Life Cycle Assessment of Warm Mix Asphalt with Recycled Concrete Aggregate

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Abstract. Life-cycle assessment (LCA) is a systematic methodology used to assess the potential environmental impacts associated with all the stages of a product or system. Generally, the LCA is performed for all stages of the evaluated product; nevertheless, based on the goal and scope of an LCA study, several phases may be considered, whereas others may be excluded. In this study, an LCA was conducted to evaluate the potential environmental benefits related to the use of recycled concrete aggregates (RCA) as a partial replacement of natural aggregates in the production of Warm Mix Asphalt (WMA). In order to estimate the potential environmental impacts associated with the use of these alternative resources in the construction and rehabilitation of road pavements in Barranquilla, Colombia, primary data were collected in some companies in the region. 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 characterized during life cycle impact assessment (LCIA) phase into potential impacts according to the impact assessment methodology TRACI v.2.1. The pavement life cycle phases and processes included within the system boundaries were the following: (1) extraction and processing of natural and recycled aggregates and production of asphalt binder, (2) transportation of materials, and (3) production of the asphalt mixtures. Three percentages of RCA replacements were analyzed:15, 30 and 45%. By comparing both asphalt mixtures with different RCA replacements levels, it was shown that RCA use implies an increase in the optimal asphalt content, which in turn, originates higher potential environmental impacts than those stemming from conventional mixtures.

1. Introduction

Life Cycle Analysis (LCA) is a systematic methodology intended to evaluate the potential environmental impacts of a product or system by accounting for the environmental exchanges (e.g. emissions, consumption of raw materials, energy, etc.) throughout the life cycle of a product, service or system [1]. Generally, the LCA is performed for all stages of the evaluated product; that is, from the acquisition of the raw material, through production, construction, use and maintenance, and ending with the final disposal at the end of its useful life. This technique is based on the ISO 14044 (2006) "Environmental Management-Life Cycle Assessment-Requirements and Guidelines" [2] and consists of four phases for: 1) goal and scope definition, 2) life cycle inventory analysis (LCI), 3) life cycle impact assessment (LCIA) and 4) interpretation. Based on the goal and scope of an LCA study, several phases may be considered, whereas others may be excluded. In addition, the comprehensiveness of the study is constrained by the availability of the data needed to model each stage/phase. Figure 1 displays the main life cycle system boundaries considered in an LCA.

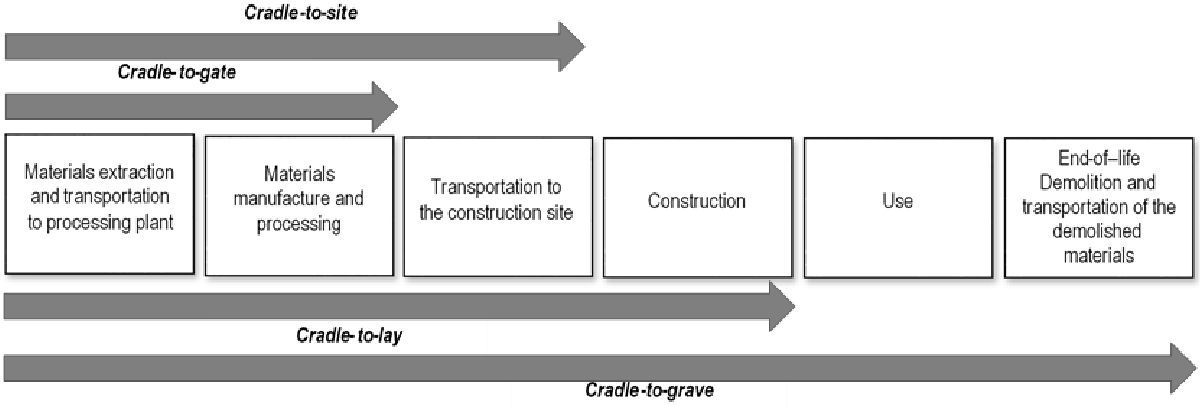


Figure 1. Main life cycle system boundaries considered in an LCA [3].

