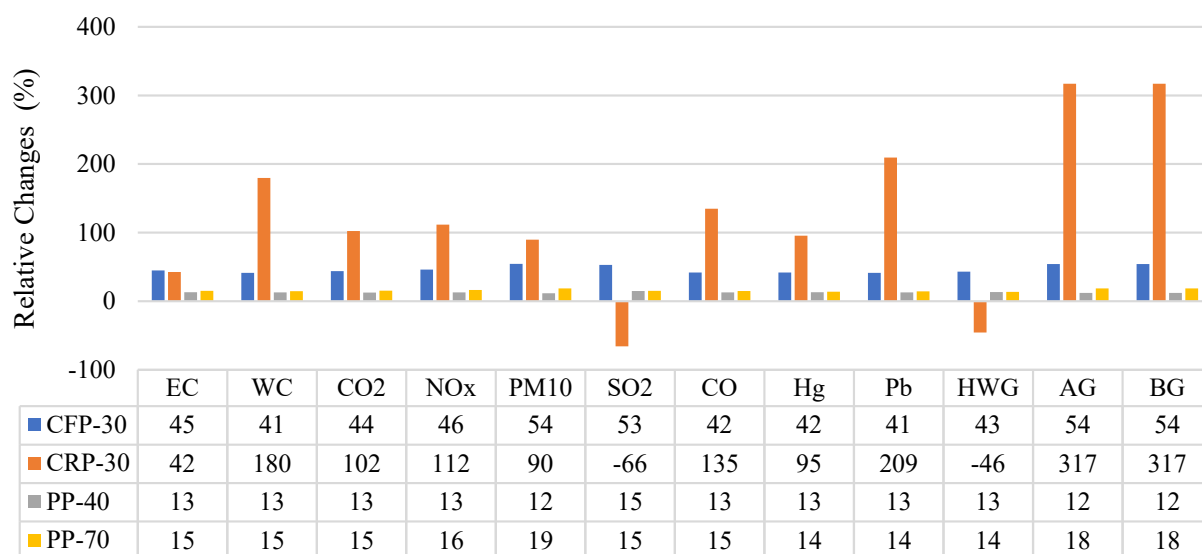
**Table 7.** LCIA results for a functional unit \*.

Impact Category	Unit	Value				
		CFP-30	CRP-30	PP-30	PP-40	PP-70
Energy consumption (EC)	GJ	35,827	35212	24,728	27,932	28,439
Water consumption (WC)	kg	11,099	21,977	7861	8861	9002
Carbon dioxide emissions (CO <sub>2</sub> )	ton	1882	2649	1310	1475	1511
Nitrogen oxide emissions (NO <sub>x</sub> )	kg	18,733	27,123	12,821	14,452	14,896
Particle size less than 10 µm emissions (PM10)	kg	7345	9025	4759	5310	5641
Sulfur dioxide emissions (SO <sub>2</sub> )	kg	400,310	89,115	261,885	300,847	301,049
Carbon monoxide emissions (CO)	kg	6796	11,246	4791	5397	5499
Mercury emissions (Hg)	g	43.73	60.31	30.85	34.89	35.11
Lead emissions (Pb)	g	2148	4706	1521	1716	1739
Hazardous waste generated (HWG)	ton	438	167	306	347	348
Aldehydes generated (AG)	g	11,746	31,759	7618	8535	9023
Benzo[a]pyrene generated (BG)	g	0.76	2.06	0.50	0.55	0.59

\* Width and length of 24 ft and 1 mile, respectively.

### 3.4.2. Relative Environmental Impacts

In order to analyze the relative changes in the environmental burden, one of the pavement alternatives must be used as the reference datum. The PP-30 was selected for this purpose because it allowed comparing (on equal terms) the conventional pavement alternatives (CFP-30 and CRP-30) with the PP structure. Furthermore, this choice permitted the sensitivity evaluation of increasing the design traffic level (PP-40 and PP-70) versus the increase in the environmental impacts. Figure 6 shows these relative environmental damages.

**Figure 6.** Relative environmental impacts using PP-30 as the reference datum.

In Figure 6, positive numbers mean that the evaluated pavement alternative has a higher environmental impact (in percentage) than the reference datum (i.e., PP-30). Likewise, negative numbers indicate that the evaluated pavement alternative presents less environmental burden than the reference datum. In this way, the following can be observed:

- Under the same design conditions, CFP generates between 41% and 54% more potential for environmental impact than a PP structure.
- Under the same design conditions, CRP ranks as the most contaminating pavement alternative. In 9 of 12 impact categories, it has the highest potential for environmental impact. Nevertheless, CRP-30 generates the most negligible emissions in two impact categories (SO<sub>2</sub> and HWG). Notably, this structure requires less energy consumption than CFP-30.

- The PP-40 was designed to resist 10 MESALs more than PP-30; nonetheless, it only generates about 12~15% more environmental impacts. Meanwhile, the PP-70 was designed to withstand 40 MESALs more than PP-30, causing only 14~19% more environmental impacts.
- The environmental benefits of the PP structures were most prominent in impact categories such as water consumption, CO<sub>2</sub> emissions, nitrogen oxide emissions, CO emissions, lead emissions, aldehydes generated, and benzo[a]pyrene generation.

