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A Comparative Life Cycle Assessment of Asphalt and Rigid Pavements

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Abstract

It is an indisputable fact that the environmental impacts of road construction are very important, given the hundreds of kilometers of roads paved with asphalt or portland cement concrete (PCC). However, the environmental burdens of asphalt and PCC pavements have not been determined precisely. Nowadays, significant scientific surveys are being conducted, which recognizes the importance of the environmental impacts of road pavements. In this context, the aim of this study is to evaluate the environmental impacts of asphalt and PCC pavements in terms of global warming, ozone depletion, acidification, photochemical oxide creation, and eutrophication. Within the framework of this aim, a hypothetical case study using the life cycle assessment methodology was conducted in this study. The life cycles of asphalt and PCC pavements were comparatively assessed limited with the material production phase, and it was determined which alternative has fewer environmental impacts during this phase. It was found that the asphalt pavement has considerably fewer environmental impacts than PCC pavements.

Keywords: *Asphalt, Life Cycle Assessment Methodology, Portland Cement Concrete (PCC), Road Pavement, Material Production Phase*

Introduction

1

According to Turkish Directorate of Highways, Turkey's highways are composed 37.72% of asphalt concrete (AC) pavements, in other words, flexible pavements (FPs), 56.89% of chip seal and 5.38% of other surface types (Karayolları Genel Müdürlüğü, 2020). FPs are widely used in Turkey. On the other hand, there are not rigid pavements (RPs), namely, portland cement concrete (PCC) pavements, apart from a few kilometers test sections. Since Turkey is a developing county, authorities attach importance to construct many new roads and to improve current roads (Karayolları Genel Müdürlüğü, 2019). Construction and maintenance of these roads are one of the main reasons of environmental pollutants including greenhouse gas (GHG) in the construction industry. That is why it is crucial to find out the environmental impacts of various pavement types and consider such impacts while planning a new pavement construction or improvement.

In most recent studies, life cycle assessment (LCA) of pavements have been carried out in three different ways: (1) economic input-output LCA (EIO-LCA); (2) process-based LCA; and (3) hybrid LCA which is a method containing both option (1) and (2) (Inyim, Pereyra, Bienvenu, & Mostafavi, 2016).

(Horvath & Hendrickson, 1998) performed EIO-LCA to compare the 1-km section of FP and continuously reinforced concrete pavement (CRCP), and according to their findings, FPs were looking more environment-friendly than CRCP. (Kucukvar & Tatari, 2012) have compared CRCP and hot-mix asphalt (HMA) pavements with hybrid LCA, and they suggest that HMA pavements are more sustainable in terms of energy usage. In contrast to these studies, (Yu & Lu, 2012) suggest that PCC pavement could lead to less environmental burdens than asphalt pavement according to performed LCA as a case study. In addition, (Embacher & Snyder, 2001) suggest that RPs are more cost-effective than FPs according to their case study implemented with life cycle cost assessment (LCCA).

Much of the current literature on LCA of pavements pays particular attention to reduce environmental burdens, and much of these burdens are related to material production. For example, a previous study demonstrated that cement and reinforcement steel production constitute 94% of energy consumption for the CRCP in the material production phase (Zapata & Gambatese, 2005). In the same study, it was demonstrated that asphalt mixing, drying aggregates, and production of bitumen constitute 88% of energy consumption in the asphalt pavement. That is why, in order to reduce environmental burdens, many approaches have studied based on materials type and mixing methods such as; reclaimed asphalt pavement (RAP), warm mix asphalt (WMA), fly ash (FA) and recycled concrete aggregate (RCA).

(Aurangzeb, Al-Qadi, Ozer, & Yang, 2014) have performed a hybrid life cycle assessment on asphalt pavement modified with RAP, and they have found that using 40% RAP in HMA can decrease energy consumption and GHG up to 28%. (Giani, Dotelli, Brandini, & Zampori, 2015) have suggested a combined pavement design that consists of using RAP and WMA, and this option decreased the environmental impacts up to 12% compared to the conventional design with virgin asphalt. In another study about WMA, by performing LCA, (Mazumder, Sriraman, Kim, & Lee, 2016) have found WMA can reduce global warming potential (GWP) in the ratio of 26% and acidification (AP) in the ratio of 29% compared to HMA. Another study by (Ma, Zhang, Zhao, & Wu, 2019) also suggests that WMA is more environment-friendly than HMA. (Zapata & Gambatese, 2005) state that replacement of cement to FA could provide a significant decrease in energy consumption. (Shi, Mukhopadhyay, Zollinger, & Grasley, 2019) suggest that according to their EIO-LCA study, using RCA in the RP is a more environment-friendly option compared to conventional RP.

