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Life cycle assessment of hot mix asphalt with recycled concrete aggregates for road pavements construction

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ABSTRACT

In this study a comparative life cycle assessment (LCA) was conducted according to a 'cradle-to-laid' approach to evaluate the potential environmental impacts related to the use of recycled concrete aggregates (RCAs) as a partial replacement of coarse natural aggregates in the production of Hot Mix Asphalt (HMA). Specifically, three percentages of RCA replacements were analyzed: 15, 30 and 45%. Primary data collected mainly through surveys performed in Colombian contractors from the region of Barranquila were used to model the foreground system. The SimaPro 8.4.0 software was used for modelling the processes analyzed in the case study and all the life cycle inputs and outputs related to the functional unit were characterised during life cycle impact assessment (LCIA) phase into potential impacts according to the TRACI v.2.1 impact assessment methodology. The results of the case study showed that the mixtures incorporating 15 and 30% of RCA can be considered as eco-friendly alternatives to the conventional mixture (i.e. no RCA content), as both allow reductions in all impact categories scores. On the contrary, the mixture that contains 45% of RCA denoted a lower environmental performance than that of the conventional mixture.

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KEYWORDS
Life cycle assessment (LCA); hot mix asphalt (HMA); recycled concrete aggregate (RCA); sustainable pavement construction and management

Introduction

The construction industry in Colombia has achieved a significant growth in recent years. According to the National Administrative Department of Statistics (DANE), in 2016 the aforementioned sector grew 3.3% in Gross Domestic Product (GDP) comparatively to 2015 (National Administrative Department of Statistics DANE 2012). Furthermore, in the last 8 years more than 1.5 million houses and 2,700 km of new roads were built and about 40,000 km of existing roads were rehabilitated (Martinez-Arguelles, Acosta, *et al.* 2019b). Despite the social benefits obtained through the development of such projects, they are often associated with adverse impacts on the environment that cannot be disregarded. Among these impacts, the depletion and deterioration of land, the consumption of energy, the generation of solid waste, the emission of dust and gases, noise pollution and the consumption of non-renewable natural resources deserve particular attention (Lu and Yuan 2011). For instance, in 2016 the transport sector was responsible for the second-largest amount of greenhouse gas (GHG) emissions (EIA 2017), among which 74% were attributed to road transport (Marcilio *et al.* 2018). Given that the number and extension of roads are likely to continue to grow considerably (Laurance *et al.* 2014), their negative impacts are expected to follow the same trend if no effective actions are taken.

Due to the increasing concerns over the recent environmental issues related to transportation activities, the interest to develop and evaluate eco-friendly alternative solutions for this sector has increased considerably. In particular, the pavement industry and the scientific community have been forced to improve the production processes of asphalt mixtures through the development of the so-called sustainable technologies and solutions (Santos *et al.* 2018). One example of such solutions is the incorporation of recycled materials in asphalt mixtures, such as, for instance, recycled rubber, recycled asphalt pavement (RAP), steel slag, recycled concrete aggregate (RCA), among others (Bonicelli *et al.* 2017, Saberi *et al.* 2017, Kim *et al.* 2018, Bressit *et al.* 2019, Castro *et al.* 2019, Li *et al.* 2019, Martinez-Arguelles, Dugarte, *et al.* 2019a, Landi *et al.* 2020, Praticò *et al.* 2020).

RCA, in particular, has been studied as a replacement in different percentages of natural aggregates (NA) in asphalt mixtures (Gallego and Toledano 2010). It is produced by crushing old concrete from sidewalks, pavements, curbing and building slabs into smaller pieces (Marinković *et al.* 2010, Vega Araujo *et al.* 2019). These residues are part of the composition of construction and demolition waste (CDW), and given their physical and mechanical characteristics, have shown a relatively good performance that enable them to be considered as a potential replacement of NA in hot mix asphalt (HMA) (Paranavithana and Mohajerani 2006, Mills-Beale and You 2010, Zulkati *et al.* 2013). Likewise, it has been observed that RCA can have relevant preponderance in the mechanical and volumetric properties of HMA (Zhang *et al.* 2016). Specifically, satisfactory results have been reported for moisture damage resistance when

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the replacement percentages are lower than 75% of the total mass of aggregates (Mills-Beale and You 2010). In term of stiffness, contrasting results have been found. Some research studies have found that the addition of RCA decreases the stiffness of the mixtures when the replacement is made in the coarse fraction of NA (Cupo-Pagano *et al.* 1994, Albayati *et al.* 2018). However, when the fine fraction of NA is replaced by fine RCA, no influence on stiffness has been reported (Arabani and Azarhoosh 2012, Pasandín and Pérez 2015). Therefore, it can be said that overall the percentage of replacement and the properties of the RCA influence the behaviour of the mixtures (Pasandín and Pérez 2015).

Nevertheless, the mechanical and volumetric properties of the mixtures incorporating RCA are only two aspects to be considered when assessing the feasibility of their application in real practices. Their environmental sustainability implications, due to the reasons mentioned previously, cannot also be neglected. For the purpose of ascertaining the extent to which the use of alternative materials in road pavement construction is advantageous from the environmental perspective, the Life Cycle Assessment (LCA) methodology can be used. LCA is a systematic approach that allows the evaluation of the potential environmental impacts generated by a product, process or system throughout its life cycle (ISO 2006). According to the ISO 14040 standards, it consists of four main phases: (i) goal and scope definition, (ii) life cycle inventory analysis (LCI), (iii) life cycle impact assessment (LCIA) and (iv) interpretation.

Over the last years, LCA has received increasing attention as a methodology to evaluate the environmental sustainability of road pavements (Santero *et al.* 2011a, 2011b, Santos *et al.* 2015a, 2015b, Azarijafari *et al.* 2016, Inyim *et al.* 2016, Balaguera *et al.* 2018, Santos *et al.* 2018, Jiang and Wu 2019). As far as its application to RCA is concerned, Table 1 presents an overview of the main characteristics of the recent studies on the topic. In general, they concluded that the potential environmental impacts of RCA are closely related to the hauling distances (Wang and Gangaram 2014, Zhang *et al.* 2019). Furthermore, under certain conditions, the use of NA can even be considered as preferable from the environmental perspective (Parajuli *et al.* 2011). Notwithstanding the existence of the research efforts described in Table 1, the effects of mixtures design in the LCA results of RCA are scarce (Jiménez *et al.* 2015, Zhang *et al.* 2019).

Within this context, the research study presented in this paper aims to evaluate by means of LCA the potential environmental impacts of using RCA as a partial replacement of coarse NA in the production of HMA based on laboratory tests and mixture design results.

Methodology

The LCA analysis was performed taking into account the four-step methodology defined by the ISO 14040 guidelines (ISO 14040 2006) as well as the Federal Highway Administration's (FHWA's) Pavement LCA Framework (Harvey *et al.* 2016). It includes the goal and scope definition, the LCI, the LCIA and the interpretation. Further details on the methods, model development, and calculations conducted in this research study are provided in the next subsections.

Goal and scope definition

Goal

The main goal of this study is to estimate the potential environmental impacts related to the production of HMA with different RCA contents, namely 15, 30 and 45% by weight of coarse aggregates. The results are compared with those arising from the use of conventional HMA (i.e. HMA without RCA), and are intended to be used by highway agencies and pavement practitioners striving for delivering more sustainable road pavement infrastructures.