### 3.4.3. Stages and Sub-Stages Contribution Analysis

This research employs two stages, namely initial construction processes and M&R activities. Figure 7 shows the discrimination of the environmental impacts according to the contribution made by each stage. The findings determined in Figure 7 are listed below:

- In all the impact categories, the pavement alternative that generated the lowest environmental damage in the initial construction stage was CFP-30.
- In the initial construction stage, the PP alternatives were the largest producers of SO<sub>2</sub> and HWG. However, in the other ten impact categories, the most significant environmental impact was generated by CRP-30.
- Regarding the M&R activities stage, the CFP-30 pavement alternative generated the highest environmental impact (except for water consumption and lead emissions, where the CRP-30 was the most contaminating alternative). This response behavior is expected for traditional asphalt pavements since they require frequent intervention activities.
- The PP alternatives were the ones that caused the least environmental impact during the M&R activities stage. Only in three impact categories (EC, SO<sub>2</sub>, and HWG) were they surpassed by the CRP-30 alternative.
- For the CRP-30 and PP alternatives, most of the environmental impact was predominantly associated with the initial construction stage. For CFP-30, however, the M&R activities stage was the most influential.

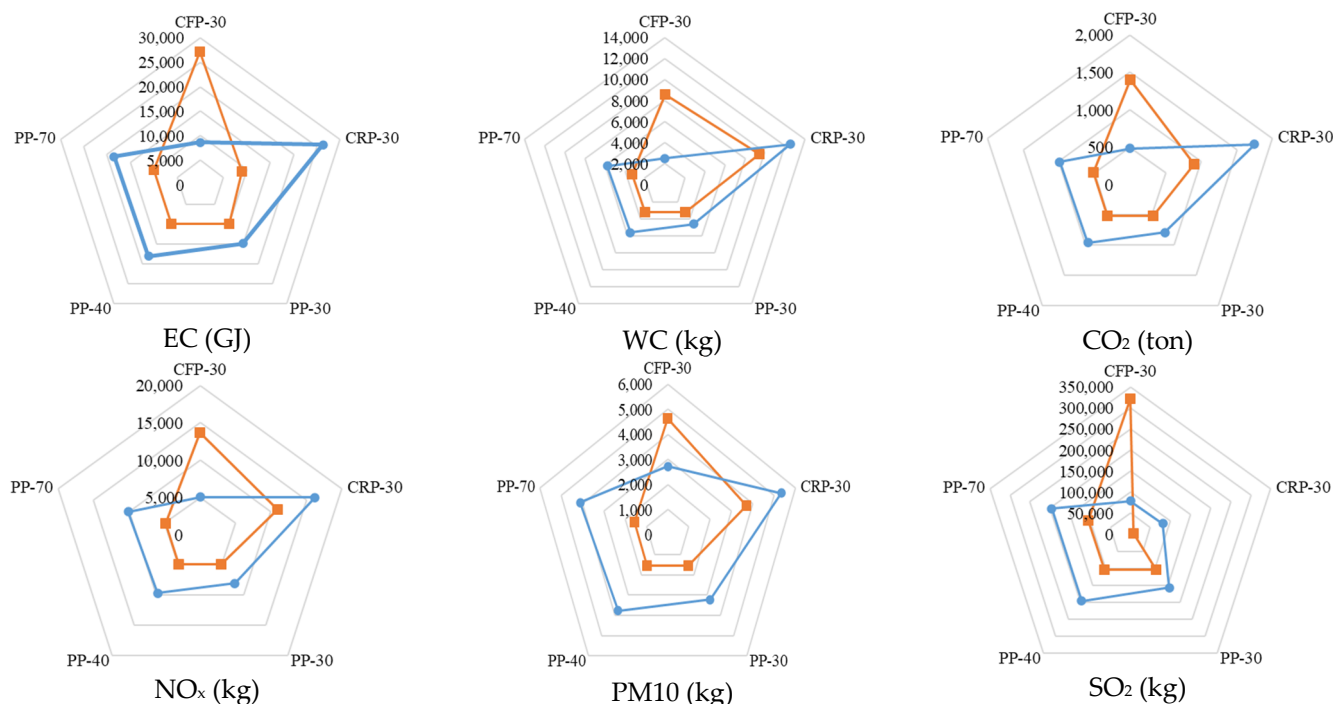
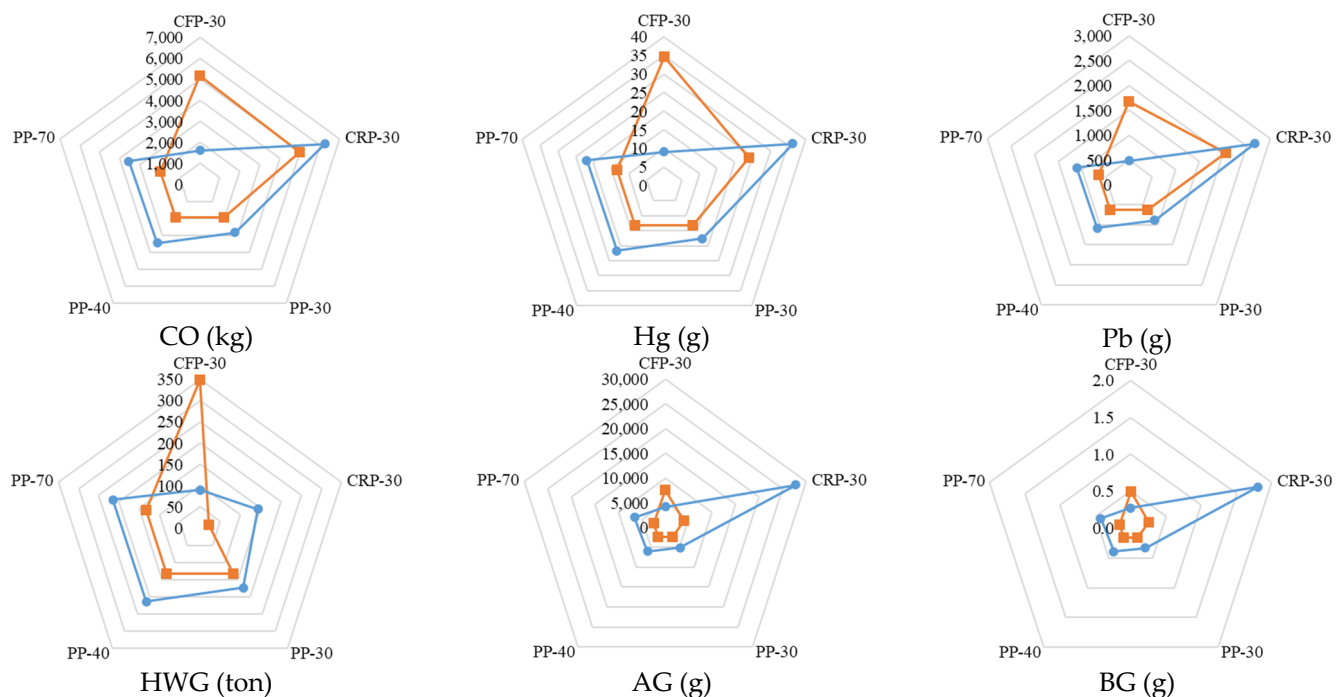