Due to the well-known consequences of the pavements materials production (asphalt binders, aggregates, additives, etc.) to the environment and human health, governments and paving industry have increased the interest in estimating the related environmental burdens of road pavements systems [4]. In that sense, the paving industry has been encouraged to use the often-called eco-friendly materials (e.g. recycled materials, etc.) in the construction and rehabilitation of highway infrastructures [5]–[7], Among these technologies, the use of Warm Mix Asphalt (WMA) have gained recognition in different countries [8]–[10]. WMA represents a broad range of technologies used to reduce the mixing temperature, allowing the mixture to stay workable and compactable at lower temperatures [15]. These techniques usually reduce the mixing temperature in a range of 20 to 40 °C, comparatively to that of the HMA [10], [11]. Depending on its production technique [10], [12], [13], it might be associated with mechanical, functional and environmental advantages as well as drawbacks [11], [14]. The most used technologies involve the use of organic additives, chemical additives, foaming processes with water and foaming processes with natural or synthetic additives [11], [12]. In general, when a WMA is applied, a reduction of up to 15% in the potential negative environmental impacts can be achieved [4], [10], [13]. Table 1 provides an overview of the reduction of airborne substances released during the production of WMA. As it can be noticed, WMA allows for significant reductions in emissions of carbon dioxide (CO2), sulfur dioxide (SO2), carbon monoxide (CO), nitrogen oxides (NOx), Polycyclic Aromatic Hydrocarbons (PAH), Volatile Organic Compounds (VOC) and dust.

Table 1. Percentual reduction of airborne substances released during the production of WMA.

Pollutant/ Substance	**D' Angelo et al. (2008)** [10]		**Vaitkus et al. (2009a)** [14]	**Vaitkus et al. (2009b)** [15]	**EAPA (2010)** [12]	**Zaumanis 2010** [16]	**Hassan (2010)** [13]	**Sargand et al. (2012)** [17]
	Norway	**Italy**						
CO_2	31.5	30-40	30-40	15-40	20-40	35	15-40	-
SO_2	-	35	35	20-35	20-35	25	20-35	83.3
CO	28.5	oct-30	oct-30	oct-30	oct-30	8	oct-30	63.2
NOx	61.5	60-70	60-70	60-70	60-70	60	60-70	21.2
PAH	30-50 (Germany)		-	-	30-50	-	-	-
VOC	-	50	50	<50	<50	50	<50	51.3
Dust	54	25-55	20-25	25-55	-	25-30	-	-

In terms of mechanical behavior, WMA exhibits similar performance to HMA in some properties [18]. For instance, resistance to moisture damage has been reported as superior to that of conventional mixtures mainly due to antistripping agents contained in several WMA additive families. In the same way, during the last two decades a consistent interest on the use of recycled aggregate has been raised, as well as the feasibility to properly replace partially/completely naturals aggregates (NA), both in HMA and Portland Cement Concrete (PCC) [9], [19]. Reclaimed asphalt pavement (RAP) has been one of the most studied materials when trying to reduce the use of NA in the HMA applied in different pavement layers [20], [21]. In addition to RAP, one of the materials with a high potential to replace NA in asphalt mixtures and PCC is the Recycled concrete aggregate (RCA). RCA is produced by crushing old concrete from sidewalks, pavements and curbing and building slabs into smaller pieces. Given its characteristics, it has shown a good performance as a replacement in the granular matrix of the mixtures [22], [23]. In general, the literature shows promising results in the performance of asphalt mixtures [19], [21], [22] when RCA is incorporated in their formulation. However, the extent to which the use of RCA in the formulation of WMA has the potential to further enhance its environmental performance was still barely studied. Therefore, this research works aims at evaluating the potential environmental impacts related to the production of WMA with RCA as a partial replacement of NA, by means of an LCA study.

2. Methodology

A comparative attributional process-based LCA study was carried out according to a cradle-to-gate approach, and taking into account, as far as possible and suitable, the ISO 14040 series [2] and the Federal Highway Administration's (FHWA's) Pavement LCA Framework [3]. It started with the goal and scope definition and was followed by inventory analysis, LCIA, and interpretation. The software SimaPro version 8.4.0 was used for modelling the processes analyzed in this case study.

2.1. Goal and scope definition

2.1.1. Goal. The main objective of this research study was to estimate the potential environmental impacts related to the production of WMA with several RCA contents. Therefore, a conventional HMA without RCA content (control mixture) was compared to three alternative WMA, in which the percentage (in terms of weight) of NA in the mixture formulation was respectively replaced by three percentages of RCA: 15, 30 and 45%.