System description and boundaries

The LCA analysis was conducted according to a 'cradle-to-laid' approach. Figure 1 presents the system boundaries and main processes considered in the study. In particular, the analysis includes four main pavement life cycle phases: (i) materials production and transportation to the asphalt mixing plant; (ii) materials processing and mixtures production at the asphalt mixing plant; (iii) mixtures transportation to the construction site; and (iv) pavement construction. Furthermore, the boundaries for the pavement structure were limited to the binder course (BC).

Finally, a 'cut-off' allocation approach was considered for dealing with the RCA. Thus, only the impacts associated with the processing of RCA to render it suitable aggregate for asphalt mixtures applications were attributed to the system receiving the recycled materials (Schrijvers *et al.* 2016, Santos *et al.* 2018). That means that the environmental burdens related to the pavement demolition and the transportation of the demolition materials to the recycling facility were not included in the system boundaries of the present case study.

Functional unit

In this study the functional unit was defined as the provision of the BC of 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 value of 5×10^6 Equivalent Single Axle Load (ESAL) of 80kN, a CBR of 7.5% and a service life of 10 years. The geometric characteristics of a pavement structure designed with a conventional HMA (i.e. 0% RCA content) in the BC are illustrated in Figure 2. The definition presented above is intended to follow as much as possible the recommendations presented by the Pavement LCA Framework (Harvey *et al.* 2016). According to this reference the functional unit for pavements should include: (i) specifications related physical dimensions (e.g. length, width, and number of lanes); (ii) indicators of the performance of the pavement (e.g. design life) and; (iii) criteria for performance (e.g. safety, ride quality, traffic levels, load spectrum, speed characteristics, climatic conditions and engineering, etc.).

In order to ascertain the potential environmental advantages related to the use of HMA with RCA content in BC, the reference pavement structure (Figure 2) was compared with three structures with similar geometry, but in which the BC was alternatively made of HMA with three RCA contents. Those alternatives represent structures with equivalent structural

Table 1. Overview of the main characteristics of the research studies involving the LCA of RCA.

Study	Location	Goal	Functional unit	System boundaries	Data sources	Impact assessment methodology	Software	Main results
Hossain *et al.* (2016)	China	Compare the environmental consequences of recycled and natural aggregates production	One ton of aggregates, i.e. fine/coarse natural or fine/coarse recycled aggregate	Cradle-to-site: materials extraction; on-site transportation and handling; crushing and sieving; transportation to construction site	Databases, i.e. CLP, CLCD and ELCD	IMPACT 2002+	SimaPro	Compared to coarse NA, coarse recycled aggregates produced from CDW reduce by 65% the GHGs emissions and by 58% the consumption of non-renewable energy. Significant reductions in health, resource, climate change and ecosystem damage scores can be obtained by producing recycled aggregates from both waste materials, comparatively to those associated with producing and importing aggregates from virgin sources
Estanqueiro *et al.* (2016)	Portugal	Compare the environmental impacts of three alternatives of provision of coarse aggregates for concrete mixture production: (i) natural aggregates; (ii) RCA produced in a fixed plant; and (iii) RCA produced in a mobile plant	One ton of coarse aggregates, natural or recycled, ready to be used in concrete production	Cradle-to-site: transportation from the demolition site (for RCA); extraction/ processing; non-useful inert deposition (for RCA); transportation to concrete plant; transportation to construction site	Real data from the region	Eco-indicator 99, CML Baseline and Cumulative Energy Demand	SimaPro	The use of RCA in the production of concrete is preferable to the use of NA only in terms of land use and respiratory inorganics. However, coarse recycled aggregates can present a better environmental performance than that of NA if fine recycled aggregates are also used in concrete production instead of being sent to a landfill
Rosado *et al.* (2017)	Brazil	Perform a comparative LCA study on the environmental impacts related to the production of NA and MixRA (combination of NA and RCA)	One ton of aggregates, i.e. NA or MixRA	Cradle-to-site: transportation; basalt blasting; truck loading and handling; crushing and sieving; sorting, crushing and sieving (for RCA); transportation to construction site	Real data from the region; databases, i.e. Ecoinvent v.3 and USLCI	IMPACT 2002+	SimaPro	MixRA is the best option for all impact categories analysed (with the exception of the 'non-carcinogens') only if the distance from the production site to the consumer site is up to 20 tkm longer than the distance from the NA production site to the consumer site
Braga *et al.* (2017)	Portugal	Compare the life cycle environmental and economic impacts of concrete mixtures with coarse natural and RCAs	One m^3 of ready concrete mixture with natural or recycled aggregates	Cradle-to-gate: production/ extraction of raw materials; transportation to concrete plant; production at the plant	Literature and databases, i.e. Ecoinvent v.3 and ELCD	CML baseline method and Cumulative Energy Demand	SimaPro	The use of RCA can significantly reduce the environmental impacts and costs; the concrete mixes with the best mechanical performance were those that used RCA with better characteristics (low water absorption and porosity, higher density and specific mass); usually, that corresponds to lower environmental impacts and costs
	Italy					Eco-indicator 99	SimaPro	

(*Continued*)

Table 1. Continued.

Study	Location	Goal	Functional unit	System boundaries	Data sources	Impact assessment methodology	Software	Main results
Colangelo *et al.* (2018)		Compare the life cycle environmental impacts associated with the production of three types of different concrete mixtures containing CDW, marble sludge and CKD	One m^3 of ready concrete mixture	Cradle-to-grave: materials extraction and processing; mixtures production; transportation to the construction site and placement; transportation of waste at the end-of-life	Literature, databases, real data from the region and data provided by ATECAP			Mixtures that generate lower environmental impacts are those in which CDW and CKD are used
Martinez-Arguelles, Acosta *et al.* (2019b)	Colombia	Compare the environmental impacts arising from the production of coarse NA and the combination of coarse NA with RCA (NA-RCA)	One ton of aggregates, i.e. NA and NA-RCA	Cradle-to-gate: extraction; crusher loading (for RCA); truck loading; crushing and sieving; transportation to the storage site	Real data fromthe region and databases, i.e. Ecoinvent v.3	IMPACT 2002+	SimaPro	For the NA-RCA combination, the transportation distance of the limestone to the plant represents the most critical input parameter in the LCA; transportation distances of the raw materials should not exceed 200 km
Shi *et al.* (2019)	United States	Compare the economic, social and environmental impacts of RCA-based portland cement concrete (PCC) pavements with those of a plain PCC pavement	Pavement section 12.8-km long and 14.4-m wide (two lanes in each direction; each lane is 3.6 m wide) with the same PCC layer thickness (25 cm)	Cradle-to-grave: materials production; construction; use; maintenance; end of life	RSMeans database; Oklahoma DOT AADT Traffic Counts database	TRACI	EIO-LCA model developed by CMU	The use of RCA in PCC originates environmental benefits in materials production and construction phases but contributes to higher negative environmental impacts during the use phase. Specifically, RCA-PCC was found to be more environmentally friendly than the plain pavement in the impact categories ecotoxicity, human health cancer and human health non-cancer

Acronyms: AADT – Annual average daily traffic; ATECAP – Italian Technical Economic Association for Ready-Mix Concrete; CDW – construction and demolition waste; CKD – cement kiln dust; CLCD – Chinese life cycle database; CLP – Chinese Light and Power; GHGs – greenhouse gases; CMU – Carnegie Mellon University; EIO-LCA – economic input-output life cycle assessment; ELCD – European life cycle database; MixRA – combination of NA and RCA; NA – natural aggregates; PCC – Portland cement concrete; RCA – recycled concrete aggregate; USLCI – United States life cycle inventory.

