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Comparative life cycle assessment of warm mix asphalt with recycled concrete aggregates: A Colombian case study

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ABSTRACT

This paper presents the results of a comparative life cycle assessment undertaken to compare the potential environmental impacts associated with the use of Recycled Concrete Aggregate (RCA) as a partial replacement of natural aggregates in the production of Warm Mix Asphalt (WMA), with those of a conventional Hot Mix Asphalt (HMA). Laboratory testing results were used as inputs in a pavement design software with the purpose of designing several pavement structures with different percentages of RCA and according to the typical Colombian pavement design conditions. Primary data was collected from several companies in the northern region of Colombia. The SimaPro 8.4.0 software was used for modeling the processes analyzed in the case study and all the life cycle inputs and outputs related to the functional unit were characterized during the life cycle impact assessment (LCIA) phase into potential impacts according to the impact assessment methodology TRACI v.2.1. The LCIA results of the case study showed that the use of WMA with RCA as a replacement of coarse natural aggregates leads to a deterioration of the environmental profile of the pavement structures.

1. Introduction

With the ever-increasing awareness of climate change, practitioners in transportation infrastructure have been striving for innovations to save natural resources and to reduce energy consumption and emissions. Within the transportation sector, the paving industry has been encouraged to increase the use of the often-called eco-friendly technologies and materials in the construction and rehabilitation of highway infrastructures (Turk et al., 2015; Rosado et al., 2017; Santos et al., 2019; Vega et al., 2019). Among those new technologies, the use of asphalt mixtures requiring lower manufacturing temperatures, such as the warm mix asphalt (WMA), have received particular attention (Kheradmand et al., 2014). These techniques usually reduce the mixing temperature in a range of 20 to 40 °C, comparatively to that of a conventional hot mix asphalt (HMA) (Vega et al., 2019; Rubio et al., 2012; D'Angelo et al.). Furthermore, depending on their production technique (D'Angelo et al.; European Asphalt Pavement Association, 2010; Hassan, 2009), they might also be associated with mechanical, functional and environmental advantages (Rubio et al., 2012; Vaitkus et al., 2009).

Similarly, during the last two decades a consistent interest in the use of recycled aggregates to partially/completely replace naturals aggregates (NA), both in HMA and Portland Cement Concrete (PCC), has been observed (Wang et al., 2018; Vidal et al., 2013). Reclaimed Asphalt Pavement (RAP) and Recycled Concrete Aggregates (RCA) are two of the most used materials when trying to reduce the use of NA in asphalt mixtures (Cho et al., 2011; Farooq et al., 2018; Mills-Beale and You, 2010; Ding et al., 2016). Although RCA have been widely studied and showed promising results as a replacement for coarse NA in HMA (Pasandin and Pérez, 2015; Pérez et al., 2012; Zulkati et al., 2012), the research studies related to its application in WMA are still limited.

Given the circumstances above stated, the study presented in this paper aims to investigate the extent to which the use of RCA in WMA applied in the binder course (BC) of flexible road pavements is beneficial from an environmental point of view.

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Nomenclature

Ac	acidification
BC	binder course
BC-G	base course granular
Ca	human health cancer
Eu	eutrophication
Ec	ecotoxicity
FFD	fossil fuel depletion
FHWA	Federal Highway Administration
GW	global warming
HFO	heavy fuel oil
HMA	hot mix asphalt
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
NA	natural aggregates
NCa	human health noncancer
OD	ozone depletion
RCA	recycled concrete aggregates
RE	respiratory effects
SF	photochemical smog formation
SBC-G	subbase course granular
SC	surface course
TE	thermal energy
WMA	warm mix asphalt

2. Methods

A comparative attributional process-based life cycle assessment (LCA) was developed taking into account, as much as possible and suitable, the International Organization for Standardization (ISO) guidelines for LCA (International Standard Organization, 2006) and the Federal Highway Administration's (FHWA's) Pavement LCA framework (Harvey et al., 2016).

The LCA stages adopted in this study include goal and scope definition, inventory analysis, impact assessment and interpretation.

