Carbon footprint of asphalt road pavements using Warm Mix Asphalt with Recycled Concrete Aggregates: A Colombian case study

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Content

- Background and Motivation
- Objective
- Methodology
  - Scope and Case Study
- Results and Discussion
- Conclusions
Background and Motivation

• COLOMBIA - Location
Background and Motivation

- Literature shows that recycling practices on Recycling Concrete Aggregate (RCA) and related environmental/mechanical assessments in Developing Countries are limited.

- Recycling, not only preserve sources (virgin materials) and reduces cost, also contributes to the reduction of wasted material stocking.

- Global consumption of NA exceeds 15 billions per year.

- The U.S consumption of aggregate in construction is more than 2 billion tons annually and an estimate of recycled concrete is about 5%(100 millions tons).

FHWA, Pasandin 2014, U.S. Geological Survey (USGS)
Background and Motivation

Recycled Concrete Aggregates, RCA

- Increasing interest on RCA to replace partially/completely naturals aggregates (NA) in HMA or WMA.

- RCA is produced by crushing old concrete from sidewalks, pavements and curbing and building slabs into smaller pieces.

- Performance evaluation of asphalt mixtures when RCA is incorporated and its environmental impacts is limited.

Background and Motivation

Recycled Concrete Aggregates, RCA

State Transportation Agencies were surveyed to determine their use of recycled concrete aggregate.

https://www.fhwa.dot.gov/pavement/recycling/rca.cfm
Background and Motivation

Warm Mix Asphalt, WMA

- WMA represents a broad range of technologies used to reduce the mixing temperature (20 to 40 °C lower vs. HMA) by using organic additives, chemical additives, foaming processes with water or additives.

- Reduction up to 15% in the potential negative environmental impacts can be achieved with WMA. (CO₂, SO₂, CO, NOₓ, PAH, VOC and dust).

- WMA exhibits similar performance to HMA. Resistance to moisture damage could be increased due to antistripping agents contained in several additives.

Fuente: www.fhwa.dot.gov/innovation

Objectives

• The main goal of this study was to estimate the potential environmental benefits, expressed as CO₂ equivalent emissions, related to the production of WMA with several RCA contents, namely 15, 30 and 45%.
Methodology

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

• the ISO 14067 standards “Greenhouse gases- Carbon footprint of products- Requirements and guidelines for quantification and communication” (ISO 2013)
### 2.1. System description and boundaries

<table>
<thead>
<tr>
<th>Pavement life cycle phase</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material production and transportation to the mixing plant</td>
<td>NA extraction</td>
</tr>
<tr>
<td></td>
<td>NA load movements and transportation</td>
</tr>
<tr>
<td></td>
<td>Asphalt production</td>
</tr>
<tr>
<td></td>
<td>Asphalt transportation</td>
</tr>
<tr>
<td></td>
<td>Additive production</td>
</tr>
<tr>
<td></td>
<td>Additive transportation</td>
</tr>
<tr>
<td>Materials processing and mixtures production at the mixing plant</td>
<td>NA processing</td>
</tr>
<tr>
<td></td>
<td>RCA crushing</td>
</tr>
<tr>
<td></td>
<td>Mixtures production</td>
</tr>
<tr>
<td>Mixtures transportation to the construction site</td>
<td>Mixtures transportation</td>
</tr>
<tr>
<td>Pavement construction</td>
<td>Finisher operation</td>
</tr>
<tr>
<td></td>
<td>Vibratory roller operation</td>
</tr>
<tr>
<td></td>
<td>Pneumatic roller operation</td>
</tr>
</tbody>
</table>

- The “cut-off” allocation methodology was adopted for dealing with the RCA.
- That means that the environmental impacts associated with the pavement demolition and the transportation of the recycled materials were not included in the system boundaries.
- Thus, only the burdens related to RCA processing were considered in the study.
Methodology

**Functional unit:**

In this case study it was defined as a typical Colombian highway section, **with 1km in length and 1 lane 3.5m wide.**

They were designed for a traffic of $5 \times 10^6$ Equivalent Single Axle Load (ESAL) of 80kN, a CBR of 7.5% and a service life of 10 years.