2.1.2. Scope.
2.1.2.1. System description and boundaries. As was mentioned above, the analysis was carried out using a cradle-to-gate approach. The systems boundaries included three pavement life cycle phases: 1) the extraction and transportation of raw materials to the mixing plant; and 2) mixtures production at the mixing plant. For this study, the mixtures transportation to construction site was not taking into account because this process is the same for all the mixtures evaluated. Figure 2 presents the system boundaries and processes included in the study.

2.1.2.2. Functional unit. The functional unit is the basis for all the comparisons that can be made based on LCA results [4]. Taking into account the goal and scope of this research study, the functional unit was defined as 1 ton of asphalt mixture produced in 2019, in Barranquilla, Colombia, suitable for application in the surface layer of a flexible pavement structure.

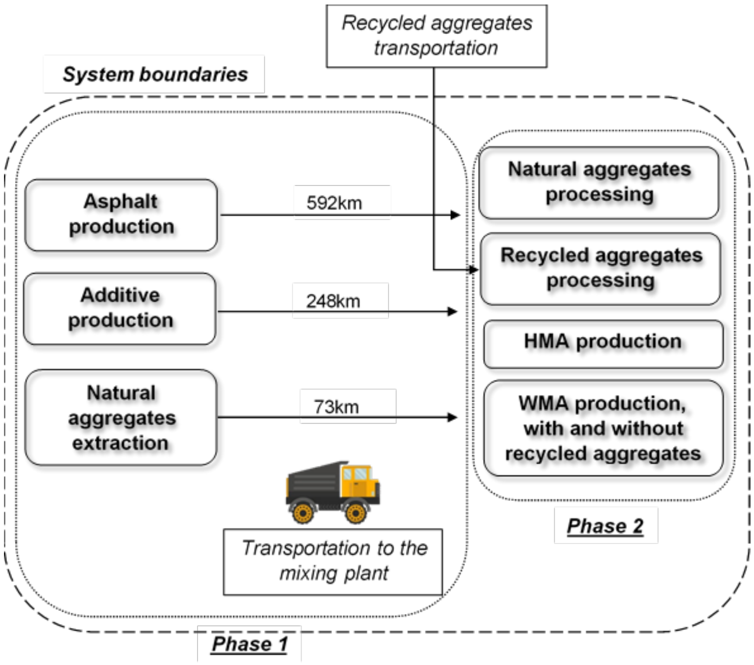


Figure 2. System boundaries considered in the case study.

2.1.2.3. Case study features. In terms of the composition of the mixtures, tests carried out in the laboratory were considered for the purpose of determining the proportions of the several components (Table 2). In table 2, the mixtures are identified according to the key "XY", where "X" represents the type of mixture (i.e. HMA or WMA) and "Y" the percentage of RCA (i.e., 0, 15, 30 or 45%).

Table 2. Composition and characteristics of the mixtures.

Item	Type of mixture				
	HMA0	WMA0	WMA15	WMA30	WMA45
Natural Aggregate					
Quantity (%/m[1])	95.6	95.6	88.3	80.9	73.5
Absorption (%)			3		
Recycled Concrete Aggregate					
Quantity (%/m)	-	-	7.2	14.3	21.3
Absorption (%)			3		
Asphalt					
Quantity (%/m)	4.4	4.4	4.5	4.8	5.2
WMA additive					
Type	-	Chemical			
Quantity (%/Am[2])	-	0.3			

[1] Percentage of total mixture mass
[2] Percentage of asphalt mass

All mixtures contain 50% of coarse aggregates and 50% of fine aggregates. The RCA replacements were made only in the fraction corresponding to the coarse aggregates. Also, all samples contain 4% air voids and satisfy the Colombian standards for road materials [24].

2.1.2.4. Data sources. In order to be as much representative of the geographical context as possible, primary data collected from surveys carried out in some companies in the region was privileged over secondary data collected from commercial databases (e.g. ecoinvent v.3) and literature. Specifically, four different asphalt mixing plants were examined and based on the information available, the relevant data was selected.

2.2. Life Cycle Inventory (LCI)

The data collected during the surveys corresponds to general information related to the operation of the asphalt mixing plants, consumptions of the equipment (fuel and lubricant, mainly) and specific processes referring to each material (aggregates, bitumen and additives). Nevertheless, it was necessary to use other sources of data for modelling some of the processes analyzed. Table 3 presents the primary data considered in the case study.

Table 3. Primary data considered in the case study.