A previous report by (Harvey et al., 2016) suggests that the pavement life cycle consists of six phases: material production, pavement design, construction, use phase, maintenance, and end-of-life (EOL). Material production contains both raw material acquisition and manufacturing HMA and ready-mix concrete. Pavement design is a decision-making phase, such as; determining the structural and functional needs of the pavement and deciding the composition of the pavement structure. Many studies dealing with these phases have been done. For example, (Xu, Akbarian, Gregory, & Kirchain, 2019) argue that according to their LCA study, the use phase can contribute up to 78% to environmental impacts of the life cycle of the pavement. (Zapata & Gambatese, 2005) neglecting the use phase, maintenance phase, and EOL phase have argued that the construction phase has a minor share of total energy consumption. To be more precise, the material production phase is very important, together with the use phase and maintenance phase.

In this study, the aim is to compare RP and FP in terms of environmental impacts for the material production phase. To achieve this, one road section for each RP and FP were designed in the same conditions (e.g., soil, climate, traffic, etc.). Then, the life cycle inventory was

generated for these pavements. For the FP, usage of RAP and for the RP, usage of FA was also taken into account. In order to determine the environmental burdens of the products used in pavements (e.g., HMA, ready-mix PCC, aggregate for base layers, dowels, and tie bars), the published environmental product declarations (EPDs) were utilized. Life cycle impacts (LCI) were determined based on a certain impact assessment method. Within the limits of this study, only the material production phase (i.e., raw material acquisition and manufacturing the construction products) were studied.

Methodology

Functional unit

The functional unit was selected as the construction of 1 km pavement. The width of the road was 7.2 m (traffic lanes 2×3.6 m). The analysis period was 20 years, and it is assumed that no maintenance was carried out during the service life.

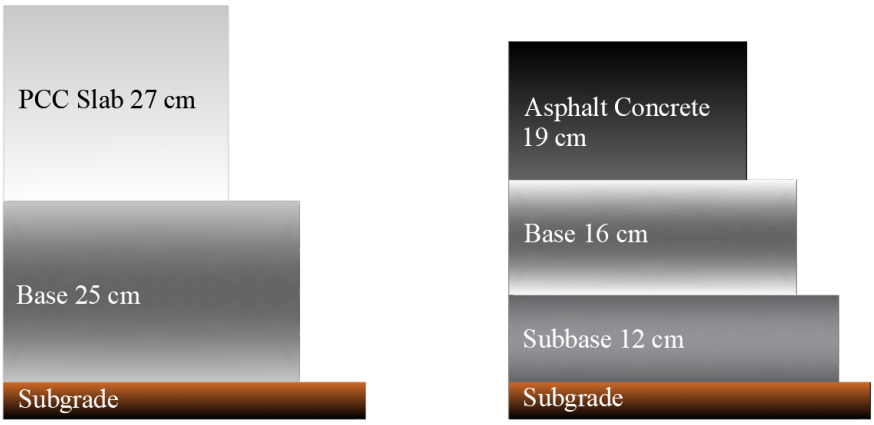
Description of the road section

A hypothetical road section was determined, and its characteristics were listed in Table 1. Two types of pavement were studied: FPs and RPs. These pavements were designed for the same road section; in other words, they are equal in terms of soil support and traffic loads.