2.1. Goal and scope definition

2.1.1. Goal

The main goal of this study is to compare the potential life cycle environmental impacts generated by the use of WMA containing different levels of RCA as replacements of coarse NA, with those of conventional HMA (i.e., HMA with only NA), in the construction of BC of flexible road pavements.

2.1.2. System description and boundaries

The scope of the LCA is from cradle-to-laid (Vega et al., 2019; Harvey et al., 2016). The system boundaries include four pavement life cycle phases: (1) material production and transportation to the mixing plant; (2) material processing and mixtures production at the mixing plant; (3) mixtures transportation to the construction site; and (4) pavement construction. Furthermore, the boundaries for the pavement structure were limited to the BC layer. Table 1 presents the main processes considered in the LCA study per phase.

Moreover, the "cut-off" allocation methodology was adopted for dealing with the RCA (Santos et al., 2018; Schrijvers et al., 2016). That means that the environmental impacts associated with the pavement demolition and the transportation of the recycled materials were not included in the system boundaries. Thus, only the burdens related to RCA processing were considered in the study.

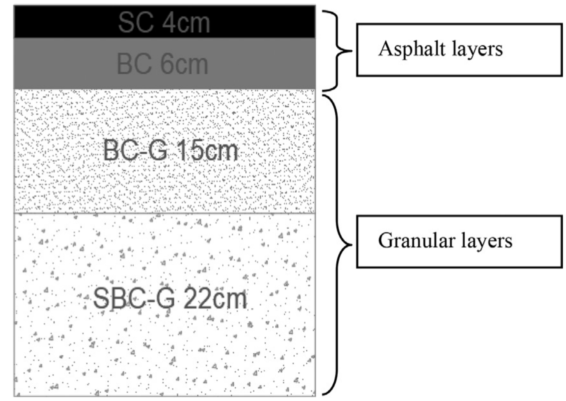

Fig. 1. Geometric characteristics of a pavement structure designed with a conventional HMA. Acronyms: SC – Surface Course; BC – Binder Course; BC-G – Base Course Granular; SBC-G – Sub Base Course Granular.

2.1.3. Functional unit

The functional unit forms the basis for comparisons between different products with the same utility for the same function. In the pavement domain, this means a unit of pavement that can safely and efficiently support the same volume of traffic over the same project analysis period. Then, it is defined by their geometry, service life and level of traffic supported. In this case study it was defined as a typical Colombian highway section, with 1 km in length and 1 lane 3.5 m wide.

The pavement structures were designed according to the conventional characteristics of traffic and subgrade support in Barranquilla, Colombia. Specifically, they were designed for a traffic of 5×10^6 Equivalent Single Axle Load (ESAL) of 80 kN, a CBR of 7.5% and a service life of 10 years. The geometric characteristics of a pavement structure designed with the conventional HMA (i.e., 0% RCA content) in the BC are illustrated in Fig. 1.

In order to ascertain the potential environmental advantages related to the use WMA, with and without RCA content, the reference pavement structure (Fig. 1) was compared to four alternatives structures with equal geometry, but in which the mixture applied in the BC of the initial structure was a WMA produced with four RCA contents. Those alternatives represent structures with equivalent structural capacity, where the only design parameter that changed was the thickness of the BC. Tests carried out in the laboratory were performed with the purpose of determining the components proportions and mixtures performance.

Table 2 presents the composition and characteristics of the mixtures analyzed in the case study. They are identified according to the key "XY", where "X" stands for the type of mixture (i.e., WMA or HMA) and "Y" represents the RCA content (i.e., 0%, 15%, 30% or 45%). In addition, all mixtures contain 50% of coarse aggregates and 50% of fine aggregates. In this way, the RCA replacements were made only in the 50% of the total mass of the aggregates. The mixtures were designed according to Marshall design specifications, which is the official mix design method in the country (Instituto Nacional de Vias – Colombia INVIAS, 2014) and all samples satisfied the Colombian standards for road materials (Instituto Nacional de Vias – Colombia INVIAS, 2013). Regarding the mixtures performance, resilient modulus tests were performed according to the EN 12697-26 (C). The results presented in Table 2 correspond to the tests carried out at 40 °C and 4 Hz.