Item	Diesel [gal/ton]	Lubricant [g/ton]	Electricity [kWh/ton]	Water [kg/ton]
Natural Aggregates				
Extraction [25]	1,85	20	-	-
Load to the dump truck [25]	1,85	20	-	-
Transportation to the mixing plant	0,56	9,42	-	-
Processing [25]	0,075	0,69	2,33	100
Recycled Concrete Aggregates				
Crushing	0,075	0,69	2,33	100
Asphalt				
Transportation to the mixing plant	4,17	70,66	-	-
Additive				
Transportation to the mixing plant	1,94	32,95	-	-
Mixture	**HMA**	**WMA**	-	-
Production temperature (°C)	160	120		
Asphalt mixing plant	0,2	**Land occupation [m^2]**	**Type**	-
		2,33	Continuous	

In the case of bitumen and additive, all inputs were taken from the ecoinvent v.3 database. The quantity of thermal energy provided by Heavy Fuel Oil (HFO) to produce the asphalt mixtures was determined according to the energy balance proposed by Santos et al. [4].

2.3. Life Cycle Impact Assessment (LCIA)

LCIA was performed using the TRACI v.2.1 methodology. It assesses the potential environmental impacts according to ten impact categories: 1) ozone depletion, 2) global warming, 3) photochemical smog formation, 4) acidification, 5) eutrophication, 6) human health cancer, 7) human health noncancer, 8) human health particulate, 9) ecotoxicity, and 10) fossil fuel depletion. These impact categories estimate the potential damage to: 1) human health, 2) ecosystem diversity, and 3) resource availability [9].

3. Results and discussions

Table 3 provides the energy required, in kg of HFO, to produce 1 ton of each mixture studied. The Emission Factors (EF) represent the reduction of fuel consumption (FC) between WMA and HMA. Those results are consistent with those reported in literature concerning European practices [10]. In fact, European studies found reductions of FC ranging between 11 to 35%. Moreover, Table 3 also shows that the replacement of coarse aggregate by RCA originates slight reductions of FC. It is worth highlighting, however, that the data used to calculate the energy consumption was obtained from representative asphalt plants in Barranquilla, Colombia.

Table 4. Thermal Energy [TE] consumed for producing each type of mixture.

Mixture	TE [MJ/ton mixture]	FC [Kg HFO/ton mixture]	EF [%]
HMA0	241,35	5,72	-
WMA0	202,75	4,81	20,49
WMA15	202,19	4,79	20,71
WMA30	201,96	4,79	20,8
WMA45	201,89	4,79	20,82

The results referring to the potential environmental impacts are shown in Table 4. Apart from the impact category ozone depletion, the results displayed in that table show that the potential environmental impacts are not only likely to increase as the RCA percentage in the WMA increases, but also to be greater than those associated with the control mixture. Such as an outcome can be justified by the fact that the benefits stemming from energy savings related to the use of RCA are offset by the consequences of a higher consumption of asphalt and additive when RCA is considered in the formulation of the mixtures.

Table 5. Results per impact category for each type of mixture.

Impact category	Unit	Type of mixture				
		HMA0	WMA0	WMA15	WMA30	WMA45
Ozone depletion	kg CFC-11 eq	5,21E-06	4,50E-06	4,50E-06	4,50E-06	4,51E-06
Global warming	kg CO2 eq	2,48E+03	2,48E+03	2,53E+03	2,68E+03	2,89E+03
Smog	kg O3 eq	1,02E+03	1,02E+03	1,04E+03	1,11E+03	1,20E+03
Acidification	kg SO2 eq	32,360	32,401	33,069	35,172	37,995
Eutrophication	kg N eq	1,938	1,942	1,983	2,108	2,277
Carcinogenics	CTUh	3,70E-05	3,71E-05	3,78E-05	4,02E-05	4,34E-05
Non carcinogenics	CTUh	3,54E-04	3,54E-04	3,62E-04	3,85E-04	4,16E-04
Respiratory effects	kg PM2.5 eq	0,779	0,781	0,795	0,838	0,896
Ecotoxicity	CTUe	6,83E+03	6,84E+03	6,98E+03	7,43E+03	8,03E+03
Fossil fuel depletion	MJ surplus	5,16E+03	5,16E+03	5,27E+03	5,60E+03	6,05E+03

In order to perform an evaluation of the contribution of each impact category to the total global damage, the results obtained for each type of mixture were normalized using the latest TRACI normalization factors (although for the USA), measured for the year 2008 (Figure 3) [26]. A normalized impact value represents the number of average American individuals who produces the same quantity of impact every year. From the analysis of Figure 3 it can be observed that the impact categories carcinogenic, eco-toxicity, smog and non-carcinogenic present, respectively, the highest normalized scores.