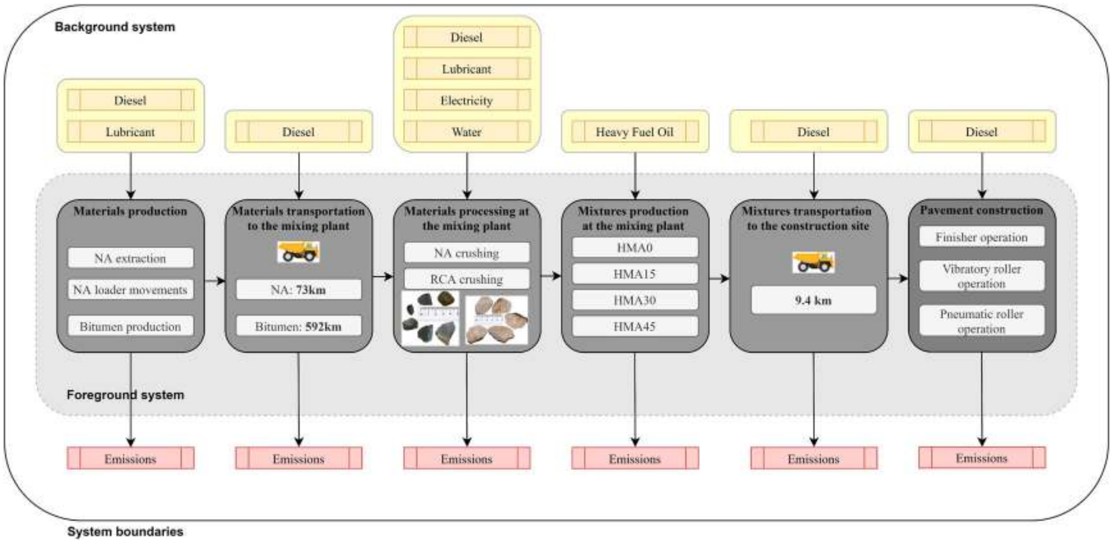

Figure 1. System boundaries considered in the case study. Acronyms: NA – natural aggregate; RCA – recycled concrete aggregate; HMA – hot mix asphalt.

capacity, where the only design parameter that changed was the thickness of the asphalt BC. Therefore, the mixture implemented in the surface course (SC) corresponds to a conventional mixture and the granular layers (i.e. GB – granular base and SGB – sub granular base) correspond to those commonly used in the region of Barranquilla for asphalt pavements and satisfy the Colombian standards for road materials (INVIAS 2014a). Furthermore, tests carried out in the laboratory were performed with the purpose of determining the proportion of the mixture components and their performance.

Table 2 presents the composition and characteristics of the mixtures analysed in the case study. The key 'XY' was adopted to identify the several mixtures. According to this key, 'X' stands for the type of mixture (i.e. HMA) and 'Y' represents the percentage of RCA (i.e. 0, 15, 30 or 45%). In addition, all mixtures contain 50% of coarse aggregates and 50% of fine aggregates and the RCA replacements were made in the fraction corresponding to the coarse aggregates. The mixtures were designed according to Marshall design specifications (INVIAS 2013) and all samples satisfied the Colombian standards for road materials (INVIAS 2014b). 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. They show that mixtures containing RCA replacements of 15 and 30% present the highest resilient modulus, whereas the mixture containing a replacement equal to 45% exhibits the lowest value amongst all mixtures (including the control mixture). Some authors have explained such behaviour due to the influence of the fine fraction existing in the adhered mortar of RCA. In particular, it influences the volumetric properties of the mixture by increasing the asphalt binder absorption and the optimum asphalt binder content (Pasandín and Pérez 2014). Beyond a given RCA content the mixtures performance decreases due to an extensive increase in the weak bond between the RCA and the asphalt binder (Zhang *et al.* 2016). However, it should be mentioned that such RCA behaviour has been identified when the coarse fraction of the NA is replaced by RCA.

Finally, the Pitra Pave 1.0.0 tool (Universidad De Costa Rica 2015) was adopted to design the pavement structure of all alternatives taking into account the characteristics and

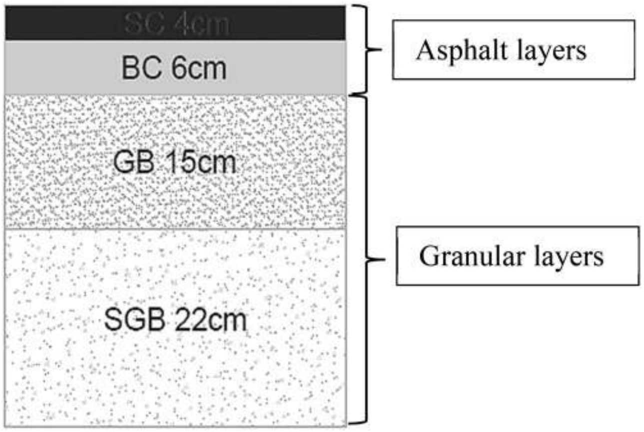

Figure 2. Geometric characteristics of a pavement structure designed with a conventional HMA. Acronyms: SC – Surface Course; BC – Binder Course; GB – Granular Base; SGB – Sub Granular Base.

Table 2. Composition and characteristics of the mixtures.

	Mixture			
Item	HMA0	HMA15	HMA30	HMA45
Natural Aggregate				
Quantity[a] (%)	95.6	88.3	80.9	73.5
Absorption (%)	3			
Recycled Concrete Aggregate				
Quantity[b] (%)	-	15	30	45
Asphalt				
Quantity[a] (%)	4.4	4.5	4.8	5.2
Properties				
Density (kg/m^3)	2366	2310	2305	2289
Air voids (%)	4.3	4.8	4.6	4.8
Voids filled with asphalt (%)	66.6	66.5	67.2	66.0
Voids in the mineral aggregate (%)	12.7	14.2	13.9	14.2
Stability (kN)	17.2	14.8	16.7	20.1
Flows (mm)	2.9	2.7	3.0	3.4
Resilient modulus (MPa)	1531	2077	2066	1223

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

mechanical performance of the several mixtures and according to the standard practice in Colombia. In this way, maximum critical stresses and strains were calculated at different points of the pavement structure for assessing rutting and cracking performance. Those critical values were posteriorly compared with the corresponding admissible thresholds to make sure that rutting and cracking requirements were satisfied. Table 3 shows the input data for the pavement designs of each type of mixture. The results of the pavement designs are presented in Table 4.

Data source

In this study, primary data were collected from surveys and laboratory tests. Specifically, four different asphalt mixing plants were examined, and their relevant data collected. Those data were combined with information related to asphalt mixtures design, aggregate properties and mechanical performance of the asphalt mixtures obtained from specific tests performed in the laboratory. Furthermore, existing research studies (i.e. Thenoux *et al.* 2007) and databases (i.e. Ecoinvent v.3 and USLCI) were used to complement the data sources above mentioned.

Life cycle inventory (LCI)

In this LCA phase, all data used for the analysis were defined in such a way that the primary and secondary data of each evaluated process and their corresponding sources are specified (ISO 14040 2006, Santos *et al.* 2018). Table 5 presents the sources and values of the data per pavement life cycle phase and main processes.