Table 1. Design characteristics of the hypothetical road section

Parameter	**Value**	**Parameter**	**Value**
ESALs (80-kN equivalent single-axle loads) for 1 year	750,000	Load Transfer Coefficient	2.8
Traffic Grow Rate	3%	Composite modulus of subgrade reaction, k	190 pci
Total ESALs	20 million	Roadbed modulus, M_R	10,000 psi
Analysis period	20 years	Subbase modulus, E_{SB}	15,000 psi
Initial serviceability index	4.7	Base elastic modulus E_{BS}	30,000 psi
Terminal serviceability index	2.5	Concrete modulus of rupture	650 psi
Drainage coefficient of rigid and FP	1	Concrete elastic modulus	4,200,000 psi
Overall standard deviation	0.39	Concrete compressive strength	5,430 psi
Reliability	%90	Road type	Typical two-lane
Standard normal deviate	-1.282	Pavement width	7.2 m

The design of the pavements was made according to the AASHTO-1993 design manual. For the FP, it is assumed the highway section was comprised of subbase, base, and asphalt concrete layers. For the RP, on the other hand, the concrete slab was located on a subbase layer. The layer thicknesses were shown in Figure 1.



a) Rigid Pavement b) Flexible Pavment

Figure 1: Designed pavement sections

In this study, it was employed process based LCA, and the system boundaries have shown in Figure 2. In the study, only road materials were considered. Construction, usage, maintenance, and EOL phases were not taken into account.

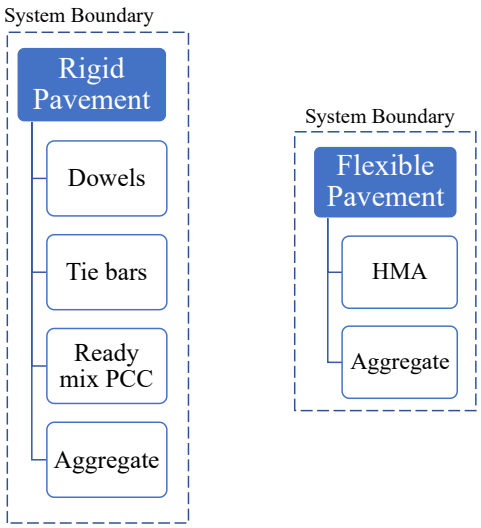


Figure 2: Life cycle system boundary

Inventory Analysis

Quantities of the materials were calculated according to designed pavements. In order to generate inventory data, the EPD values of some companies were used. These EPDs were prepared by the environmental corporations using the cradle-to-gate approach. The list of the used EPDs are provided in Table 2. The system boundaries of these EPDs are shown in Figure 3.

Table 2. List of the EPDs used in the life cycle inventory

Product	Declaration Owner	Declaration Number	Declared Product
Ready-mix PCC	National Ready-Mix Concrete Association	EPD10294	5001-6000-00-FA/SL
Ready-mix PCC containing FA			5001-6000-40-FA
HMA	George Reed, Inc. Greg Reader	19.55.52 v10	2018-TM-004D-VSS-64-10-R0
HMA containing RAP		19.55.53 v4	2018-TM-004D-VSS-64-10-R25
Aggregate for base courses	Holcim Romania	S-P-00528	Aggregates
Dowels	Outokumpu Oyj	EPD-OTO-20190107-IBD1-EN	Structural steels
Tie bars	ArcelorMittal Europe-Long Products	EPD-ARM-20160051-IBD3-EN	Reinforcing Steel