Finally, the Pitra Pave 1.0.0 tool (Universidad De Costa Rica, 2015) was adopted to design the pavement structure of all alternatives according to the characteristics and mechanical performance of the several mixtures. The results of the pavement designs are presented in Table 3.

Table 1
Processes considered in the LCA study per pavement life cycle phase.

Pavement life cycle phase	Process
Material production and transportation to the mixing plant	NA extraction NA load movements and transportation Asphalt production Asphalt transportation Additive production Additive transportation
Materials processing and mixtures production at the mixing plant	NA processing RCA crushing Mixtures production
Mixtures transportation to the construction site	Mixtures transportation
Pavement construction	Finisher operation Vibratory roller operation Pneumatic roller operation

Table 2
Composition and characteristics of the mixtures.

Item	Mixture				
	HMA0	WMA0	WMA15	WMA30	WMA45
Natural aggregate					
Quantity (%)[a]	95.6	95.6	88.3	80.9	73.5
Absorption (%)	3	3	3	3	3
Recycled concrete aggregate					
Quantity (%)[b]	-	-	15	30	45
Asphalt					
Quantity (%)[a]	4.4	4.4	4.5	4.8	5.2
Additive					
Type	-	Chemical	Chemical	Chemical	Chemical
Quantity (%)[c]	-	0.3	0.3	0.3	0.3
Properties					
Density (kg/m^3)	2366	2366	2310	2305	2289
Air voids (%)	4.3	4.3	4.8	4.6	4.8
Voids filled with asphalt (%)	66.6	66.6	66.5	67.2	66.0
Voids in the mineral aggregates (%)	12.7	12.7	14.2	13.9	14.2
Stability (kN)	17.2	17.2	14.8	16.7	20.1
Flows (mm)	2.9	2.9	2.7	3.0	3.4
Resilient modulus (MPa)	1531	1633	1501	1372	1374

[a] Percentage of total mixture weight.
[b] Percentage of coarse aggregates.
[c] Percentage of asphalt weight.

Table 3
Pavement design for each type of mixture. Acronyms: SC – Surface Course; BC – Binder Course; BC-G – Base Course Granular; SBC-G – Sub Base Course Granular.

Mixture	Thickness (cm) Asphalt layers		Granular layers		Total
	SC	BC	BC-G	SBC-G	
HMA0	4.0	6.0	15.0	22.0	47.0
WMA0	4.0	6.0	15.0	22.0	47.0
WMA15	4.0	6.5	15.0	22.0	47.5
WMA30	4.0	7.0	15.0	22.0	48.0
WMA45	4.0	7.0	15.0	22.0	48.0

2.2. Life Cycle Inventory (LCI)

The inventory data required to perform a LCA study are classified into two main categories: primary and secondary data. Primary data are those specific to the production processes related to the product or service studied in the LCA. In turn, secondary data represents generic or average data for the product or service subject to analysis (EU-European Commission, 2010; Santos et al., 2018). In this study the data sources were selected in order to be as much time, geographical and technological representative as possible. Therefore, laboratory tests results, data obtained from surveys and data from previous research work related to the same case study were used as primary data (Martinez-Arguelles et al., 2019). Table 4 specifies the source of primary data by process.

In turn, the secondary data were obtained from databases and literature but modified whenever possible and suitable to best approximate Colombian conditions and practices. Table 5 presents the source of secondary data by process, whereas Table 6 reports the values of the input data.

In the mixture production phase, the thermal energy (TE) provided by the combustion of heavy fuel oil (HFO) was determined according to the energy balance proposed by Santos et al. (2018). The quantity of energy and fuel consumed to produce each mixture is presented in Table 7.

Finally, the quality of the primary and secondary data was assessed according to International Standard Organization (2006) and Zampori et al. (2016) in terms of representativeness (i.e., technological, geographical time-related and completeness), methodological appropriateness and consistency, and uncertainty. The results of the assessment show that the quality of the data can be classified as between “good” and “very good” (primary data) and between “fair” and “good” (secondary data).

2.3. Life Cycle Impact Assessment (LCIA)

The LCIA was performed by applying the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) v.2.1 impact assessment methodology. It assesses the potential en-

Table 4
Primary data sources per process. Acronyms: NA- natural aggregates; RCA- recycled concrete aggregates.