Materials production and transportation to the mixing plant phase

This pavement LCA phase accounts for the environmental impacts related to the production of the raw materials as well as their transportation to the mixing plant. It covers all the processes required to extract the raw materials and ends up at the mixing plant. Specifically, it considers the following processes: (i) NA extraction, (ii) loading the dump truck with NA, (iii) bitumen production, and (iv) transportation of raw materials to the mixing plant.

Materials production sub-phase

As previously mentioned, each type of mixture contains 50% of coarse aggregate and 50% of fine aggregate. Therefore, the NA required for the case study were modelled as gravel and sand. The LCI data related to their extraction were obtained from a previous LCA study (Martinez-Arguelles, Acosta, *et al.* 2019b). In the case of the bitumen production, it was modelled according to '*bitumen, at refinery/kg/US*' process existing in the USLCI database. Finally, for modelling the process referring to the load of NA to the dump truck, it was taken into account the information obtained from surveys.

Table 3. Pavement design input data for each type of mixture.

Type of mixture	Subgrade Mr (MPa)	Traffic ESAL (80kN)	Modulus (MPa)			
			SC	BC	GB	SGB
HMA0	78	5,000,000	2856	1531	250	200
HMA15	78	5,000,000	2856	2077	250	200
HMA30	78	5,000,000	2856	2066	250	200
HMA45	78	5,000,000	2856	1223	250	200

Materials transportation to the mixing plant sub-phase

This sub-phase accounts for the impacts related to the materials transportation to the mixing plant. The LCI data required in this sub-phase were obtained from surveys and consisted of the real transportation distances for the case study (Figure 1).

Materials processing and mixtures production at the mixing plant phase

This phase refers to the modelling of the manufacturing processes required to transform the raw materials into an asphalt mixture. It includes the burdens related to: (i) NA processing, (ii) RCA processing, (iii) hauling movement of the aggregates (natural and recycled) from the stockpiles to the feed bins, and (iv) mixture production.

Materials processing sub-phase

Within this sub-phase is included the calculation of the potential environmental impacts associated with the aggregates manufacturing processes and their hauling movements. Those LCI data were taken from a previous and broader research effort that also includes the research study presented in this paper (Martinez-Arguelles, Acosta, *et al.* 2019b). Therefore, it can be affirmed that the inventory data taken from that previous research study are primary data for the present study.

Mixtures production sub-phase

This sub-phase aims to estimate the potential environmental impacts arisen from the production of the different types of mixtures assessed in this case study. A thermodynamic relationship (Equation 1) was used for the calculation of the Thermal Energy (TE) provided by the combustion of Heavy Fuel Oil (HFO) and required to produce each type of mixture. This input was determined according to the energy balance proposed by Santos *et al.* (2018), which considers the values

Table 4. Results of the pavement design for each type of mixture.

	Thickness (cm)				
	Asphalt layers		Granular layers		
Type of mixture	SC	BC	GB	SGB	Total
HMA0	4.0	6.0	15.0	22.0	47.0
HMA15	4.0	5.0	15.0	22.0	46.0
HMA30	4.0	5.0	15.0	22.0	46.0
HMA45	4.0	7.5	15.0	22.0	48.5

Acronyms: SC – Surface Course; BC – Binder Course; GB – Granular Base; SGB – Sub Granular Base.

Table 5. LCI data considered in the case study.

Pavement LCA phase	Process name	Data set	Data type	Data item	Data value	Data unit
Materials production and transportation to the mixing plant	Natural Aggregate (NA) extraction	*'Gravel, crushed {RoW}| production | Alloc Def, U'* – Ecoinvent v.3 database	Primary	Fuel	0.272	MJ/Kg
	NA load movements	*'Loader operation, large'* – USLCI	Primary	Fuel	26	gal/hr
				Lubricant	0.3446	gr/hr
	NA transportation	*'Transport, freight, lorry 16–32 metric ton, EURO4 {RoW}| transport, freight, lorry 16–32 metric ton, EURO4 | Alloc Def, U"* – Ecoinvent v.3 database	Primary	Fuel	0.025	kg/tkm
				Distance	73	Km
	Asphalt production	*'Bitumen, at refinery/kg/US'* – USLCI database	Secondary	-		
	Asphalt transportation	*'Transport, freight, lorry 16–32 metric ton, EURO4 {RoW}| transport, freight, lorry 16–32 metric ton, EURO4 | Alloc Def, U'* – Ecoinvent v.3 database	Primary	Fuel	0.023	kg/tkm
				Distance	592	Km
Materials processing and mixtures production at the mixing plant	NA processing	*Diesel, burned in building machine {GLO}| market for | Alloc Def, U* – Ecoinvent v.3 database	Primary	Fuel	10.989	MJ/ton
				Lubricant	0.69	gr/ton
				Electricity	2.33	kWh/ton
				Water	100	kg/ton
	RCA crushing	*Diesel, burned in building machine {GLO}| market for | Alloc Def, U* – Ecoinvent v.3 database	Primary	Fuel	10.989	MJ/ton
				Lubricant	0.69	gr/ton
				Electricity	2.33	kWh/ton
				Water	100	kg/ton
	Mixture production (BC layer), with and without RCA replacements	*'Heat, district or industrial, other than natural gas {RoW}| heat production, heavy fuel oil, at industrial furnace 1MW | Alloc Def, U'* – Ecoinvent v.3 database	Primary	Thermal Energy	-[a]	MJ/ton
Mixture transportation to the construction site	Mixture transportation	*'Transport, freight, lorry 16–32 metric ton, EURO4 {RoW}| transport, freight, lorry 16–32 metric ton, EURO4 | Alloc Def, U'* – Ecoinvent v.3 database	Primary	Fuel	0.025	kg/tkm
				Distance	9.4	Km
Pavement construction	Finisher operation	*'Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | Alloc Def, U'* – Ecoinvent v.3 database	Secondary	Performance	60	m^3/hr
	Vibratory roller operation	*'Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | Alloc Def, U'* – Ecoinvent v.3 database	Secondary	Performance	65	m^3/hr
	Pneumatic roller operation	*'Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| market for | Alloc Def, U'* – Ecoinvent v.3 database	Secondary	Performance	65	m^3/hr

[a] Value calculated according to the procedure described in subsection *'Mixtures production sub-phase'*.
Acronyms: BC- binder course; NA- natural aggregate; RCA- recycled concrete aggregate.

presented in Table 6.

$$TE = [\sum_{i=1}^{M} m_i \times C_i \times (t_{\text{mix}} - t_o) + m_{\text{asph}} \times C_{\text{asph}} \times (t_{\text{mix}} - t_o) + \sum_{i=1}^{M} m_i \times W_i \times C_{\text{water}} \times (100 - t_o) + L_v \times \sum_{i=1}^{M} m_i \times W_i + \sum_{i=1}^{M} m_i \times W_i \times C_{\text{vap}} \times (t_{\text{mix}} - 100)] \times (1 + CL) \tag{1}$$

Where *TE* is the thermal energy (MJ/ton mixture) required to produce a given asphalt mixture, *M* is the total number of aggregate fractions, m_i is the mass of aggregate of fraction *i*, C_i is the specific heat of aggregate of fraction *i*, *CL* is the component of the TE used to heat the plant iron and radiated posteriorly to the atmosphere (West *et al.* 2014). Its value was considered to be same for all mixtures and was taken from Santos *et al.* (2018). Likewise, the values of the other parameters were considered to remain constant for all the mixtures studied.

