Manuscript



**Title**

# Comprehensive analysis of the environmental impact of electric arc furnace steel slag in asphalt mixtures

**Authors**

Lizasoain-Arteaga, Esther[1]*; Lastra-González, Pedro[1]; Indacoechea-Vega, Irune[1]; Flintsch, Gerardo[2]

**Affiliations**

[1]GITECO Research Group, Universidad de Cantabria, Av. de los Castros 44, 39005, Santander, Spain

[2]Center for Sustainable Transportation Infrastructure, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

**Email addresses**

lizasoaine@unican.es (E. Lizasoain-Arteaga); pedro.lastragonzalez@unican.es (P. Lastra-González); indacoecheai@unican.es (I. Indacoechea-Vega); flintsch@vt.edu (G. Flintsch)

*Corresponding author. Tel +34942203943; Fax: +34942201703

**Total words 7290**

**Abstract**

This paper analyses the environmental impact of replacing high quality coarse aggregates by electric arc furnace (EAF) steel slag. A Life Cycle Analysis (LCA) was performed on three asphalt mixtures containing different aggregates: namely ophite, slag 1 and slag 2. The inventory gaps were filled by performing several laboratory tests and applying theoretical models. Furthermore, the sensitivity of the results when applying several allocation procedures, aggregates' moisture content and ophite transport distances was also analysed. The results showed the great importance of the aggregates absorption rate and, above all, of their humidity. Slags can replace ophite located more than 144 km from the asphalt plant.

**Keywords**

Life cycle assessment; LCA; Environmental impact; Slag; Electric arc furnace; Asphalt mixture;

## 1. Introduction

On September 2015, 193 countries adopted the 17 sustainable development goals, which look for "satisfying the needs of the present without compromising the ability of future generations to meet their own needs" (IISD, n.d.). These goals are focused on solving three world-shared problems by 2030: extreme poverty, inequality and injustice and climate change. In particular, goals related to the environment search for a more efficient production and consumption of resources, a decrease in wastes' generation, a prevention and reduction in sea pollution and a fight against desertification and deforestation, among others (United Nations, n.d.).

Road industry can significantly contribute to the accomplishment of these environmental world goals. The European total network length is estimated to be 4.9M km, accounting paved roads for 90% (around 4.41M km) (ERF, 2017). Constructing a single kilometre of a new road requires the consumption of 30,000 tons of aggregates and around 90 tons of bitumen (UEPG, 2017). This implies not only the consumption of raw materials but also of energy (electricity and fuels), bringing about a great environmental impact. Furthermore, maintaining reliable performance of such a big network supposed an expenditure of 21,206 million Euros in 2014 (ERF, 2017). However, this figure is expected to increase in a near future since freight traffic is estimated to triple between 2015 and 2050, overloading existing infrastructures and making more frequent maintenance actions necessary (OECD, 20109). Thus, it seems clear that searching for alternative materials for the construction of roads is a must for reducing the economic and environmental loads.

Replacing natural aggregates by wastes and by-products is one of the most widespread technique used to achieve sustainable roads since it provides a double benefit. On the one hand, the extraction and production of raw materials decrease, reducing the consumption of water, electricity, diesel, and also the production of noise and dust. On the other hand, the deposit of wastes in the landfill is avoided, extending landfills' lifetime and reducing emissions. Electric Arc Furnace (EAF) slag is widely used with this aim. According to the Worldsteel Association (2018), around 168.4 million tons of crude steel were produced in Europe in 2017, coming from the EAF around 40% (67.36 million tons). Besides, for every ton of steel produced, around 130 kg of EAF slags are generated (Arenal, 2016), thus, 9 million tons of EAF slags were available in Europe that year, 4 million tons of which were used for road construction purposes (EUROSLAG and EUROFER, 2012).