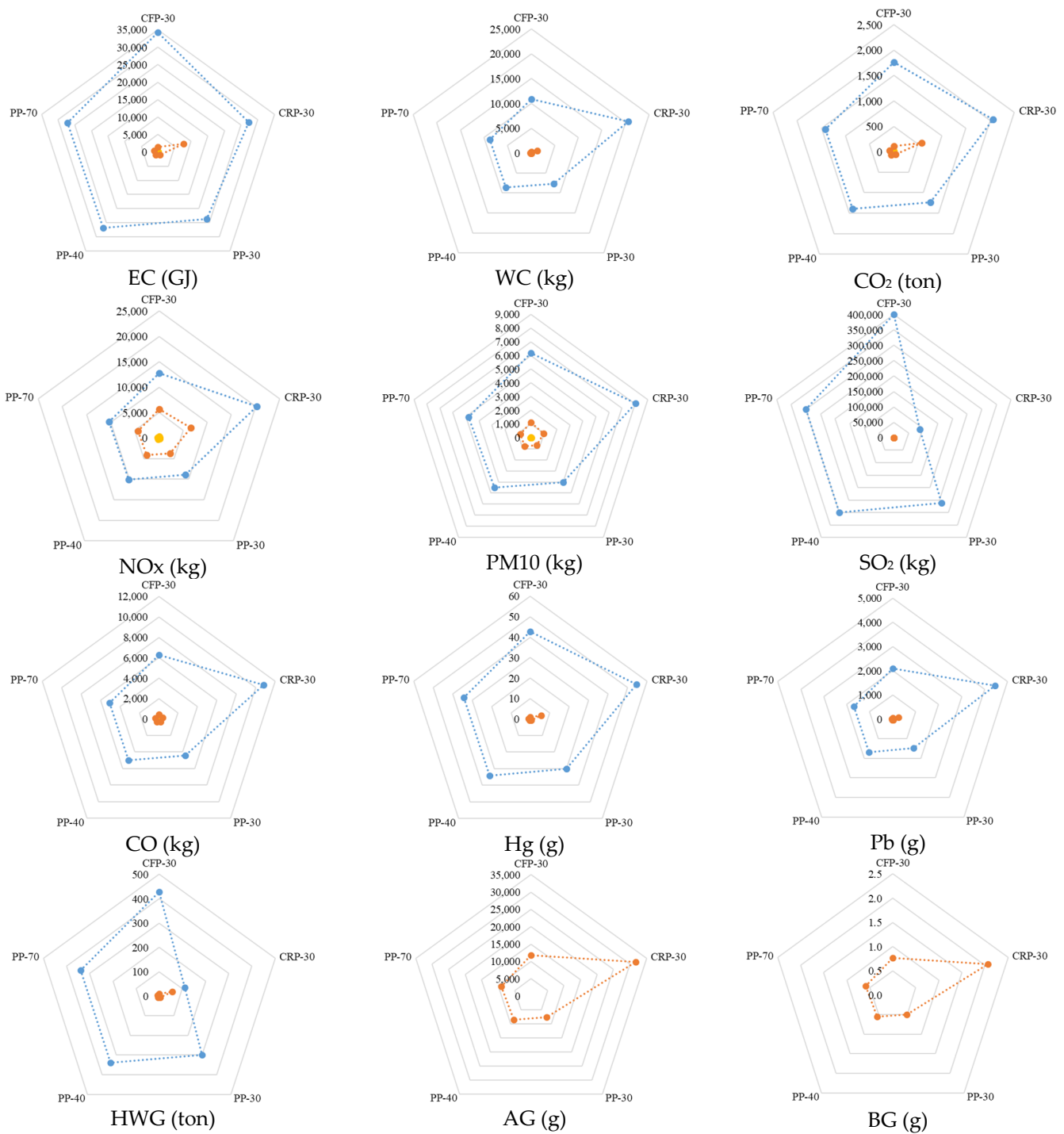
Figure 7. Cont.