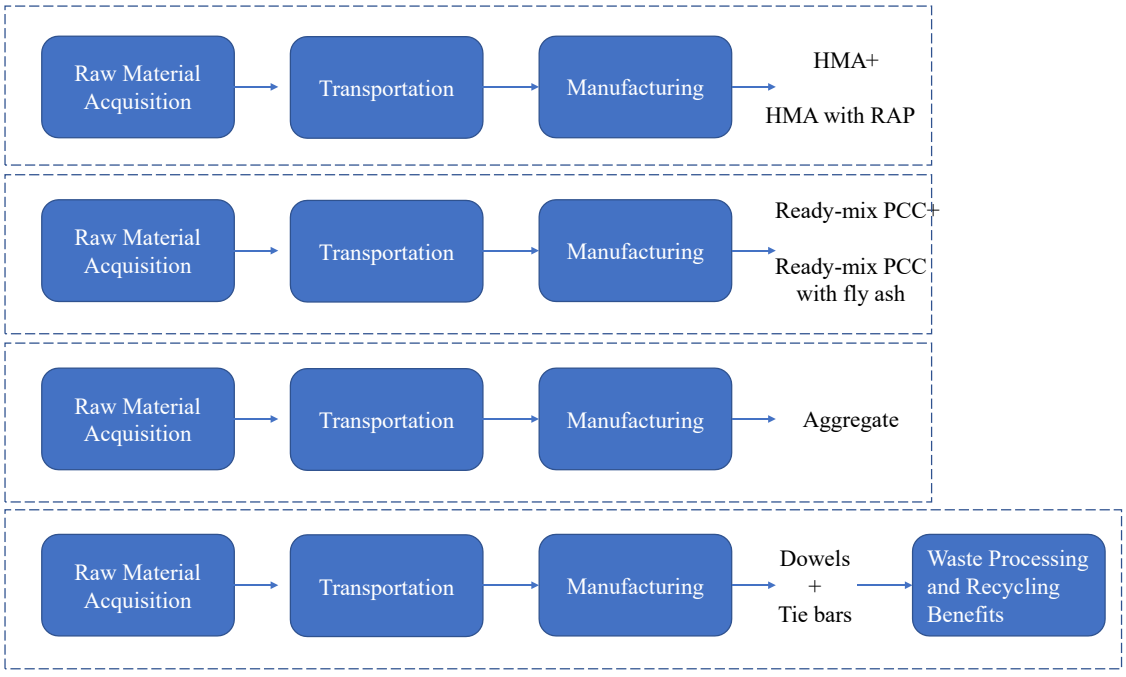


Figure 3: System boundaries of used EPDs

Rigid Pavement (RP)

The RP comprises of concrete slab, subbase layer, dowels, and tie bars. Quantities of these components are shown in Table 3, Table 4, and Table 5. The placement plan of the dowels and the tie bars are shown in Figure 4. Two type of PCC were studied: ready-mix PCC and ready-mix PCC containing FA at a ratio of 30% to 40%. EPDs of these mixtures are utilized to create inventory data of the concrete slab. Since the subbase layer is constructed with aggregate, an

EPD of aggregate production was used for the subbase layer. Finally, EPDs were used in order to generate inventory data of dowels and tie bars. The created life cycle system of the RP is shown in Figure 2.

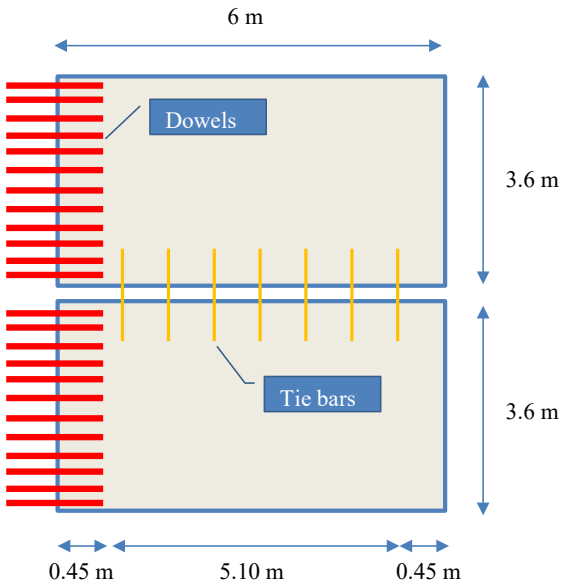


Figure 4: The RP's section plan

Flexible Pavement (FP)

FP comprises of AC, base, and subbase layer. Quantities of these components were shown in Table 6. Two types of asphalt mix were studied for the asphalt concrete layer: HMA and HMA containing RAP at the ratio of 25%. EPDs of these mixtures were used in order to generate inventory data. For the base and subbase layer, on the other hand, EPD values of aggregate production were used. The created life cycle system of the FP was shown in Figure 2.

Table 3. Life cycle inventory of the layers of RP

Layer name	**Thickness (m)**	**Volume (m^3)**	**Specific Gravity (t/m^3)**	**Weight (t)**
Concrete Slab	0.27	1,944	2.4	4,665.60
Subbase	0.25	1,800	2.3	4,140.00

Table 4. Life cycle inventory of the dowels

Design Variables of Dowels	**Value**
Unit weight of the dowel, kg/m^3	7,900
Dowel diameter, in	1.5
Dowel length, in	18
Number of dowels for two slabs (Figure 4)	24
Number of dowels for 1 km	4,000.08
Weight of a dowel, kg	4.12
Weight of dowels, kg	16,471.80