Pavement LCA phase	Process	Source
Materials production and transportation to the mixing plant	NA extraction	Previous research (Martinez-Arguelles et al., 2019)
	NA load movements and transportation	Previous research (Martinez-Arguelles et al., 2019)
	Asphalt transportation	Survey
	Additive transportation	Survey
Materials processing and mixtures production at the mixing plant	NA processing	Survey
	RCA crushing	Survey
	Mixture production (binder course layer), with and without RCA replacements	Survey
Mixture transportation to the construction site	Mixture transportation	Survey

Table 5
Secondary data sources per process.

Pavement LCA phase	Process	Source
Materials production and transportation to the mixing plant	Asphalt production	*"bitumen, at refinery/kg/US"* –USLCI database
	Additive production	*"fatty acid/market for/Alloc Def, U"* –Ecoinvent database
Pavement construction	Finisher operation	Literature (Thenoux et al., 2007)
	Vibratory roller operation	Literature (Thenoux et al., 2007)
	Pneumatic roller operation	Literature (Thenoux et al., 2007)

Table 6
Input data considered in the case study.

Item	Diesel (gal/ton)	Lubricant (g/ton)	Electricity (kWh/ton)	Water (kg/ton)
Materials production and transportation to the mixing plant				
Natural aggregates				
Extraction (Martinez-Arguelles et al., 2019)	1.85	20	–	–
Load to the dump truck (Martinez-Arguelles et al., 2019)	1.85	20	–	–
Transportation to the mixing plant	0.56	9.42	–	–
Asphalt				
Transportation to the mixing plant	4.17	70.66	–	–
Additive				
Transportation to the mixing plant	1.94	32.95	–	–
Materials processing and mixtures production at the mixing plant				
Natural aggregates				
Processing (Martinez-Arguelles et al., 2019)	0.075	0.69	2.33	100
Recycled concrete aggregates (RCA)				
Crushing	0.075	0.69	2.33	100
Mixtures transportation to the construction site				
Dumper	0.072	1.21	Capacity (m^3) 18	–
Pavement construction				
	Diesel (l/h)	Performance (m^3/h)		
Finisher (Thenoux et al., 2007)	13	60		
Vibratory roller (Thenoux et al., 2007)	18	65		
Pneumatic roller (Thenoux et al., 2007)	16	65		

Table 7
Thermal energy (TE) and heavy fuel oil (HFO) consumed for producing 1 ton of each type of mixture.

Mixture	TE (MJ/ton mixture)	Fuel consumption (Kg HFO/ton mixture)
HMA0	241.4	5.72
WMA0	202.8	4.81
WMA15	202.2	4.79
WMA30	202.0	4.79
WMA45	201.9	4.79

vironmental impacts according to 10 impact categories: (1) ozone depletion (OD); (2) global warming (GW); (3) photochemical smog formation (SF); (4) acidification (Ac); (5) eutrophication (Eu); (6) human health cancer (Ca); (7) human health noncancer (NCa); (8) human health particulate or respiratory effects (RE); (9) ecotoxicity (Ec); and (10) fossil fuel depletion (FFD). These impact categories estimate the potential damage to: (1) human health; (2) ecosystem diversity; and (3) resource availability (Ryberg et al., 2014; Sharaai et al., 2010). Finally, the SimaPro 8.4.0 software was used for modeling the processes analyzed in this case study.

3. Results

Table 8 summarizes the LCIA results for the baseline and alternatives mixtures in which the conventional HMA and WMA with different levels of RCA replacement are used in the production of the BC mixtures. Fig. 2 shows the relative variation of the impacts scores for each alternative mixture in relation to those associated with the conventional mixture (i.e., HMA0). The relative values should be understood as follows: positive relative numbers mean that the use of RCA improves the LCIA results in relation to those associated with HMA0. In turn, negative numbers represent a worsening of the environmental profile.