**Figure 7.** Environmental impacts by stages: initial construction and M&R activities. Color-coding: blue—initial construction; orange—M&R activities.

At each stage, the contributions made by the sub-stages of materials production, materials transportation, and materials processing were evaluated. Each sub-stage involved the contributions made during the initial construction processes and M&R activities. Figure 8 shows this analysis. From this graph, the following findings can be drawn:

- For all pavement alternatives, the environmental impacts associated with AG and BG occur exclusively in the materials transportation sub-stage. CRP-30 and PP-30 cause the maximum and minimum environmental impact in both categories. Therefore, it is recommended to use local (or at least close) sources of materials as much as possible.
- Most of the environmental burden occurred in the materials production sub-stage for the other impact categories. Meanwhile, marginal impacts were generated in the materials transportation sub-stage. On the other hand, materials processing caused negligible environmental impacts. Hence, to reduce the environmental impact of road infrastructure, it is necessary to diminish the depletion of non-renewable resources. In this way, materials reuse techniques and recycling technologies can be implemented, which for instance, include partial replacement of the raw materials using construction and demolition waste materials, recovery of asphalt binders, and utilization of industrial waste as supplementary cementitious material (SCM), among others [88–91].
- In the materials production and transportation sub-stages, it is evident that the PP alternatives had the least environmental impact, whilst CRP-30 was the most contaminating.
- Concerning the materials processing sub-stage, the CFP-30 alternative generated the most detrimental environmental effects in most of the impact categories evaluated.



**Figure 8.** Environmental impacts by sub-stages: materials production, transportation, and processing. Color-coding: blue—materials production; orange—materials transportation; yellow—materials processing (negligible).

## 4. Discussion

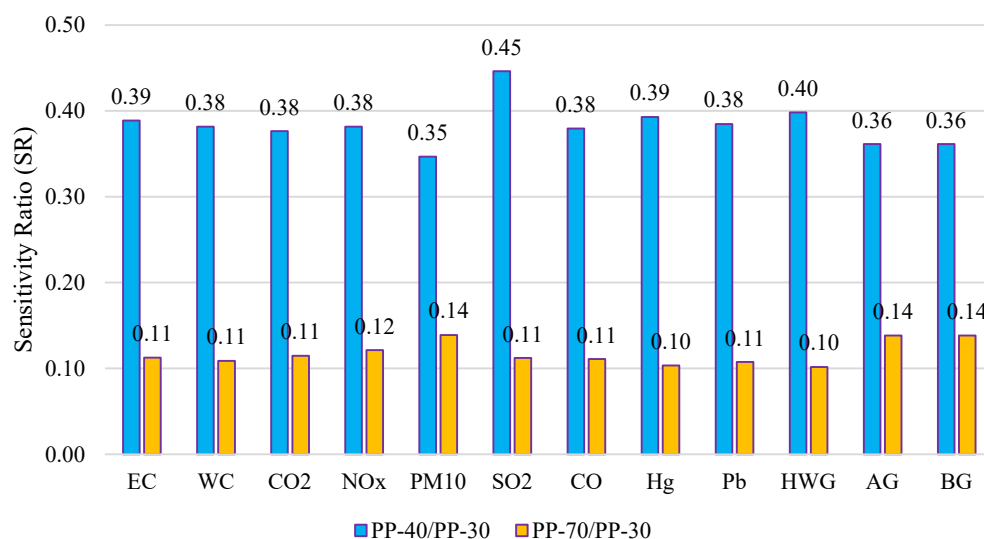
### 4.1. Traffic Sensitivity Analysis

A sensitivity analysis was performed to measure how better pavements can be designed and constructed without drastically increasing the environmental impacts. For this purpose, the sensitivity ratio (SR) was determined by varying the traffic design level for the