**Functional unit:** In the pavement domain, this means a unit of pavement that can safely and efficiently support the same volume of traffic over the same project analysis period.
Methodology

Life cycle inventory:

Pavement design

Table 2. Pavement design for each type of mixture.

<table>
<thead>
<tr>
<th>Type of mixture</th>
<th>Asphalt layers</th>
<th>Granular layers</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC 4cm</td>
<td>4.0</td>
<td>15.0</td>
<td>47.0</td>
</tr>
<tr>
<td>BC 6cm</td>
<td>6.0</td>
<td>15.0</td>
<td>47.0</td>
</tr>
<tr>
<td>BC-G 15cm</td>
<td>4.0</td>
<td>15.0</td>
<td>48.0</td>
</tr>
<tr>
<td>SBC-G 22cm</td>
<td>4.0</td>
<td>15.0</td>
<td>48.0</td>
</tr>
</tbody>
</table>

Table 2. Pavement design for each type of mixture.

<table>
<thead>
<tr>
<th>Item</th>
<th>Mixture 0</th>
<th>Mixture 1</th>
<th>Mixture 2</th>
<th>Mixture 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Aggregate Quantity (%)</td>
<td>95.6</td>
<td>88.3</td>
<td>80.9</td>
<td>73.5</td>
</tr>
<tr>
<td>Absorption (%)</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recycled Concrete Aggregate Quantity (%)</td>
<td>-</td>
<td>15</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Bitumen Quantity (%)</td>
<td>4.4</td>
<td>4.5</td>
<td>4.8</td>
<td>5.2</td>
</tr>
<tr>
<td>Additive Type</td>
<td>Chemical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additive Quantity (%)</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Properties Density (kg/m³)</td>
<td>2366</td>
<td>2310</td>
<td>2305</td>
<td>2289</td>
</tr>
<tr>
<td>Air voids (%)</td>
<td>4.3</td>
<td>4.8</td>
<td>4.6</td>
<td>4.8</td>
</tr>
<tr>
<td>Voids filled with asphalt (%)</td>
<td>66.6</td>
<td>66.5</td>
<td>67.2</td>
<td>66.0</td>
</tr>
<tr>
<td>Voids in the mineral aggregates (%)</td>
<td>12.7</td>
<td>14.2</td>
<td>13.9</td>
<td>14.2</td>
</tr>
<tr>
<td>Stability (kN)</td>
<td>17.2</td>
<td>14.8</td>
<td>16.7</td>
<td>20.1</td>
</tr>
<tr>
<td>Flows (mm)</td>
<td>2.9</td>
<td>2.7</td>
<td>2.0</td>
<td>3.4</td>
</tr>
<tr>
<td>Resilient modulus (MPa)</td>
<td>1633</td>
<td>1501</td>
<td>1372</td>
<td>1374</td>
</tr>
</tbody>
</table>
# Methodology