The analysis of the results presented in table and figure introduced previously shows that overall the use of WMA with RCA contents leads to a detrimental effect of the environmental profile of the BC with respect to the control mixture (i.e., HMA0). The increase in the impact category scores can be as high as 29% for the Ecotoxicity impact category when the WMA45 is considered. WMA15 presents environmental benefits in only three impact categories, namely Ozone depletion, Global warming and Respiratory

Table 8
LCIA results per binder course mixture considered in the case study. Acronyms: OD- ozone depletion; GW- global warming; SF- photochemical smog formation; Ac- acidification; Eu- eutrophication; Ca- human health cancer; NCa- human health noncancer; RF- human health particulate; Ec- ecotoxicity; FFD- fossil fuel depletion.

Impact category	HMA0	Alternative mixture			
		WMA0	WMA15	WMA30	WMA45
OD (kg CFC-11 eq)	6.03E−03	5.59.E−03	5.75.E−03	6.01.E−03	5.80.E−03
GW (kg CO_2 eq)	3.39E+04	3.23.E+04	3.38.E+04	3.65.E+04	3.67.E+04
SF (kg O_3 eq)	4.75E+03	4.68.E+03	4.82.E+03	5.11.E+03	5.06.E+03
Ac (kg SO_2 eq)	3.18E+02	3.07.E+02	3.22.E+02	3.50.E+02	3.56.E+02
Eu (kg N eq)	2.82E+01	2.89.E+01	2.99.E+01	3.17.E+01	3.14.E+01
Ca (CTUh)	1.70E−03	1.70.E−03	1.79.E−03	1.98.E−03	2.05.E−03
NCa (CTUh)	1.27E−02	1.27.E−02	1.36.E−02	1.54.E−02	1.63.E−02
RE (kg $PM_{2.5}$ eq)	2.23E+01	2.16.E+01	2.21.E+01	2.31.E+01	2.24.E+01
Ec (CTUe)	2.50E+05	2.50.E+05	2.68.E+05	3.03.E+05	3.21.E+05
FFD (MJ surplus)	2.14E+05	2.10.E+05	2.24.E+05	2.52.E+05	2.65.E+05

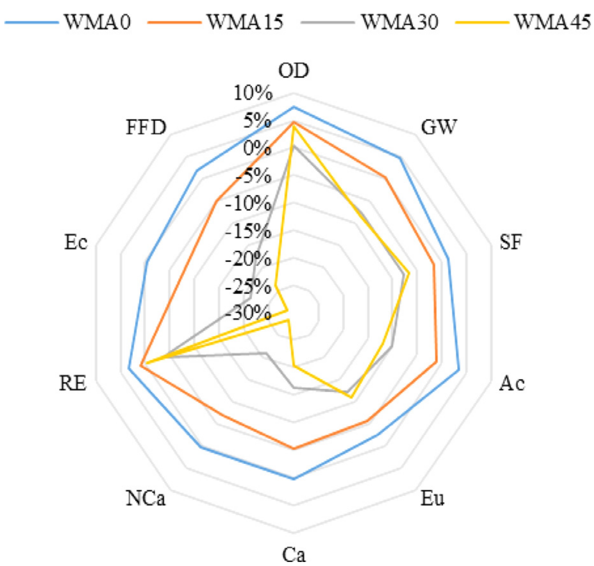

Fig. 2. Relative variation of the LCIA results for each alternative BC mixture in relation to those of the baseline mixture (i.e., HMA0). Acronyms: OD- ozone depletion; GW- global warming; SF- photochemical smog formation; Ac- acidification; Eu- eutrophication; Ca- human health cancer; NCa- human health noncancer; RF- human health particulate; Ec- ecotoxicity; FFD- fossil fuel depletion.

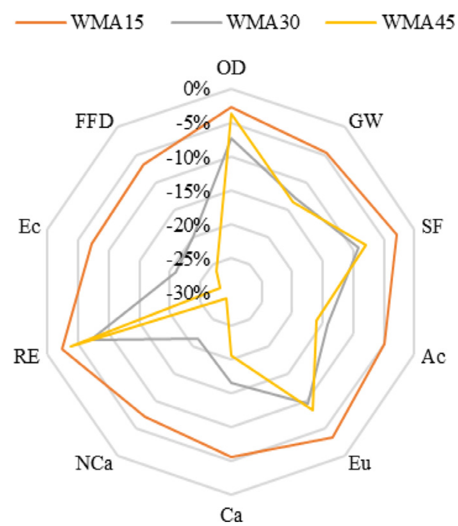

Fig. 3. Relative variation of the LCIA results for each alternative BC mixture, in relation to those of the WMA0. Acronyms: OD- ozone depletion; GW- global warming; SF- photochemical smog formation; Ac- acidification; Eu- eutrophication; Ca- human health cancer; NCa- human health noncancer; RF- human health particulate; Ec- ecotoxicity; FFD- fossil fuel depletion.