The mechanical performance of EAF slags in asphalt mixtures when they replace natural coarse aggregate has been evaluated in depth obtaining very good results regarding workability, stiffness and resistance to fatigue, moisture damage and permanent deformation (Ameri et al., 2013; Kavussi and Qazizadeh, 2014; Pasetto and Baldo, 2010; Sorlini et al., 2012). However, the environmental aspects have not been studied in such detail.

Most of the environmental analysis of using slags in roads have been focused on Blast Furnace Slags (BFS) used in unbound layers. Mroueh et al. (2001) evaluated the advantages of replacing natural aggregates by coal ash, crushed concrete waste and granulated BFS showing that the last two materials allow reducing the energy consumption. Sayagh et al. (2010) compared a flexible pavement in which the binder and base layers were manufactured using BFS with a rigid pavement to determine the influence on the results of the waste allocation procedure. Results concluded that considering BFS as a waste or a co-product may tremendously affect the decision making. Huang et al. (2013) also investigated the allocation method for BFS but in this case slags were used in the whole pavement section, corroborating in this way the high variability of the results detected by Sayagh et al. (2010). On the contrary, few authors have centre their research on EAF slags used in asphalt layers. Mladenovič et al. (2015) compared the production and construction of two asphalt wearing courses in which siliceous coarse aggregates were replaced by steel slags. Despite the more binder required in the alternative mixture, slags ended up to be the most sustainable option in 4 of the 7 impacts analysed. A year later, Ferreira et al. (2016) performed a similar analysis in which  the potential variability of the results depending on the slags' porosity was pointed out. Nevertheless, any of these researches considered important aspects such as asphalt mixtures leaching, the affection of aggregates' specific heat capacity or differences in the compaction energy.

The objective of this work is double: to provide recommendations in the selection and use of EAF slag in asphalt mixes that ensure environmental improvements and to establish a methodology to perform LCAs of mixtures that incorporate this material. To do so, a comprehensive Life Cycle Assessment (LCA) was carried out following the ISO 14040 (ISO, 2006a) and 14044 (ISO, 2006b) standards. The inventory gaps were filled by performing several laboratory tests and applying theoretical models. Furthermore, the sensitivity of the results when applying several allocation procedures, aggregates' moisture content, transportation distances and two characterization methods (ReCiPe and CML) was also analysed.

## 2. Goal and scope

This LCA evaluates environmental impact of replacing ophite (a diabase whose pyroxene has been altered which is commonly employed in the north of Spain in highly trafficked roads) by EAF steel slag as high quality coarse aggregates in asphalt mixtures. As the production process and applied post-treatment directly influence their final properties, two EAF slags with very different properties were selected for this study. Furthermore, conventional aggregates (limestone) were employed in the filer fraction of the mixes. The characteristics of the aggregates employed in this work can be seen in Table 1 and Table 2.

***Table 1. Coarse aggregates' properties.***

| Test | Standard | Ophite | Slag 1 | Slag 2 |
|---|---|---|---|---|
| Specific weight (g/cm$^3$) | EN 1097-6 | 2.937 | 3.735 | 3.92 |
| Los Angeles coefficient | EN 1097-2 | 16 | 18 | 17 |
| Flakiness index | EN 933-3 | 8 | 2 | 5 |
| Water absorption (8/11.2 fraction) | EN 1097-6 | 0.60% | 0.95% | 1.72% |
| Water absorption (2/4 fraction) | EN 1097-6 | 0.20% | 0.81% | 3.09% |
| Expansiveness index | EN 1744-1 | 0% | 0.6% | <3.5% |

***Table 2. Fine aggregates' properties.***

| Test | Standard | Limestone |
|---|---|---|
| Specific weight (g/cm$^3$) | EN 1097-6 | 2.725 |
| Sand equivalent | EN 933-8 | 78 |

The LCA was performed considering as functional unit a 1-km lane with a width of 3.75 m and a wearing course of 0.04 m thickness. An analysis period of 30 years was also selected. Regarding the system boundaries, the material production, construction, use (maintenance and leaching) and end-of-life stages were taken into account. Since this is a fictitious road and all the mixtures would undergo the same maintenance activities, congestion was not evaluated despite being a very important stage of a road life-cycle (Lizasoain-Arteaga et al., 2020).