PP structures. The SR is the ratio between the two relative changes and is mathematically computed as expressed in Equation (1) [92]:

$$SR = \frac{\frac{\Delta_{result}}{Initial\ result}}{\frac{\Delta_{parameter}}{Initial\ parameter}} \quad (1)$$

According to Equation (1), higher SR values indicate that the parameter alteration has a more significant influence on the results [93]. For example, if a parameter has an SR of two, it implies that when increasing its value by 10%, the final result is increased by 20% [92]. This study evaluated two scenarios: PP-40 versus PP-30 (first scenario) and PP-70 versus PP-30 (second scenario). In both scenarios, the results corresponded to the values obtained in each impact category, and the initial parameter corresponded to a traffic level of 30 MESALs for PP-30. For the first and second scenarios, the  $\Delta_{parameter}$  takes a value of 40 MESALs and 70 MESALs, respectively. Figure 9 shows the corresponding SR results. This graph shows that the SR fluctuates within a range of 0.35–0.45 in the first scenario. Meanwhile, in the second scenario, the variation range was 0.10 to 0.14. This decrease in magnitudes and the breadth of the range mean that the relative environmental impact decreases for higher-traffic-designed PP. Therefore, the preceding suggests that designing and constructing PP structures for high-traffic volume (trucks) highways are more eco-efficient.



**Figure 9.** SR results for PP structures.

#### 4.2. Contribution Analysis of the Binders

Binders are materials capable of combining diverse substances through chemical stabilization and physical solidification. Nevertheless, their use must be prudent because their manufacturing processes seriously contaminate [94–96]. Bitumen and Portland Cement (PC) are some of the most widely used organic and inorganic binders, respectively [97]. The bitumen comes from crude oil refinement, making it an environmentally unfriendly material since petroleum is a non-renewable source, and the associated industrial process causes high levels of environmental pollution [88,98]. PC is a powdery substance produced through the high-temperature calcination of lime (which contributes calcium oxide) and clay (which provides silica, alumina, and iron oxide) as the primary ingredients [99,100]. During this process, enormous environmental burdens associated with energy consumption, gas emissions into the atmosphere (CO, CO<sub>2</sub>, NO<sub>x</sub>, and SO<sub>2</sub>), and leachate formation (heavy metals) are generated [101,102].

In this way, binders are considered materials with a high environmental impact. Therefore, it was decided in this study to quantify the contribution that the binders (PC in the case of CRP-30 and bitumen in the other alternatives) have on the totality of the environmental

burden (i.e., regarding the characterization results). Figures 10–12 show the relative and absolute comparison of the contribution of the binders to the total environmental impact of the pavement alternatives. In the item “Contributed by the binder”, the bitumen and PC from the asphalt-treated base and cement-treated base were not considered. Because PP-40 and PP-70 exhibited the same response trend as that observed for PP-30, it was decided not to graph the data of these two alternatives. The selected impact categories examined for this analysis were EC, CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>2</sub>, CO, Hg, and Pb. From Figures 11–13, the following inferences were made:

- In the asphalt pavement alternatives (CFP-30, PP-30, PP-40, and PP-70), bitumen is the highest contributor to the environmental burden in the impact categories of EC, CO<sub>2</sub>, CO, Hg, and Pb. Additionally, the bitumen was also a considerable NO<sub>x</sub> contributor.
- Regarding CRP-30, the PC contributes almost half of the total environmental burden associated with the impact categories of EC, CO<sub>2</sub>, and NO<sub>x</sub>. Additionally, PC plays an essential role in the emission of CO and the generation of heavy metals (Hg and Pb).
- Binders are the main contributors to energy consumption and CO<sub>2</sub> emission into the atmosphere. These materials are the principal generators of the global warming potential (within the pavement alternatives assessed) and are therefore boosters of climate change.

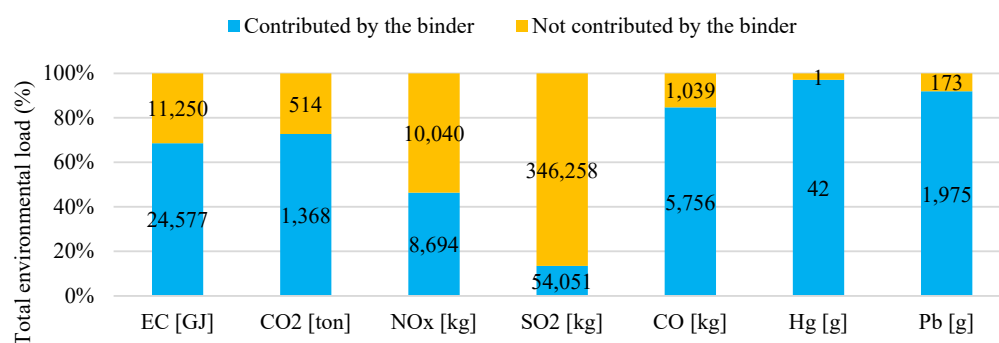


Figure 10. Environmental impacts of binders for the CFP-30 alternative.