Table 6. Parameters considered to calculate thermal energy according to Equation 1.

	Parameter	Value	Unit
t_o	Ambient temperature	25	°C
t_{mix}	Mixing temperature of HMA with 0, 15, 30 and 45% RCA replacements	160	°C
C_{agg}	Specific heat of natural aggregates[a]	0.74	KJ/Kg/°C
W_{agg}	Water content of natural aggregates	3	% by mass of aggregates
W_{RCA}	Water content of RCA	3	% by mass of RCA
C_{RCA}	Specific heat of recycled concrete aggregates[a]	0.74	KJ/Kg/°C
C_{water}	Specific heat of water at 15°C	4.19	KJ/Kg/°C
L_v	Latent heat of vaporisation of water	2256	kJ/kg
C_{vap}	Specific heat of water vapour	1.83	kJ/kg
C_{asph}	Specific heat of asphalt	2.09	KJ/Kg/°C
CL	Casing loses factor[b]	27	%

[a] Value for granitic aggregates (Santos *et al.* 2018); [b] Value taken from the literature (West *et al.* 2014, Santos *et al.* 2018).

The quantity of TE expressed in MJ/ton mixture and the corresponding fuel consumption (FC) expressed in kg of HFO/ton mixture are shown in Table 7. This table also presents the value of the Reduction Factor (RF) associated with each type of mixture. It represents the reduction of TE between each alternative mixture and the control one (i.e. HMA0).

Table 7. Thermal Energy (TE) consumed for producing each type of mixture and respective Reduction Factor (RF).

Mixture	TE (MJ/ton mixture)	FC (Kg HFO /ton mixture)	RF (%)
HMA0	241.4	5.7	-
HMA15	237.9	5.6	1.5
HMA30	234.6	5.6	2.8
HMA45	231.8	5.5	4.1

Mixtures transportation to the construction site phase

In this stage, the potential environmental impacts related to the hauling of the mixtures from the asphalt plant to the construction site were analyzed. For that purpose, it was considered the density of the mixtures obtained from laboratory tests and the truck fuel consumption data obtained from the surveys. In addition, the real transportation distances presented in Figure 1 were also considered.

Pavement construction phase

The potential environmental burdens generated during the pavement construction activities were analysed in this phase. The LCI data associated with the construction equipment considered in the case study (i.e. finisher, vibratory and pneumatic rollers) were taken from the literature (Thenoux *et al.* 2007).

Life cycle impact assessment (LCIA)

The LCI results were classified and characterised according to the characterisation factors defined by the TRACI v.2.1. impact assessment methodology (Bare 2012) for the following impact categories: (1) ozone depletion (OD), (2) global warming (GW), (3) photochemical smog formation (PSF), (4) acidification (Ac), (5) eutrophication (Eu), (6) human health cancerous (HHC), (7) human health noncancerous (HHN), (8) human health particulate (HHP), (9) ecotoxicity (Ec), and (10) fossil fuel depletion (FFD). Furthermore, the optional LCIA steps (i.e. normalisation, group and weighting) established by the ISO 14040 standards were not performed (ISO 14040 2006).

Finally, the Simapro software version 8.4.0 was used for modelling the processes analyzed in this case study (PRé Consultants 2014).

Results and discussion

Total life cycle impact assessment results

Based on the LCA methodology and assumptions described previously and the inventory data gathered, the potential environmental impacts were calculated. Table 8 presents the LCIA results for the conventional asphalt mixture (i.e. HMA0). Figure 3 illustrates the relative environmental impacts of the alternative asphalt mixtures applied in the binder course calculated in relation to those of the conventional asphalt mixture. The rationale behind the interpretation of the results is such that negative relative numbers mean that the alternative asphalt mixtures worsen the potential LCIA results in relation to those associated with the conventional asphalt mixture. In turn, positive numbers represent an improvement of the environmental profile.

Table 8. LCIA results associated with the conventional mixture (i.e. HMA0).

Impact category	Unit	Value
Ozone depletion (OD)	kg CFC_{11} eq	6,03E-03
Global warming (GW)	kg CO_2 eq	3,39E+04
Potential smog formation (PSF)	kg O_3 eq	4,75E+03
Acidification (Ac)	kg SO_2 eq	3,18E+02
Eutrophication (Eu)	kg N eq	2,82E+01
Human health cancerous (HHC)	CTUh	1,70E-03
Human health noncancerous (HHN)	CTUh	1,27E-02
Human health particulate (HHP)	kg $PM_{2.5}$ eq	2,23E+01
Ecotoxicity (Ec)	CTUe	2,50E+05
Fossil fuel depletion (FFD)	MJ surplus	2,14E+05

The results presented in this figure shows that the mixtures HMA15 and HMA30 can be regarded as eco-friendly alternatives to the conventional mixture, as both allow reductions in all impact categories scores. The most expressive reductions are obtained with the mixture HMA30 in the impact categories HHP, OD and Eu (approximately 24, 24 and 23%, respectively). On the contrary, the most modest reductions are observed with the same mixture but in the impact categories HHN, Ec and FFD (approximately, 13, 14 and 15%, respectively).

A result worth mentioning and that to some extent can be perceived as unexpected, relates to the fact that the mixture HMA45 was found to lead to an increase in the score of all impact categories in relation to the conventional mixture. This increase ranges from roughly 10% in the impact category OD to approximately 38% in the impact category HHN. According to the conditions considered in this case study, these higher scores can be explained by the combination of two facts. First, the mixture HMA45 was found to have a lower performance than that of the conventional HMA0, and therefore requires a thicker BC layer (25% thicker) in order to perform equivalently to HMA0. Second, the use of RCA was found to originate an increase in the optimum asphalt content. While this value was determined to be 4.4% in the mixture without RCA, it increased to 5.2% in the mixture HMA45. The lower performance of the mixture HMA45 can be explained by the fact that the mortar layer that covers the 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). However, the lower mechanical performance denoted by the HMA45 was not observed in the remaining mixtures containing RCA. Actually, they registered a higher performance that was translated in the design of thinner BC layers (approximately 17%). In face of such results, it appears that the use of RCA is beneficial from the mechanical performance perspective (and consequently from the environmental viewpoint as well) up to a given percentage, after which the opposite effect is observed.