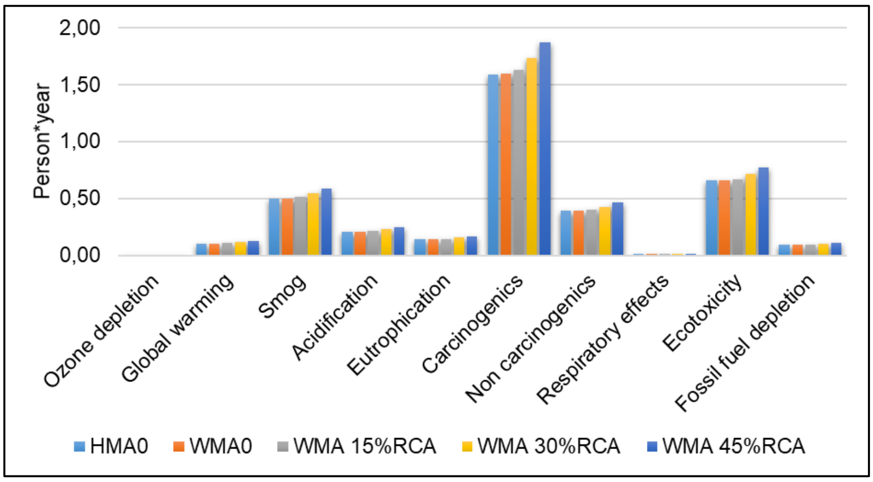
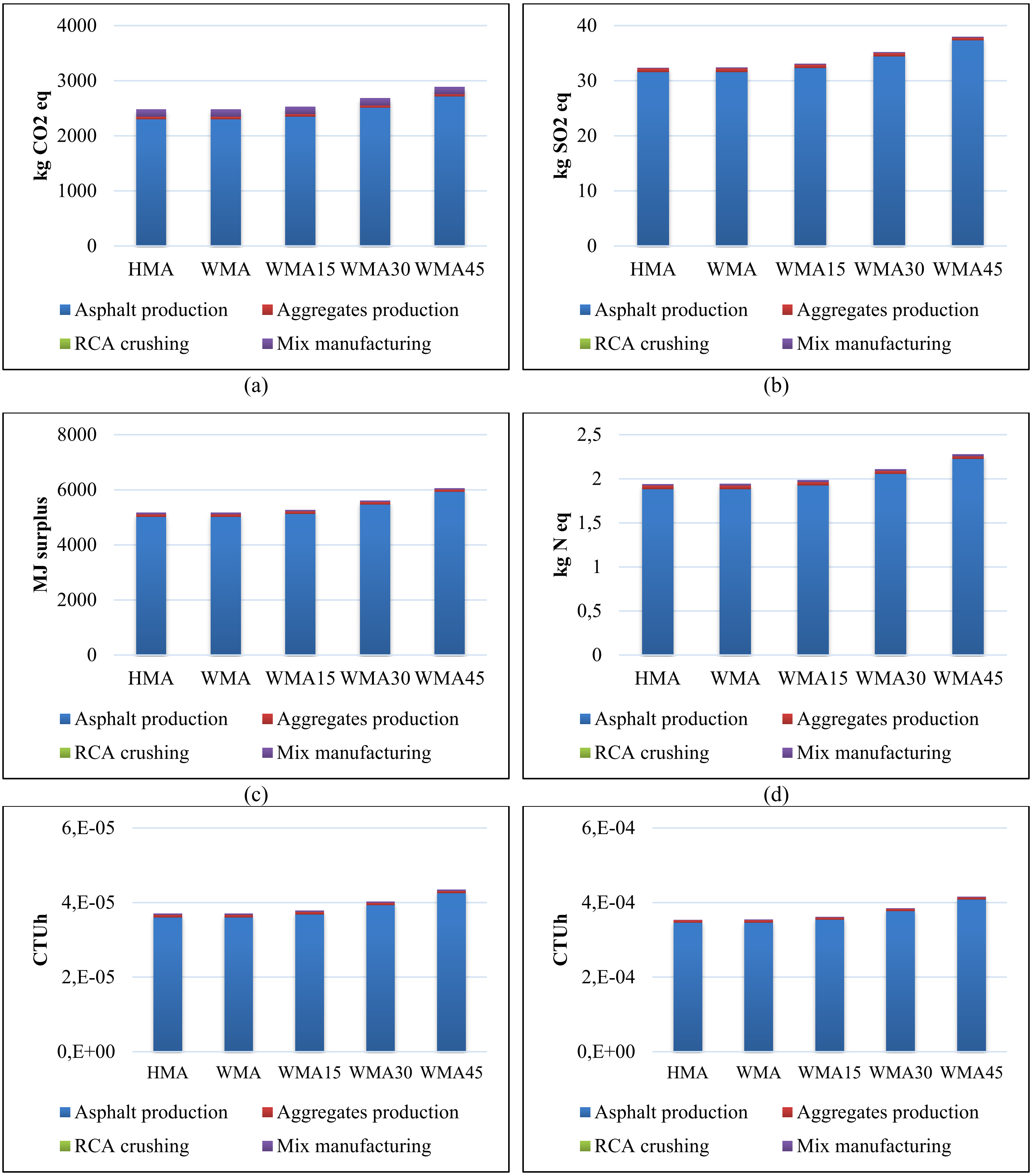