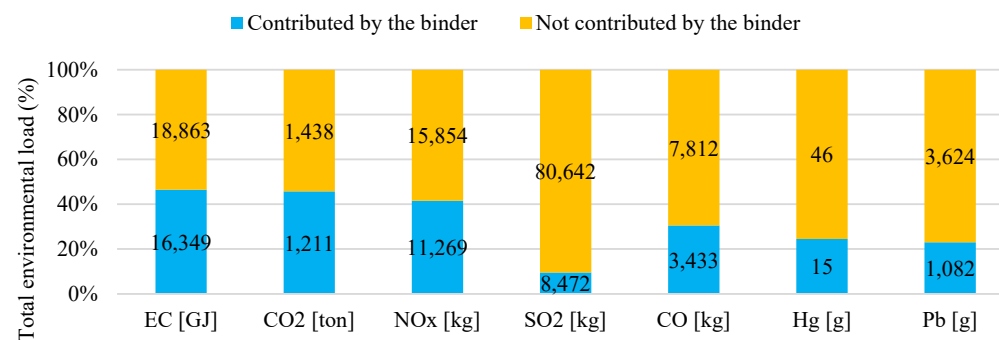


Figure 11. Environmental impacts of binders for the CRP-30 alternative.

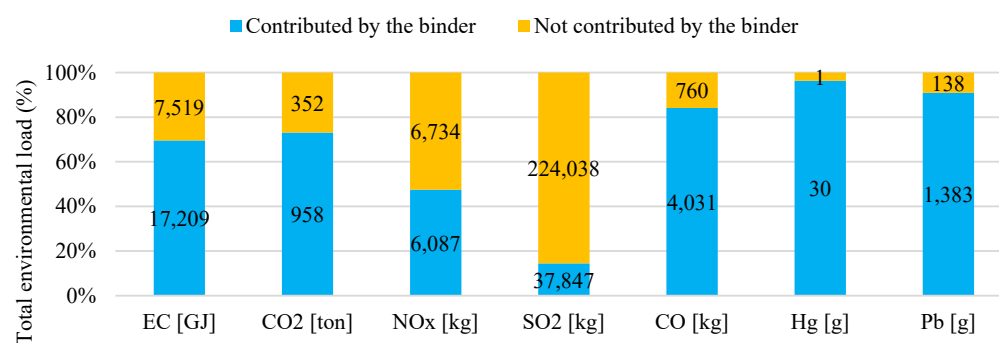
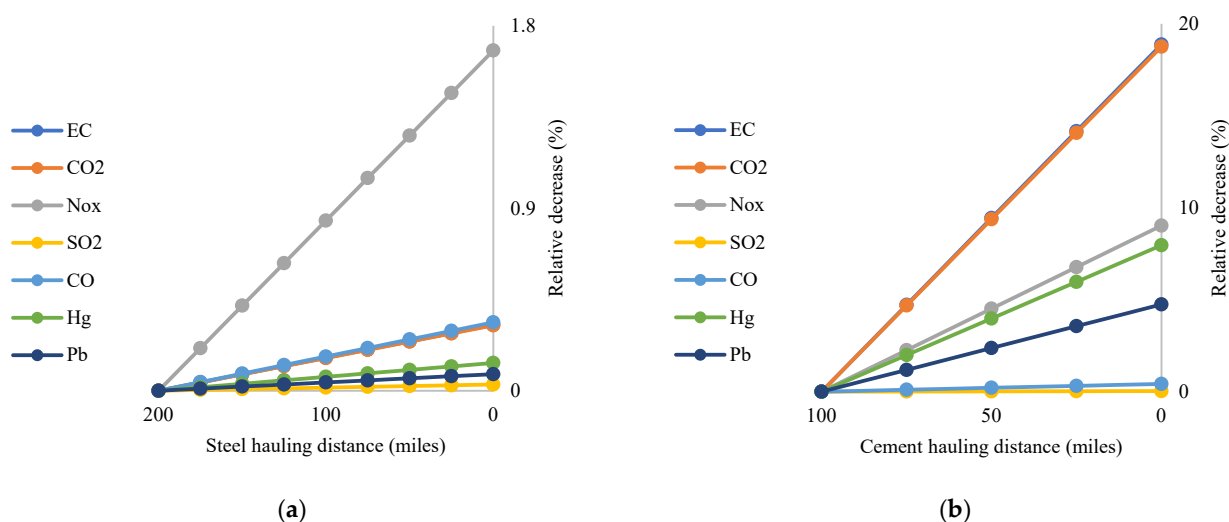


Figure 12. Environmental impacts of binders for the PP-30 alternative.