Contribution analysis

Figure 4 depicts the relative contribution of the several processes to the total environmental impact scores. From the analysis of this figure it emerges that the environmental profile of the several mixtures is mainly driven by the processes Bitumen Production, Mixtures Production and NA extraction, although the exact order varies depending on the impact

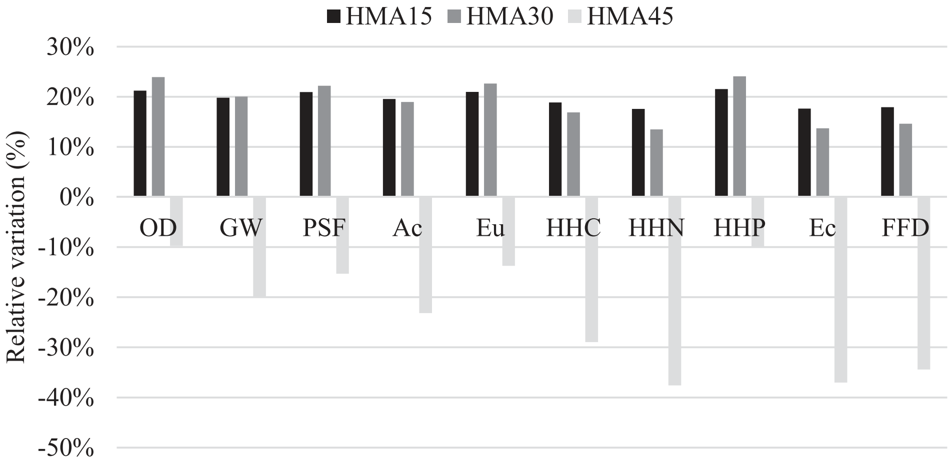

Figure 3. Relative characterised environmental impact scores of alternative asphalt mixtures. Acronyms: OD – ozone depletion; GW – global warming; PSF – photochemical smog formation; Ac – acidification; Eu – eutrophication; HHC – human health cancerous; HHN – human health noncancerous; HHP – human health particulate; Ec – ecotoxicity; and FFD – fossil fuel depletion.

category. The Bitumen Production is particularly meaningful for the impact categories HHN, Ec and FFD, with average shares of 88, 87 and 77%, respectively. The Mixture Production is responsible for the majority of the scores in the impact categories OD, GW and HHP, where the relative contribution can be as high as 48, 34 and 29%, respectively. Finally, the NA extraction is particularly relevant for the impact categories HHP, PSF and Eu, accounting for 44, 41 and 36%, respectively, of the total scores observed for those impact categories. Moreover, the results displayed in Figure 4 also show that the contributions of the processes abovementioned varies in the opposite direction with the increase in the percentage of RCA incorporated in the asphalt mixtures.

On the contrary, the contributions of the processes Mixture Transportation, RCA Crushing and NA loader movement were found to be almost residual comparatively to those of the remaining processes. For instance, on average, the former process contributes to less than 0.3% in the majority of the impact categories, whereas the latter is associated with a share that does not go beyond an average value of 3% in the impact category PSF.

Sensitivity analysis

In order to ascertain the extent to which the results are sensitive to changes in the value of some parameters, a sensitivity analysis was performed. The selection of the parameter was driven by its hypothetical relevance for a meaningful process and the uncertainties related to its value. Given those criteria, it was decided to analyse influence of the moisture content of the RCA. The rationale of this choice is twofold. First, the production of RCA involves the use of water and recent studies have found that the energy consumed in the production of asphalt mixtures is significantly influenced by the moisture content of the mineral mixture (Androjic *et al.* 2020). Second, the RCA particles are commonly stockpiled in unsheltered conditions. The last aspect is particularly relevant in the Colombian context given the high rainfall commonly observed in the country. The moisture content was then changed up to a maximum value of 8% (Federal Highway Administration Research and Technology 2016) and the sensitivity ratio (SR) was calculated according to Equation 2 (Clavreul et al. 2012). The relative change in the impact assessment result is divided by the relative change in the parameter value, and the result is the ratio of the two. According to this method, the higher the ratio is, the greater the impact that a change in the parameter has on the results.

The sensitivity analysis results are illustrated in Figure 5. From the analysis of this figure it can be concluded that the impact categories OD, HHP and GW are particularly affected by changes in the moisture content of the RCA. On the contrary, the impact categories Ec, HHN and HHC are minimally impacted. In line with the natural expectations, the same Figure also shows that the higher the RCA content of the asphalt mixture, the greater the impact of the change in the value of the moisture content.

$$\mathrm{SR} = \frac{\dfrac{\Delta \mathrm{Result}}{\mathrm{Result}_0}}{\dfrac{\Delta \mathrm{Parameter}}{\mathrm{Parameter}_0}} \qquad (2)$$

Scenario analysis

One of the measures commonly mentioned in the literature to reduce the environmental impacts of the paving industry consists of shifting to natural gas the fuel burned by the asphalt mixing plants. In order to ascertain the extent to which this measure can be environmental advantageous, a scenario analysis was performed. Specifically, it was assumed that the asphalt mixing plant is run by natural gas rather than by HFO.

Figure 6 displays for each alternative asphalt mixture the relative variation of the LCIA results in relation to those of the baseline scenario. They should be understood as follows: positive relative numbers mean that the alternative scenario improves the LCIA results in relation to those associated with the baseline scenario while negative numbers represent a deterioration of the environmental profile. The results of the scenarios analysis show a consensual reduction of the scores in all impact categories for all asphalt mixtures considered.