Table 5. Life cycle inventory of the tie bars

Design Variables of Tie Bars	**Value**
Tie bar size no.	No.4
Diameter, in (cm)	0.5 (1.27)
Bar Spacing, in (cm)	33.7 (85)
Bar length, in (cm)	36 (91.44)
Unit weight of tie bars kg/m^3	7,850
Number of tie bars for two slabs	7
Number of tie bar for 1 km	1,166.69
Weight of a tie bar, kg	0.93
Weight of tie bars for1 km, kg	1,080.58

Table 6. Life cycle inventory of the FP

Layer Name	**Layer Coefficient**	**Thickness (m)**	**Volume (m^3)**	**Specific Gravity (t/m^3)**	**Weight (t)**
Asphalt Concrete	0.42	0.19	1368	2.4	3,283.20
Base	0.14	0.16	1152	2.3	2,649.60
Subbase	0.11	0.12	864	2.3	1,987.20

Assessing life cycle impacts

Inventory data entry was made in OpenLCA software version 2.1.2. While evaluating environmental impacts, widely accepted CML Baseline impact assessment method was used. The following environmental impacts were evaluated in the study: Acidification (AP), global warming (GWP), eutrophication (EP), ozone depletion (ODP), and photochemical oxide creation (POCP).

Results and Discussion

In all environmental impact categories, the RP has truly higher impacts than the FP. In addition, RAP can moderately reduce all environmental impacts of the FP, while FA can significantly reduce all environmental impacts of the RP. The total environmental impacts of the 1-km FP and RP are shown in Table 7 and Table 8, respectively. Besides, Figure 5 illustrates these impacts as bar charts.

Table 7. Environmental impacts of 1-km FPs: FP without RAP (FP-R0) and FP with 25% RAP (FP-R25)

Indicator, unit	Pavement Type	Base and subbase	HMA	Sum
AP, kg SO_2 eq	FP-R0	2.01E+02	4.54E+02	6.55E+02
EP, kg PO_4 eq		1.70E+01	5.65E+01	7.35E+01
GWP, kg CO_2 eq		1.44E+04	1.03E+05	1.17E+05
ODP, kg CFC-11 eq		2.34E-06	1.30E-05	1.53E-05
POCP, kg C_2H_4 eq		3.08E+01	7.09E+01	1.02E+02
AP, kg SO_2 eq	FP-R25	2.01E+02	3.89E+02	5.90E+02
EP, kg PO_4 eq		1.70E+01	5.33E+01	7.03E+01
GWP, kg CO_2 eq		1.44E+04	9.07E+04	1.05E+05
ODP, kg CFC-11 eq		2.34E-06	1.02E-05	1.26E-05
POCP, kg C_2H_4 eq		3.08E+01	5.97E+01	9.05E+01

Table 8. Environmental impacts of 1-km RPs: RP without fly ash (RP-FA0) and RP with 40% fly ash (RP-FA40)

Pavement Type	Indicator, unit	Ready Mix PCC	Dowel	Tie bar	Base and subbase	Sum
RP-FA0	AP, kg SO_2 eq	3.25E+03	2.45E+02	9.06E+00	1.79E+02	3.68E+03
	EP, kg PO_4 eq	5.72E+02	1.25E+01	4.48E-01	1.52E+01	6.00E+02
	GWP, kg CO_2 eq	1.07E+06	3.20E+04	1.32E+03	1.28E+04	1.12E+06
	ODP, kg CFC-11 eq	2.74E-02	6.87E-08	2.30E-08	2.09E-06	2.74E-02
	POCP, kg C_2H_4 eq	7.69E+03	9.75E+00	6.11E-01	2.75E+01	7.72E+03
RP-FA40	AP, kg SO_2 eq	2.39E+03	2.45E+02	9.06E+00	1.79E+02	2.82E+03
	EP, kg PO_4 eq	4.00E+02	1.25E+01	4.48E-01	1.52E+01	4.28E+02
	GWP, kg CO_2 eq	7.41E+05	3.20E+04	1.32E+03	1.28E+04	7.87E+05
	ODP, kg CFC-11 eq	1.91E-02	6.87E-08	2.30E-08	2.09E-06	1.91E-02
	POCP, kg C_2H_4 eq	5.71E+03	9.75E+00	6.11E-01	2.75E+01	5.74E+03