## 3. Life cycle inventory

This stage consists of creating a consistent database containing all the resources consumed and the emissions produced throughout the road's lifecycle. Although certain processes, especially those related to conventional materials, were studied more in detail by previous researchers (Jullien et al., 2012; Mroueh et al., 2001; Stripple, 2001), a comprehensive study of the slag inventory was necessary. Regarding the electricity generation and fossil fuel production processes (shared by all stages of the LCA), those defined in Gabi v9.1 database for the European average and in the National Renewable Energy Laboratory database ("NREL," 2012) were used.

### 3.1. Production stage

This stage includes the extraction and processing of the raw materials (natural aggregates, slags, and bitumen), their transportation to the asphalt plant and the manufacturing of the asphalt mixture.

#### 3.1.1. Mix design

For the analysis, three asphalt concrete mixtures (ref, slag 1 and slag 2) were designed according to the Marshal Design method using a conventional 50/70 penetration grade bitumen. The particle size distribution of the three mixtures was defined following the limits established by the Spanish regulation for pavement design (Dirección General de Carreteras, 2017). However, due to the higher specific weight of slags, the grading size was calculated by volume. As seen in **Error! Reference source not found.**, the high specific weight of slags is reflected in the high density of the mixtures. Moreover, slag mixtures improved the stability values of the reference mixture reaching similar or even lower deformation values. Based on the results, mixtures with 5.8% voids were selected for this work, thus ensuring a similar internal structure in all the mixtures.

The percentage of bitumen used in the mixtures is highly influenced by the specific weight of slags and their absorption. In the case of slag 1, with similar absorption to ophite, the percentage of bitumen by weight is reduced compared to the reference mix due to its high specific weight. However, slag 2, which has also a high specific weight, needs a percentage of bitumen closer to the reference mix because of its higher absorption. To eliminate the effect of the specific weight of the material, the dosage was also shown by volume (see Table 3). Comparing the percentages of bitumen by volume, slag 1 mixture needs practically the same amount of bitumen than the reference mix for the same volume of asphalt mixture, while slag 2 increases 32% this amount.