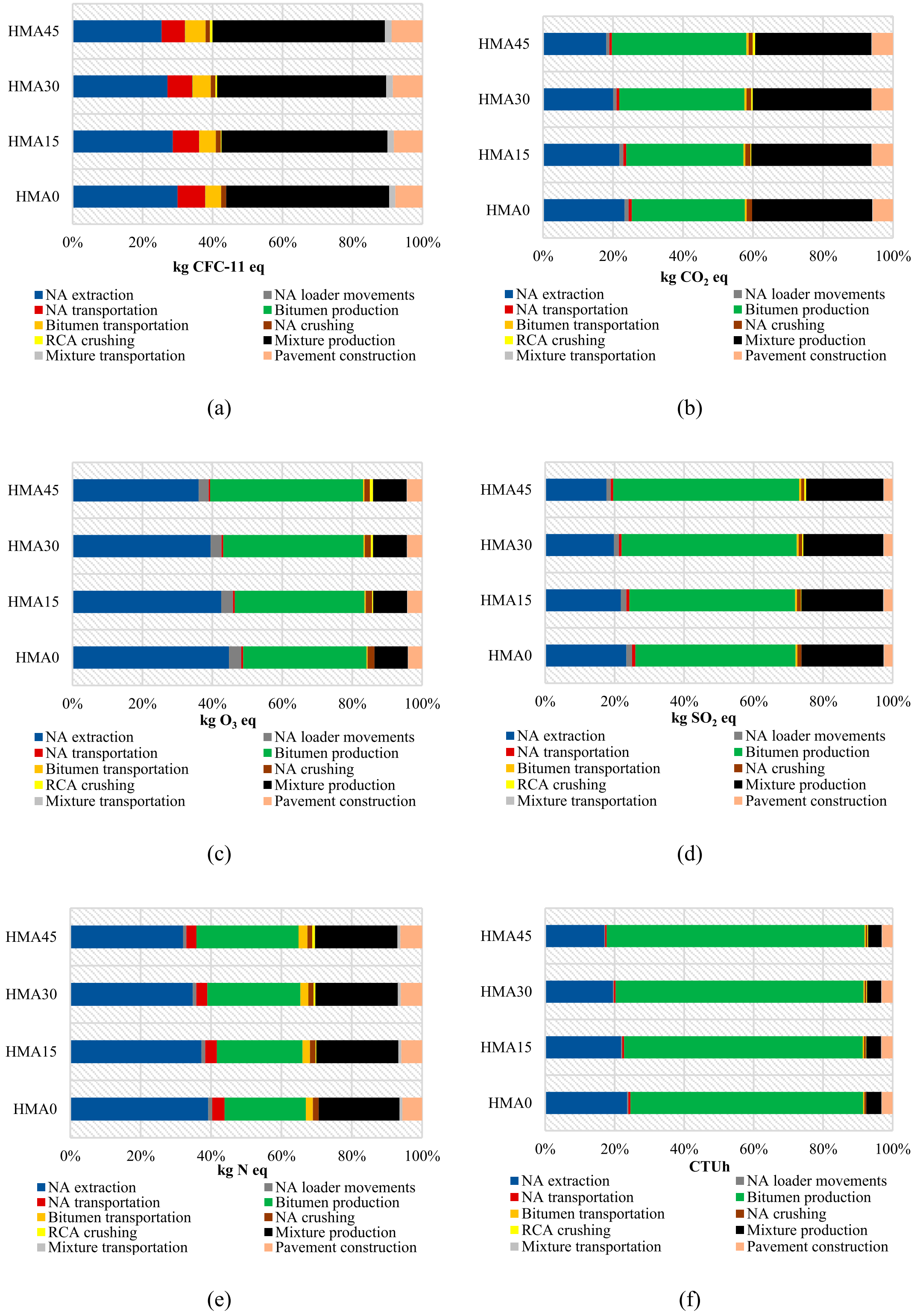

Figure 4. Relative contribution of the main processes to the total impact scores: (a) OD, (b) GW, (c) PSF, (d) Ac, (e) Eu, (f) HHC, (g) HHN, (h) HHP, (i) Ec and (j) FFD. Acronyms: OD – ozone depletion; GW – global warming; PSF – photochemical smog formation; Ac – acidification; Eu – eutrophication; HHC – human health cancerous; HHN – human health noncancerous; HHP – human health particulate; Ec – ecotoxicity; and FFD – fossil fuel depletion.

With average reductions of approximately 35 and 20%, the most expressive savings are observed for the impact categories OD and HHP, respectively. In contrast, the impact categories HHC and FFD appear to be less exposed to the benefits of the change of the type of energy source. When comparing the several alternative asphalt mixtures, the results depicted in Figure 6 reveal that overall the most expressive reductions are registered for the asphalt mixture HMA0, whereas the asphalt mixture HMA45 is likely to be less affected. The remaining types of mixtures alternate the intermediate position in the raking depending on the impact category being considered.

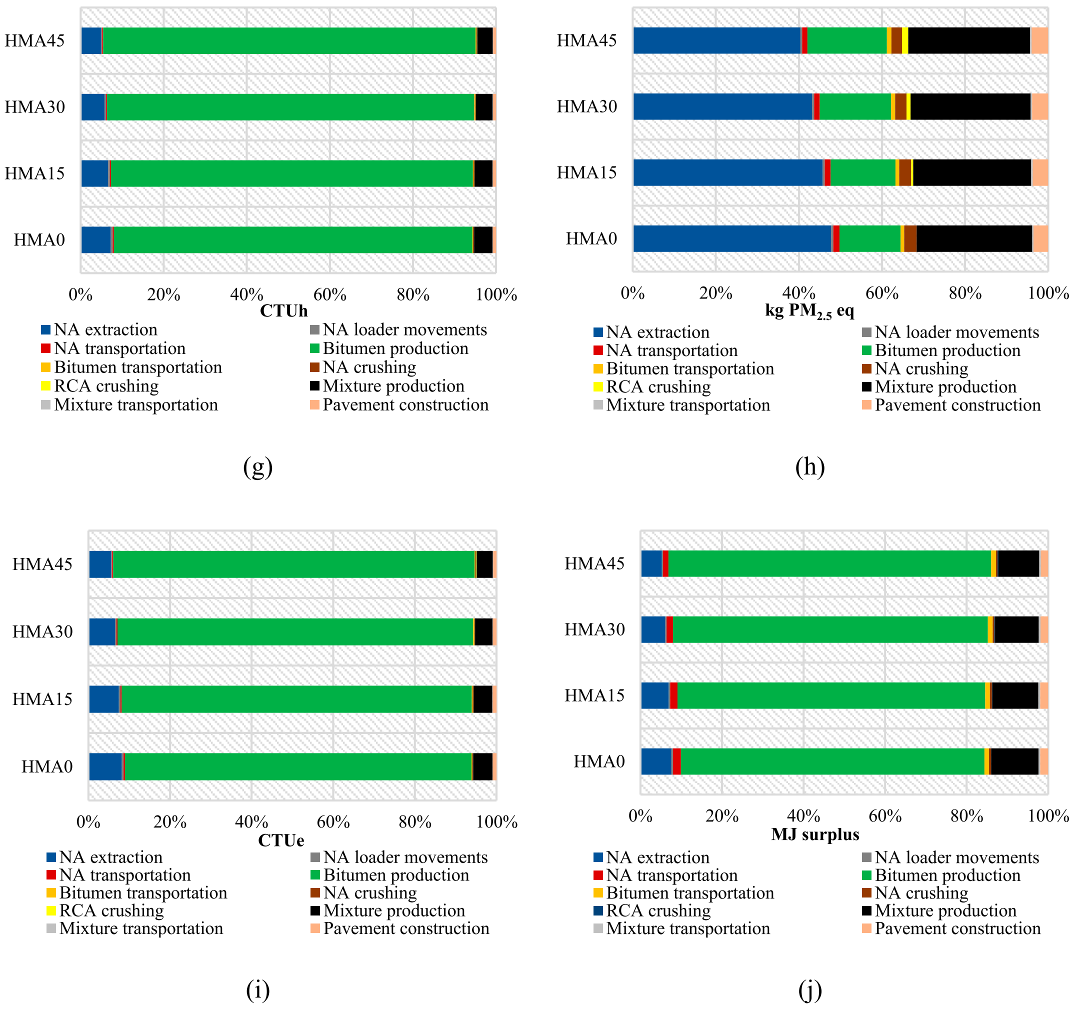

Figure 4 *Continued*

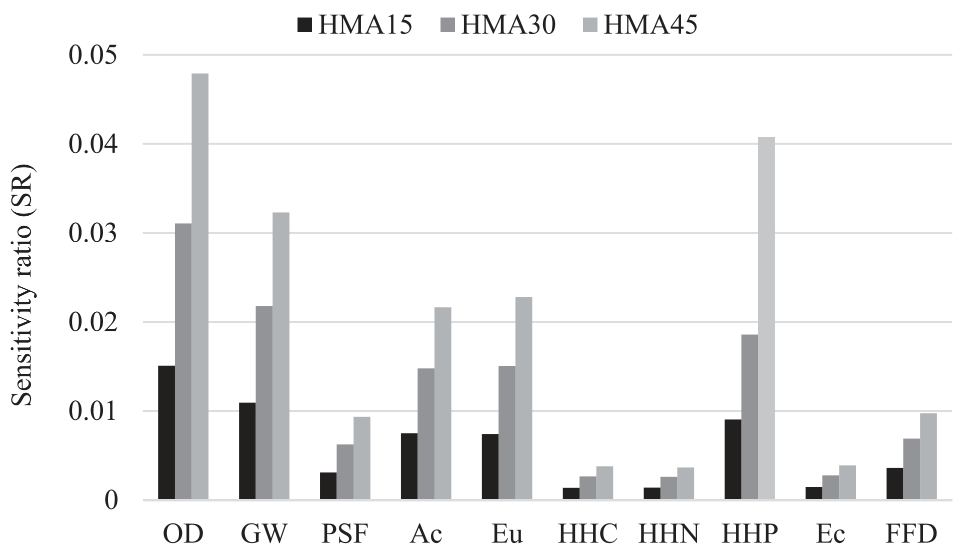

Figure 5. Sensitivity ratio results for changes in the value of the moisture content of the RCA. Acronyms: OD – ozone depletion; GW – global warming; PSF – photochemical smog formation; Ac – acidification; Eu – eutrophication; HHC – human health cancerous; HHN – human health noncancerous; HHP – human health particulate; Ec – ecotoxicity; and FFD – fossil fuel depletion.