## Life cycle inventory:

<table>
<thead>
<tr>
<th>Pavement LCA phase</th>
<th>Process</th>
<th>LCI type</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials production and transportation to the mixing plant</td>
<td>Natural Aggregates (NA) extraction</td>
<td>Primary</td>
<td>Previous investigation (Martinez-Arguelles et al. 2019)</td>
</tr>
<tr>
<td></td>
<td>NA load movements and transportation</td>
<td>Primary</td>
<td>Previous investigation (Martinez-Arguelles et al. 2019)</td>
</tr>
<tr>
<td></td>
<td>Asphalt production</td>
<td>Secondary</td>
<td>&quot;bitumen, at refinery/kg/US&quot;- USLCI database</td>
</tr>
<tr>
<td></td>
<td>Asphalt transportation</td>
<td>Primary</td>
<td>Survey data</td>
</tr>
<tr>
<td></td>
<td>Additive production</td>
<td>Secondary</td>
<td>&quot;fatty acid/market for/Alloc Def, U&quot;- Ecoinvent database</td>
</tr>
<tr>
<td></td>
<td>Additive transportation</td>
<td>Primary</td>
<td>Survey data</td>
</tr>
<tr>
<td>Materials processing and mixtures production at the mixing plant</td>
<td>NA processing</td>
<td>Primary</td>
<td>Survey data</td>
</tr>
<tr>
<td></td>
<td>RCA crushing</td>
<td>Primary</td>
<td>Survey data</td>
</tr>
<tr>
<td></td>
<td>Mixture production (binder course layer), with and without RCA replacements</td>
<td>Primary</td>
<td>Survey data</td>
</tr>
<tr>
<td>Mixture transportation to the construction site</td>
<td>Mixture transportation</td>
<td>Primary</td>
<td>Survey data</td>
</tr>
<tr>
<td>Pavement construction</td>
<td>Finisher operation</td>
<td>Secondary</td>
<td>Literature data (Thenoux &amp; Dowling 2007)</td>
</tr>
<tr>
<td></td>
<td>Vibratory roller operation</td>
<td>Secondary</td>
<td>Literature data (Thenoux &amp; Dowling 2007)</td>
</tr>
<tr>
<td></td>
<td>Pneumatic roller operation</td>
<td>Secondary</td>
<td>Literature data (Thenoux &amp; Dowling 2007)</td>
</tr>
</tbody>
</table>
Methodology

Life cycle inventory:

Input data considered in the case study.

<table>
<thead>
<tr>
<th>Item</th>
<th>Diesel (gal/ton)</th>
<th>Lubricant (gr/ton)</th>
<th>Electricity (kWh/ton)</th>
<th>Water (kg/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials production and transportation to the mixing plant phase</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Natural Aggregates</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extraction (Martinez-Arguelles et al. 2019)</td>
<td>1.85</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Load to the dump truck (Martinez-Arguelles et al. 2019)</td>
<td>1.85</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Transportation to the mixing plant</td>
<td>0.56</td>
<td>9.42</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Asphalt</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation to the mixing plant</td>
<td>4.17</td>
<td>70.66</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Additive</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation to the mixing plant</td>
<td>1.94</td>
<td>32.95</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Materials processing and mixtures production at the mixing plant phase</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Natural Aggregates</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processing (Martinez-Arguelles et al. 2019)</td>
<td>0.075</td>
<td>0.69</td>
<td>2.33</td>
<td>100</td>
</tr>
<tr>
<td><strong>Recycled Concrete Aggregates</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crushing</td>
<td>0.075</td>
<td>0.69</td>
<td>2.33</td>
<td>100</td>
</tr>
<tr>
<td><strong>Mixtures transportation to the construction site phase</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dumper</strong></td>
<td>0.072</td>
<td>1.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pavement construction phase</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Construction Equipment</strong></td>
<td>Performance (L/h)</td>
<td>Capacity (m³/h)</td>
<td>Diesel (L/m³)</td>
<td>Energy (MJ/m³)</td>
</tr>
<tr>
<td>Finisher (Thenoux &amp; Dowling 2007)</td>
<td>13</td>
<td>60</td>
<td>0.22</td>
<td>8.39</td>
</tr>
<tr>
<td>Vibratory roller (Thenoux &amp; Dowling 2007)</td>
<td>18</td>
<td>65</td>
<td>0.28</td>
<td>10.72</td>
</tr>
<tr>
<td>Pneumatic roller (Thenoux &amp; Dowling 2007)</td>
<td>16</td>
<td>65</td>
<td>0.25</td>
<td>9.53</td>
</tr>
</tbody>
</table>
Methodology

Life cycle inventory:
Input data considered in the case study.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>TE (MJ/ton mixture)</th>
<th>Fuel consumption (Kg HFO /ton mixture)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMA0</td>
<td>241.4</td>
<td>5.72</td>
</tr>
<tr>
<td>WMA0</td>
<td>202.8</td>
<td>4.81</td>
</tr>
<tr>
<td>WMA15</td>
<td>202.2</td>
<td>4.79</td>
</tr>
<tr>
<td>WMA30</td>
<td>202.0</td>
<td>4.79</td>
</tr>
<tr>
<td>WMA45</td>
<td>201.9</td>
<td>4.79</td>
</tr>
</tbody>
</table>