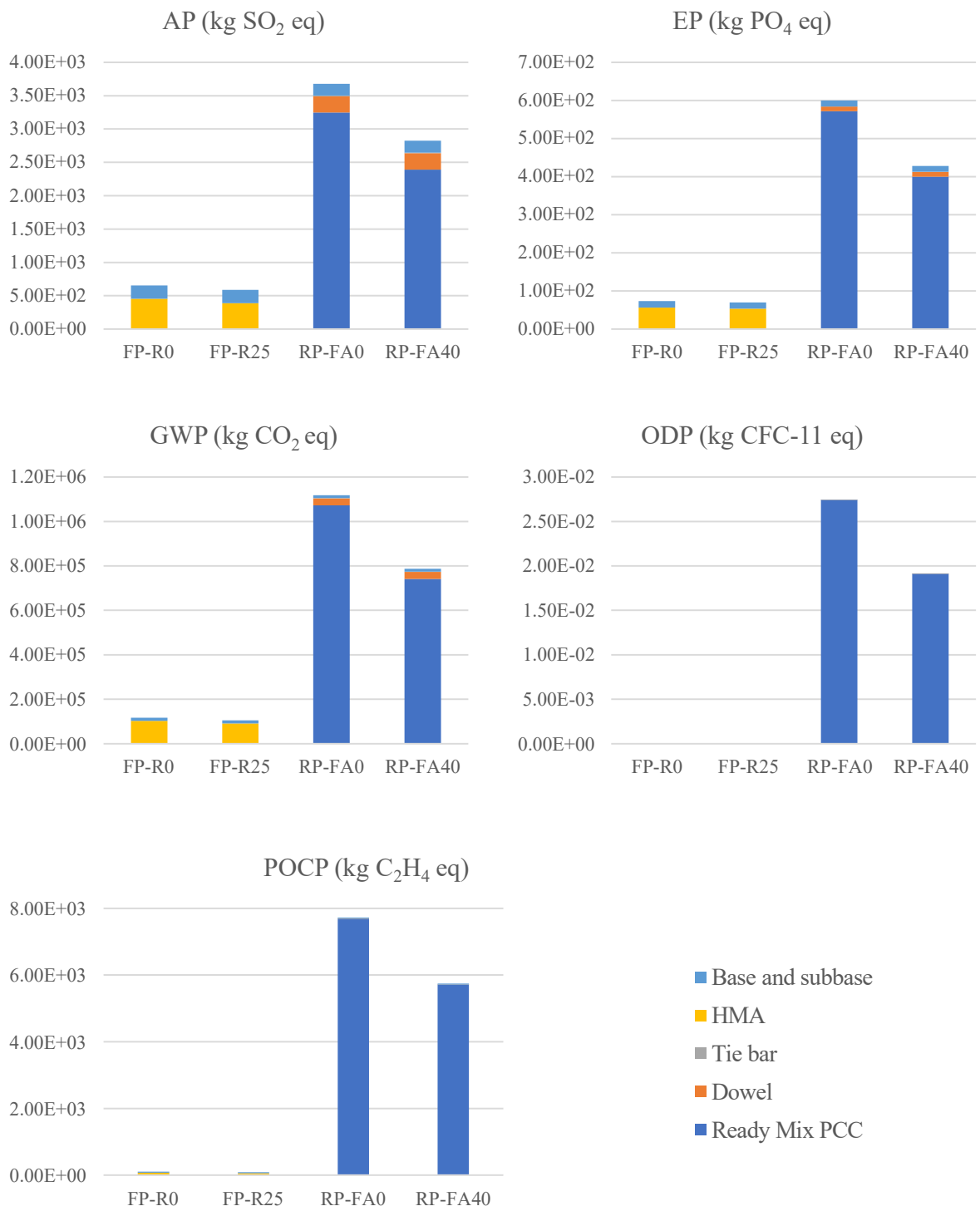


Figure 5: Environmental impacts of the pavements

Acidification

AP of FP-R0 is 76.81% less than RP-FA0's. It is demonstrated that FA can reduce AP of RP 23.24%, and RAP can reduce the AP of FP by 9.98%.