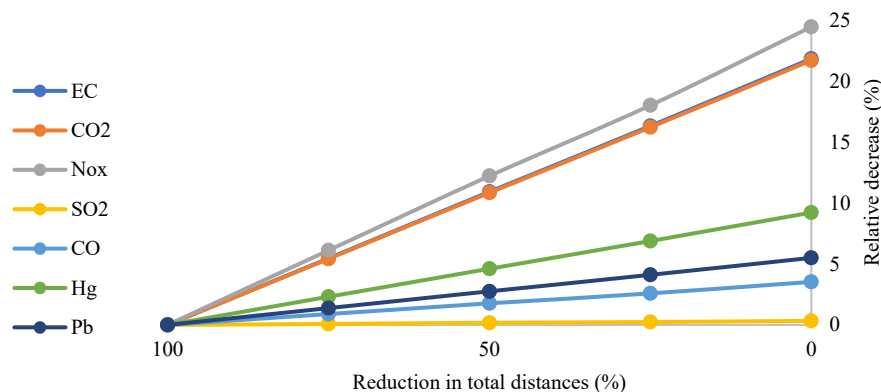
**Figure 13.** Scenarios of reducing material hauling distances for CRP-30.

#### 4.3. CRP-30 Modification and Enhancement Strategies

In the previous analysis, it was possible to demonstrate that the CRP-30 pavement alternative was the one that generated the highest environmental burden. Consequently, this manuscript section explores several scenarios to mitigate the environmental impacts associated with CRP-30. Only the most essential impact categories (EC, CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>2</sub>, CO, Hg, and Pb) were examined. Two possibilities were evaluated: reducing material hauling distances and including SCM as partial cement replacement.

In Figure 13, two scenarios for reducing material hauling distances (every 25 miles) are shown, namely: (a) decreasing the steel transport distance from 200 to 0 miles and (b) decreasing the cement transport distance from 100 to 0 miles. Meanwhile, Figure 14 exhibits decreasing from 100% to 0% for all the transport distances. Based on these analyses, the following findings were obtained:

- The steel haulage distance is negligible in contributing to the total environmental impact generated by CRP-30.
- The PC haulage distance generates a considerable environmental burden in the impact categories such as EC, CO<sub>2</sub>, NO<sub>x</sub>, and Hg. Hence, it is recommended to use nearby PC supply sources for pavement construction where large quantities of this binder (PC) are required.
- If haulage distances were reduced to zero, the environmental impacts of EC, CO<sub>2</sub>, and NO<sub>x</sub> could decrease by 20–25%.



**Figure 14.** Decreasing from 100 to 0% all transport distances for CRP-30.

In the previous analysis, it was found that PC generates a significant environmental impact. Notably, a typical way to reduce the environmental burden associated with PC is to replace it with SCMs [103,104]. The powdered residues from various industrial processes have a high value as SCM, even yielding mortars and concretes with better mechanical properties than traditional materials [90,105]. Some of the SCMs are blast furnace slag [106,107], coal bottom ash [108,109], and coal fly ash [110,111]. Blast furnace slag is a fine powder obtained from iron slag grinding that remains after casting a blast furnace into water or steam [112,113]. Coal bottom ash is a non-combustible residue that remains at the bottom of boilers, furnaces, or incinerators after industrial combustion [114,115]. Finally, coal fly ash is the primary residue produced in coal-fired plants; this product flies off with the flue gases and must be trapped by some particle filtration mechanism [116,117].

The previous SCM substances were evaluated as an option to reduce the environmental impacts of CRP-30. Due to its nature of being a waste material, it was considered that the transport distance of these cementitious materials to the concrete plant is equal to zero. In addition, it was decided to use typical densities of these products, namely 2900 kg/m<sup>3</sup> for blast furnace slag [106], 2810 kg/m<sup>3</sup> for coal bottom ash [117], and 2550 kg/m<sup>3</sup> for coal fly ash [118]. For each SCM, partial cement replacements from 5% to 30% were evaluated (analysis points were every 5%). This analysis was carried out under five impact categories: EC, CO<sub>2</sub>, NO<sub>x</sub>, PM10, and HWG. The estimates for the three materials under evaluation gave remarkably similar results (i.e., differences among them were less than 3%). Therefore, it was preferred to only plot the data of one of them, the coal fly ash. The corresponding results are shown in Figure 15 and suggest the following:

- Replacements in low quantities (up to 15%) fail to generate significant environmental benefits.
- Replacements in high quantities (greater than or equal to 20%) achieved considerable environmental benefits in the impact categories such as EC, CO<sub>2</sub>, and NO<sub>x</sub>. However, the reductions in the environmental impact of PM10 and HWG were insignificant.