Figure 3. Normalized impact category scores.

When analyzing the contribution of each process to the impact categories (a) global warming, (b) acidification, (c) fossil fuel depletion, (d) eutrophication, (e) carcinogenics, and (f) non carcinogenics, Figure 4 shows that the production of asphalt is by far the process that contributes the most to the impact indicator scores. Its contribution contrasts with that of the process RCA crushing that was found to be almost neglectable.



(a) (b)

(c) (d)

(e) (f)

Figure 4 Contribution of each process, per mixture, to the potential scores of the impact categories (a) global warming, (b) acidification, (c) fossil fuel depletion, (d) eutrophication, (e) carcinogenics and (f) non carcinogenics.

Finally, it should be mentioned that the system boundaries of the LCA study performed do not include the construction, use and EOL phases of the pavement life cycle. Thus, depending on the mechanical performance during the life cycle as well as the pavement maintenance program adopted, the potential relative life cycle environmental impacts related to the use of WMA technologies might be different from those found in this study.

4. Conclusions

A comparative LCA analysis was performed considering a control mix (HMA) and several WMA where the coarse aggregates were replaced by RCA according to three replacements percentages. The LCA was modeled with SimaPro 8.4.0 software and the potential environmental impacts determined according to the TRACI v2.1 impact assessment methodology.

For the conditions considered in this study, the main conclusion that can be drawn pertains to the fact that WMA with different levels of RCA are likely to originate higher potential environmental impacts than those stemming from conventional mixtures, as a consequence of the increase in the optimal asphalt content.

In the near future, the next steps of this research work will address the assessment of the consequences related to the consideration of different hauling distances, aggregates moisture and production temperature of the mixtures on the stability of the results presented in this paper.

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References

[1] Butera, S., Christensen, T. H., & Astrup, T. F. (2015). Life cycle assessment of construction and demolition waste management. *Waste Management*, *44*, 196-205.

[2] International Organization for Standardisation, “IS/ISO 14044 (2006): Environmental Management-Life Cycle Assessment-Requirements and Guidelines,” *Iso 14044*, 2006

[3] Harvey, J. T., Meijer, J., Ozer, H., Al-Qadi, I. L., Saboori, A., & Kendall, A. (2016). *Pavement Life-Cycle Assessment Framework* (No. FHWA-HIF-16-014).

[4] Santos, J., Bressi, S., Cerezo, V., Presti, D. L., & Dauvergne, M. (2018). Life cycle assessment of low temperature asphalt mixtures for road pavement surfaces: A comparative analysis. *Resources, Conservation and Recycling*, *138*, 283-297.

[5] Turk, J., Cotič, Z., Mladenovič, A., & Šajna, A. (2015). Environmental evaluation of green concretes versus conventional concrete by means of LCA. *Waste management*, *45*, 194-205.

[6] Rosado, L. P., Vitale, P., Penteado, C. S. G., & Arena, U. (2017). Life cycle assessment of natural and mixed recycled aggregate production in Brazil. *Journal of cleaner production*, *151*, 634-642.

[7] Santos, J., Bressi, S., Cerezo, V., & Presti, D. L. (2019). SUP&R DSS: A sustainability-based decision support system for road pavements. *Journal of Cleaner Production*, *206*, 524-540.