In the RP, the production of ready-mix PCC dominates the AP. The production of dowels and base materials contributes slightly to AP. On the other hand, the production of tie bars accounts

for a negligible proportion of AP. When it comes to the FP, the production of HMA constitutes virtually one-third of the total AP.

Eutrophication

EP of FP-R0 is 82.83% less than RP-FA0's. It is demonstrated that FA can reduce EP of the RP by 28.59%, and RAP can reduce EP of FP by 4.33%.

In the RP, the production of ready-mix PCC dominates EP. The production of dowels and base materials contributes gently to AP. On the other hand, the production of tie bars has minuscule effect on EP. In the FP, the production of HMA makes up roughly one-fourth of the total AP.

Global Warming

GWP of FP-R0 is 85.09% less than RP-FA0. Besides, it is demonstrated that FA can reduce GWP of the RP at 29.61%, and RAP can reduce GWP of FP at 10.42%.

In the RP, the production of ready-mix PCC dominates GWP. In contrary, the production of dowels and base materials constitutes a little fraction of GWP. The production of tie bars makes up a minor percentage of GWP. In the FP, the production of HMA accounts for approximately one-seventh of the total GWP.

Production of materials of 1-km FP leads to 117 tons CO_2 eq of GHG emissions. If RAP is used in HMA, it can be reduced by 12 tons CO_2 eq for 1-km FP. According to the calculator tool of the Environmental Protection Agency (EPA), a reduction of 12 tons CO_2 eq GHG equals to 180 tree seedlings grown for ten years (EPA, 2020). Considering thousands of kilometers of road construction, using RAP could make lots of contributions to reduce GHG emission of FPs.

Production of materials of 1-km RP leads to 1,120 tons CO_2 eq of GHG emissions. If FA is used in the PCC, it can be reduced by 333 tons CO_2 eq for 1-km RP. According to the calculator tool of the Environmental Protection Agency (EPA), a reduction of 333 tons CO_2 eq GHG equals to 4995 tree seedlings grown for ten years (EPA, 2020). This reduction is significantly higher than the reduction that RAP provides to FP. On the other hand, using HMA with no RAP instead of PCC with FA can reduce 670 tons CO_2 eq of GHG. This amount of GHG equals 10,050 tree seedlings grown for ten years (EPA, 2020). Considering thousands of kilometers of road construction, using FA in PCC or preferring HMA instead of PCC could make lots of contributions to reduce GHG emission of FPs.

Ozone Layer Depletion

ODP of FP-R0 is 99.92% less than RP-FA0. It is demonstrated that FA can reduce ODP of the RP by 30.28%, and RAP can reduce ODP of FP by 17.99%.

In the RP, the production of ready-mix PCC dominates 99.99% of ODP. On the other hand, the production of dowels, base materials, and tie bars contributes barely to ODP. In the FP, the production of HMA makes up nearly one-sixth of the total ODP.

Photochemical Oxide Creation

POCP of FP-R0 is 98.23% less than RP-FA0. It is demonstrated that FA can reduce POCP of by RP 25.62%, and RAP can reduce POCP of FP by 10.99%.

In the RPs, the production of ready-mix PCC dominates more than 99% of POCP. On the other hand, the production of dowels, base materials, and tie bars accounts for a minuscule percentage of POCP. In the FP, the production of HMA constitutes almost one-third of the total POCP.

Conclusion

The study evaluates the environmental impacts of FPs and RPs. These hypothetical pavements were designed in the same conditions. Then, in the limitation of the material production phase, a life cycle analysis was performed. Obtained results were interpreted, and possible conclusions have been drawn.

The most obvious finding to emerge from this study is that RPs significantly higher environmental impacts than FPs in all impact categories. The second major finding is that using FA can provide a severe amount of GHG reduction for the RP. On the other hand, RAP can reduce GHG moderately.

One of the other significant findings to emerge from this study is that the production of ready-mix PCC dominates all environmental impacts of the RP. Meaning, production of dowels, tie bars, and aggregate produces a minuscule fraction of environmental impacts compared to PCC.

The major limitation of this study is to take into account only the material production phase (e.g., HMA, ready-mix PCC). The study does not evaluate the construction, maintenance, use, and EOL phases. That is why further research is required to determine how much the other phases can create environmental impacts.

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