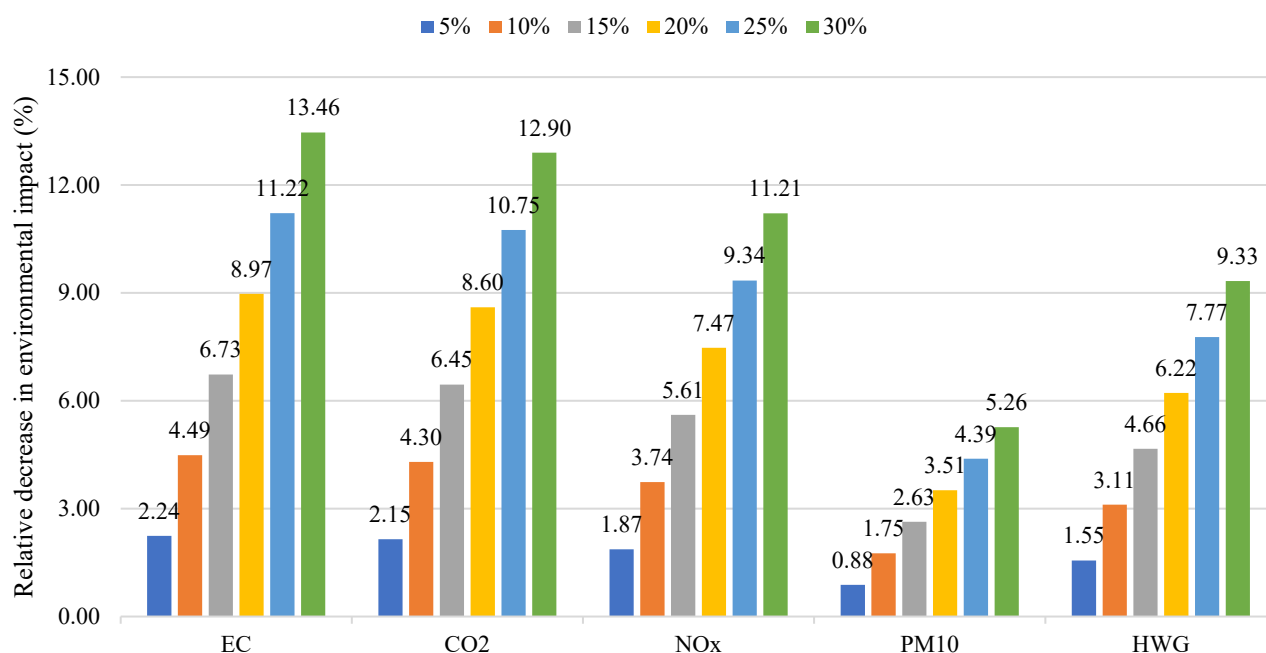


Figure 15. Environmental benefits caused by the replacement of cement with coal fly ash.

## 5. Conclusions

An environmental analysis based on LCAs was conducted using the Texas PP structures as the case study to evaluate the potential environmental benefits generated by perpetual pavements. Two conventional structures (CRP-30 and CFP-30) and three PP

structures (namely PP-30, PP-40, and PP-70) were evaluated using the PaLATE tool. Based on the research effort carried out, the following conclusions were drawn:

- In the case of CFP-30, most of the environmental impacts are generated by M&R activities. By contrast, most of the environmental burden occurred during the initial construction stage for CRP-30 and PP-30.
- For the impact categories aldehydes and benzo[a]pyrene, the total contribution to environmental impact is caused by the materials transportation stage. Nonetheless, for the other impact categories, the main contributor was the production of the materials, followed by the transportation of the materials, and the minor contributor was the materials processing stage.
- Water consumption, carbon dioxide emissions, nitrogen oxide emissions, carbon monoxide emissions, lead emissions, aldehydes generated, and benzo[a]pyrene were the impact categories in which the environmental benefits generated by the selection of PP over conventional pavement alternatives are most noticeable.
- In general terms, CRP-30 was the pavement alternative that generated the highest environmental impacts, followed by the CFP-30 alternative. Otherwise, PP-30 was the pavement alternative that produced the most negligible impact on the environment.
- As design traffic increases, the relative environmental impacts decrease. Therefore, one approach to maximize the environmental benefits of implementing PP structures is using them on highly trafficked highways.
- Binders were the main contributors to energy consumption and the CO<sub>2</sub> emission into the atmosphere and one of the most prominent generators of nitrogen oxides and heavy metals.
- The partial replacement of PC by SCMs (such as blast furnace slag, coal bottom ash, and coal fly ash) can cause significant reductions in the environmental impacts generated by conventional rigid pavements (especially concerning energy consumption, CO<sub>2</sub> emissions, and NO<sub>x</sub> emissions).
- In conjunction with some studies reported in the literature, the work contained in this paper demonstrated that PP structures could be more competitive than conventional pavements in terms of environmental efficiency.

Overall, while likely results were obtained, it is evident that the environmental benefits generated by implementing PP structures still need to be studied in more detail, along with varying variables such as construction materials and climatic conditions, among other variables. Nonetheless, although limited to the specific materials, traffic loading, and pavement structures evaluated, this research contributes to the literature's enrichment by providing a datum reference for assessing and quantifying the environmental benefits of PP structures. Consequently, the results of this case study can be used in future investigations as a reference point to delve into various aspects, for instance, the influence reached by other computational tools, impact assessment methodologies, or approaches to define the system boundaries.

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