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

\[\begin{align*}
L_o & \quad \text{Ambient temperature} & \quad 25 \quad ^\circ\text{C} \\
L_{mix-WMA} & \quad \text{Mixing temperature of WMA with 0, 15, 30 and 45% RCA replacements} & \quad 120 \quad ^\circ\text{C} \\
C_{agg} & \quad \text{Natural aggregates specific heat}^1 & \quad 0.74 \quad \text{KJ/Kg/}^\circ\text{C} \\
W_{agg} & \quad \text{Natural aggregates water content} & \quad 3 \quad \% \text{by mass of aggregates} \\
W_{RCA} & \quad \text{RCA water content} & \quad 3 \quad \% \text{by mass of RCA} \\
C_{RCA} & \quad \text{Recycled concrete aggregates specific heat}^1 & \quad 0.74 \quad \text{KJ/Kg/}^\circ\text{C} \\
C_{water} & \quad \text{Water at 15°C specific heat} & \quad 4.19 \quad \text{KJ/Kg/}^\circ\text{C} \\
L_v & \quad \text{Water latent heat of vaporization} & \quad 2256 \quad \text{kJ/kg} \\
C_{vap} & \quad \text{Water vapor specific heat} & \quad 1.83 \quad \text{kJ/kg} \\
C_{asph} & \quad \text{Asphalt specific heat} & \quad 2.09 \quad \text{KJ/Kg/}^\circ\text{C} \\
CL & \quad \text{Casing loses factor}^2 & \quad 27 \quad \% 
\end{align*}\]

Santos et al. (2018)
Methodology

Life cycle impact assessment:

SimaPro

The LCIA, which assesses the potential carbon footprint, was performed according to the Climate Change impact category specified by the TRACI v.2.1. impact methodology.
Results

Contribution of the various processes to the total carbon footprint associated with the several asphalt mixtures implemented in the BC.

- The mixtures WMA15, WMA30 and WMA45 were found to be 8, 17 and 17% thicker than the mixture WMA0, respectively. That represents an increase in the CO2-eq emissions equal to 5 and 14%, respectively, with respect to WMA0 in the BC.

- Specifically, the production of bitumen was found to contribute up to 40% in WMA45, while for the other alternative mixtures this value dropped to approximately 35%. The mixture production was found to contribute to approximately 30% for all alternatives evaluated.
Results

Breakdown of the total CO2-eq emissions without the contribution of the processes bitumen production, mixture production and NA extraction.

- **Pavement construction** and **NA crushing** are the processes that contribute most to the total CO2-eq emissions generated for each alternative mixture studied.
- Regarding **Pavement construction**, its contribution can represent around **53% of the total CO2-eq emissions** for all WMA mixtures.
- The process **NA crushing** was found to contribute **between 11% (WMA45) and 14% (WMA0)** of the total carbon footprint.
Conclusions

Based on the results obtained, the following points are worth highlighting:

✓ The use of RCA is likely to increase the optimum bitumen content and, therefore, the additive content up to 18% (for WMA45);

✓ Mixtures with RCA contents were found to show a lower performance than that of the control mixture, which translates into an increase in the thickness of the layer obtained from the pavement design;

✓ According to the conditions of the study, the bitumen production, mixture production and NA extraction were found to be the processes that contributed most to the carbon footprint of the analyzed mixtures;

✓ Finally, it can be concluded that the use of RCA in WMA is likely not to be an environmentally friendly solution, if the mixtures with RCA require greater bitumen content and show a lower performance than the control mixture.
The authors wish to acknowledge to the Colombian Department of Science, Technology and Innovation - Colciencias, and the Universidad del Norte for sponsoring this research.

The authors also thanks to the Company A Construir S.A for providing the concrete waste and to the Company Ingecost for providing the natural aggregates and perform the crushing process to obtain the RCAs.

Thanks!