[8] S. Wu and S. Qian, “Comparison of Warm Mix Asphalt and Hot Mix Asphalt Pavement Based on Life Cycle Assessment,” pp. 87–96, 2015.

[9] Vidal, R., Moliner, E., Martínez, G., & Rubio, M. C. (2013). Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement. *Resources, Conservation and Recycling*, *74*, 101-114.

[10] D'Angelo, J. A., Harm, E. E., Bartoszek, J. C., Baumgardner, G. L., Corrigan, M. R., Cowsert, J. E., ... & Prowell, B. D. (2008). *Warm-mix asphalt: European practice* (No. FHWA-PL-08-007).

[11] Rubio, M. C., Martínez, G., Baena, L., & Moreno, F. (2012). Warm mix asphalt: an

overview. *Journal of Cleaner Production*, *24*, 76-84.
[12] EAPA, “The Use of Warm Mix Asphalt,” *Masterbuilder.Co.in*, no. January, pp. 1–13, 2010.
[13] Hassan, M. (2009). Life-cycle assessment of warm-mix asphalt: an environmental and economic perspective. *Lousiana Univerty, Civil Engineering Class*.
[14] Vaitkus, A., Cygas, D., Laurinavicius, A., & Perveneckas, Z. (2009). Analysis and evaluation of possibilities for the use of warm mix asphalt in Lithuania. *The Baltic Journal of Road and Bridge Engineering*, *4*(2), 80-80.
[15] Vaitkus, A., Vorobjovas, V., & Ziliut, L. (2009, August). The research on the use of warm mix asphalt for asphalt pavement structures. In *XXVII International Baltic Road Conference* (pp. 24-26).
[16] Zaumanis, M. (2010). Warm mix asphalt investigation. Master of science thesis. Kgs. Lyngby: Technical University of Denmark in cooperation with the Danish Road Institute, Department of Civil Engineering.
[17] Sargand, S., Nazzal, M. D., Al-Rawashdeh, A., & Powers, D. (2011). Field evaluation of warm-mix asphalt technologies. *Journal of Materials in Civil Engineering*, *24*(11), 1343-1349.
[18] Chowdhury, A., & Button, J. W. (2008). *A review of warm mix asphalt* (No. SWUTC/08/473700-00080-1). College Station, TX: Texas Transportation Institute, the Texas A & M University System.
[19] Wang, H., Liu, X., Apostolidis, P., & Scarpas, T. (2018). Review of warm mix rubberized asphalt concrete: Towards a sustainable paving technology. *Journal of Cleaner Production*, *177*, 302-314.
[20] Farooq, M. A., Mir, M. S., & Sharma, A. (2018). Laboratory study on use of RAP in WMA pavements using rejuvenator. *Construction and Building Materials*, *168*, 61-72.
[21] Xiao, F., Hou, X., Amirkhanian, S., & Kim, K. W. (2016). Superpave evaluation of higher RAP contents using WMA technologies. *Construction and Building Materials*, *112*, 1080-1087.
[22] Zulkati, A., Wong, Y. D., & Sun, D. D. (2012). Mechanistic performance of asphalt-concrete mixture incorporating coarse recycled concrete aggregate. *Journal of Materials in Civil Engineering*, *25*(9), 1299-1305.
[23] Martinez, G., Dugarte, M., Fuentes, L., Sanchez, E., Rondón, H., Pacheco, C., Yepes, J., & Lagares, R. (2019). Characterization of recycled concrete aggregate as potential replacement of natural aggregate in asphalt pavement. IOP *Conf. Ser.: Meter. Sci. Eng. 471 102045*
[24] INVIAS, I. (2013). Especificaciones Generales de Construcción de carreteras. INV ARTICULO 450-13, MEZCLAS ASFÁLTICAS EN CALIENTE DE GRADACIÓN CONTINUA (CONCRETO ASFÁLTICO).
[25] Martinez, G., Acosta, M. P., Dugarte, M., Fuentes, L. (2018) Life cycle assessment of natural and recycled concrete aggregate production for road pavements applications in the Northern region of Colombia : Case study. *TRB Conference 2019, Washintong.*
[26] Ryberg M, Vieira MDM, Zgola M, Bare J, Rosenbaum RK (2014) Updated US and Canadian normalization factors for TRACI 2.1. Clean Techn Environ Policy 16(2):329–339