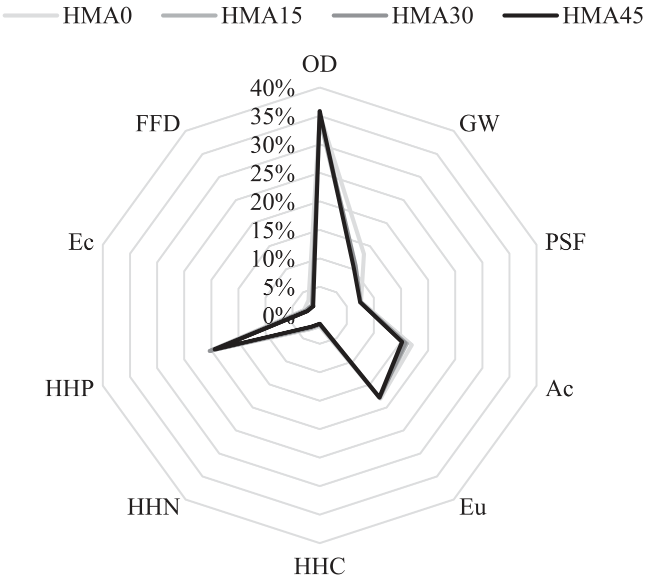

Figure 6. Relative variation of the LCIA results in relation to the baseline scenario in which the asphalt plant is run by HFO. Acronyms: OD – ozone depletion; GW – global warming; PSF – photochemical smog formation; Ac – acidification; Eu – eutrophication; HHC – human health cancerous; HHN – human health noncancerous; HHP – human health particulate; Ec – ecotoxicity; and FFD – fossil fuel depletion.

Comparison of the results with the literature

In this section, the results obtained from the case study are benchmarked with those reported by the existing literature on the LCA of the so-called eco-friendly asphalt mixtures technologies (Figure 7). Moreover, only the studies that reported the LCIA results in values are considered. The comparison focuses on the Global Warming impact category and the scores are presented per cubic metre of mixture instead of ton because the density of the mixtures is not presented in all the studies.

The analysis of the results presented in Figure 7 shows that the outcomes of the case study presented in this paper are well within the ranges reported in the literature. Specifically, they are quite similar to those referring to the calculation of the carbon footprint of the asphalt mixtures incorporating RAP. Therefore, it can be said that the findings of this case study are quite plausible given the existing differences in the system boundaries, data, assumptions and the geographical and technical contexts of all studies.

Conclusions

In order to evaluate the potential environmental effects related to the use of RCA as a replacement of NA in HMA, a comparative attributional process-based LCA study was carried out according to a ‘cradle-to-laid’ approach. The LCA was performed taking into account, as far as possible and suitable, the ISO 14044 series and the FHWA’s Pavement LCA Framework. In addition, to be as much geographical and contextual representative as possible, real data collected from Colombian contractors of the region of Barranquilla and laboratory test results were considered as the main LCI input. Three levels of RCA replacements in the coarse fraction of NA (i.e. 15, 30 and 45%) were evaluated for the asphalt binder layer of the pavement structure. Finally, the case study was modelled using the SimaPro v.8.4.0. tool and the potential environmental impacts were determined according to the TRACI v.2.1. impact assessment methodology.

Based on the conditions considered in the case study, the following conclusions can be drawn:

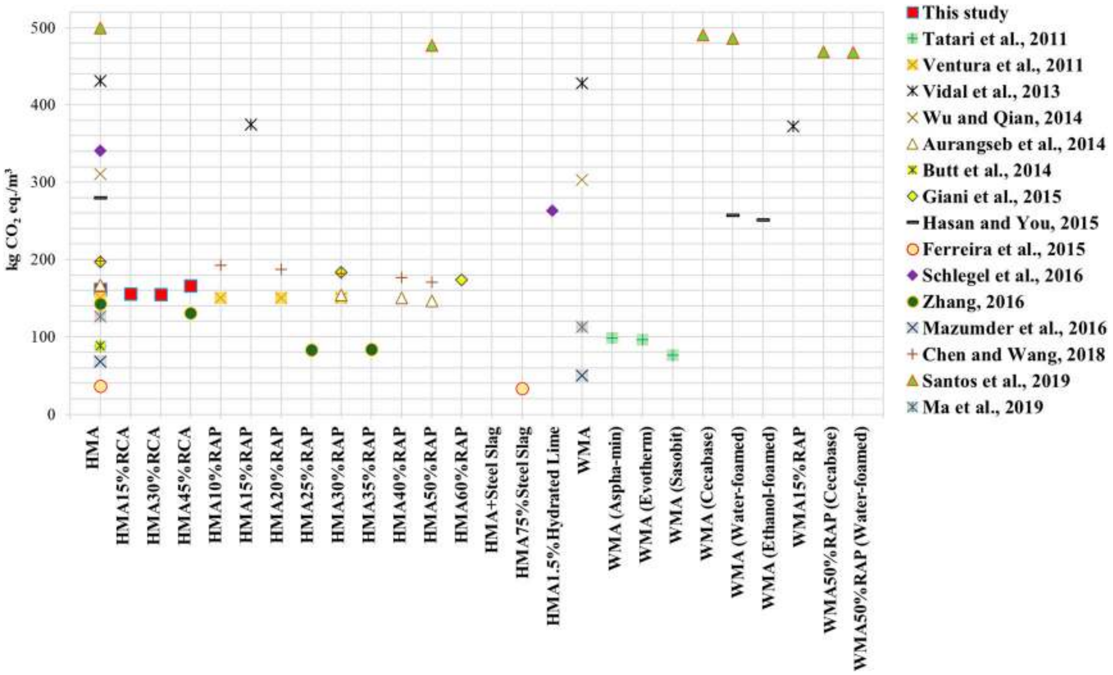

Figure 7. Global warming score of the different asphalt mixtures considered in this study compared to the scores reported by the existing literature on the LCA of the so-called eco-friendly asphalt mixtures technologies. Acronyms: HMA- hot mix asphalt; WMA- warm mix asphalt; RAP- recycled asphalt pavement.

- the mixtures HMA15 and HMA30 can be seen as eco-friendly alternatives to the conventional mixture, as both allow reductions in all impact categories scores;
- the mixture HMA45 was found to lead to an increase in the score of all impact categories in relation to the conventional mixture;
- the environmental profile of the several mixtures is mainly driven by the processes Bitumen Production, Mixtures Production and NA extraction;
- the contributions of the processes Mixture Transportation, RCA Crushing and NA loader movement to the impact category scores were found to be almost residual;
- the impact categories OD, HHP and GW are particularly affected by changes in the value of the moisture content of the RCA;
- the scores in all impact categories for all mixtures can be reduced if the asphalt plant runs on natural gas instead of HFO;
- the results of the case study presented in this paper are well within the ranges reported in the literature on the LCA of the so-called eco-friendly asphalt mixtures technologies.

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