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].](image)

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] | Vaikus et al. (2009a) [14] | Vaikus et al. (2009b) [15] | EAPA (2010) [12] | Zaumans 2010 [16] | Hassan (2010) [13] | Sargand et al. (2012) [17] |
|--------------------|-----------------------------|-----------------------------|-----------------------------|-------------------|-----------------|-------------------|-----------------------------|
| CO2                | 31.5 (Norway) 30-40 (Italy) | 30-40 (Italy)               | 15-40 (Italy)               | 20-40 (Italy)     | 35              | 15-40 (Italy)     | -                          |
| SO2                | - (Italy)                  | 35                          | 20-35 (Italy)               | 20-35 (Italy)     | 25              | 20-35 (Italy)     | 83.3 (Italy)               |
| CO                 | 28.5 (Italy)               | oct-30                      | oct-30                      | oct-30 (Italy)    | 8               | oct-30 (Italy)    | 63.2 (Ireland)             |
| NOx                | 61.5 (Italy)               | 60-70                       | 60-70                       | 60-70 (Italy)     | 60              | 60-70 (Italy)     | 21.2 (Italy)               |
| PAH                | 30-50 (Germany)            | -                           | -                           | 30-50 (Italy)     | -               | -                 | -                          |
| VOC                | - (Italy)                  | 50                          | <50                         | <50 (Italy)       | 50              | <50 (Italy)       | 51.3 (Italy)               |
| Dust               | 54                         | 25-55                       | 20-25                       | 25-55 (Italy)     | -               | 25-30 (Italy)     | - (Italy)                  |
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.
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)            | 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 | 0.3 |

1Percentage of total mixture mass
2Percentage 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.

| 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**                                    |                  |                   |                       |               |
| Production temperature (°C)                    | 160              | 120               | -                     | -             |
| **Asphalt mixing plant**                       |                  |                   |                       |               |
| Land occupation [m²]                           | 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.

| 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 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       | 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) carcinogenic, and (f) non carcinogenic, 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.
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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