effects, while WMA30 and WMA45 exhibit a better environmental performance exclusively in the impact category Ozone depletion. Regarding WMA0, benefits can be seen in eight out of ten impact categories. Eutrophication and Ecotoxicity are the impact categories where no reduction in the environmental burdens are observed comparatively to HMA0.

According to the conditions considered in this case study, the results presented above can be explained by two facts (without specific order). First, the WMA mixtures with RCA were found to have a lower performance than that of the conventional HMA0, and therefore, require thicker BC layers in order to perform equivalently to HMA0. Specifically, the mixtures WMA15, WMA30 and WMA45 were found to be 8%, 17% and 17% thicker than the mixture HMA0, respectively. Second, the use of RCA was found to originate an increase in the optimum asphalt content. While this value was found to be 4.4% in the mixtures without RCA, it increased to 5.2% in the mixture WMA45.

The lower performance of the mixtures produced with RCA can be explained by the fact that the mortar layer that covers the original NA existing in the RCA particles is more porous and less dense than the original NA and has relatively weak bonding with it, which negatively affects the RCA properties. Regarding the increase in the optimum asphalt content, it is originated by the high porosity of the mortar layer that evolves the NA (Pasandín and Pérez, 2015).

In order to compare exclusively the effect of the use of RCA in WMA, Fig. 3 shows the relative variation of the impacts scores for each WMA mixture produced with RCA in relation to those associated with the WMA0.

According to those results, it can be concluded that the hypothetical environmental savings generated by the reduction in the consumption of NA promoted by the use of RCA in WMA are offset by the additional emissions generated by the increase in optimum asphalt and additive contents. For instance, the use of WMA15, WMA30 and WMA45 in BC layers is expected to cause an increase of 7%, 21% and 29% in the score of the impact category Human health noncancer comparatively to that of the WMA0.

4. Summary and conclusions

In this paper, the results of a process-based LCA analysis referring to the construction of the BC of a Colombian road pavement section using WMA with and without RCA were compared with those in which a conventional asphalt binder mixture (HMA without RCA) is alternatively applied.

The life cycle of the road pavement sections was divided into four main phases: (1) material production and transportation to the mixing plant; (2) material processing and mixtures production at the mixing plant; (3) mixtures transportation to the construction site; and (4) pavement construction. The LCI of the inputs associated with the processes considered by the several pavement life cycle phases was performed by combining primary data, representing the current Colombian practices and conditions, with secondary data taken primarily from the ecoinvent version 3 and USLCI databases. The SimaPro 8.4.0 software and the TRACI v.2.1 impact assessment method were adopted to model and characterize the environmental performance of the road pavement section.

The LCIA results of this case study showed that the use of WMA with RCA contents as a replacement of coarse NA leads to a deterioration of the environmental profile of the pavement structure in relation to that corresponding to the use of conventional mixture (i.e., HMA0). Such a result can be explained by the lower performance of WMA in comparison to that of the control mixture, which translates into an increase in the thickness of the layer obtained from the pavement design.

To sum up, the potential environmental benefits arising from the combined effect of the reduction of the consumption of NA and mixing temperature are offset by the lower performance and the need of higher optimum asphalt contents in the WMA incorporating RCA. Comparatively to HMA0 only the WMA0 mixture presents environmental benefits in most of the impact categories considered.

Authors contribution

Daniela Vega: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original Draft, Visualization; **João Santos**: Conceptualization, Methodology, Writing - Original Draft, Visualization, Supervision; **Gilberto Arguelles**: Conceptualization, Methodology, Resources, Writing - Original Draft, Visualization, Supervision, Funding acquisition.

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