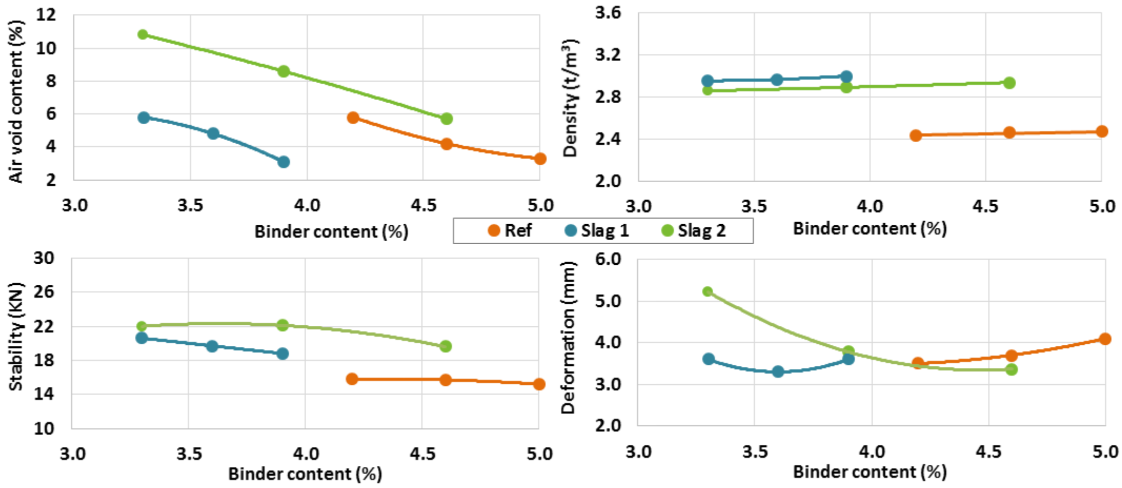


*Figure 1. Asphalt mixtures design.*

*Table 3. Asphalt concrete mixture definition.*

| Details | %w/w | | | %v/v | | |
|---|---|---|---|---|---|---|
| | **Ref** | **Slag 1** | **Slag 2** | **Ref** | **Slag 1** | **Slag 2** |
| Ophite | 61.60 | - | - | 56.38 | - | - |
| Limestone | 34.20 | 29.40 | 29.19 | 33.69 | 33.87 | 33.89 |
| Slag | - | 67.30 | 66.21 | - | 56.68 | 53.00 |
| Binder | 4.20 | 3.30 | 4.60 | 9.93 | 9.45 | 13.11 |
| Density (t/m3) | 2.43 | 2.95 | 2.94 | 2.43 | 2.95 | 2.94 |
| Voids (%) | - | - | - | 5.80 | 5.80 | 5.70 |

#### 3.1.2. EAF slag allocation

To calculate the slag's inventory, the process described in Arenal (2016) was assumed. The steel production process results in the generation of two other materials, black and white slag, about 130 kg and 25 kg of each being produced per ton of steel manufactured. Black slag, once extracted from the furnace, is cooled abruptly by means of a high-pressure water cannon, being then immersed in a pool to continue its cooling. After the cooling process, the remaining steel that might be left in the slag fraction (around 2%)

is separated with an overband magnetic separator. Finally, slags are crushed (when needed) and sieved to achieve an adequate size.

There is no consensus about whether slag should be considered as a waste or a by-product. According to some authors (Di Maria et al., 2018; Iacobescu et al., 2016; Mroueh et al., 2001) slags should be considered as a waste since it does not completely meet the requirements established in the Waste Framework Directive 200/98/EC (EU, 2008) as its use is not certain and the environmental problems are not sufficiently studied (Di Maria et al., 2018). Consequently, no environmental burden would be assigned to slag. However, other authors claim that from their point of view, slags are by-products since those requirements are met (Habert, 2013). This being the case, part of the impact generated during the steel production could be assigned to slags. However, impact allocation is a very controversial issue in LCA (Saade et al., 2013), reason for which, even ISO 14044 (ISO, 2006b) recommends avoiding it whenever possible by dividing the unit process into sub-processes or by extending the product system to include the additional functions related to the by-products. Nevertheless, as system expansion seems to be dedicated to the evaluation of main products and it can present inconsistencies when analysing by-products, different approaches emerged (Chen et al., 2010). PE International (2014) and Saade et al. (2013) understand that when a by-product is used to replace another material, the by-product assumes the environmental impact of its own treatment but also receives a credit for the avoided impact. On the other hand, Weidema (2001) states that the environmental burden of the by-product treatment should be assumed by the main product (in this case steel), which also receives the credit for the avoided impacts. Therefore, in order to respect the mass conservation, the by-product assumes the impact of producing the avoided material which were previously subtracted from the main product. However, this would not be appealing to companies that want to use the by-product, as all the environmental advantages go to the main product, leaving the downstream processes of the by-product unaffected. Furthermore, in this case study, subtracting the impact of producing aggregates from that of steel would practically not change its environmental burden while greatly damaging the use of slags. For this reason, Martin et al. (2015) developed an intermediate approach by dividing the by-product treatment and the credit received between the main product and the by-product with the 50/50 method. However, as proposed by Weidema (2001), the by-product would still assume the impact of producing the displaced product in order to conserve the mass. To analyse the influence of different allocation alternatives, four of them were taken into account in this work (see Figure 2).

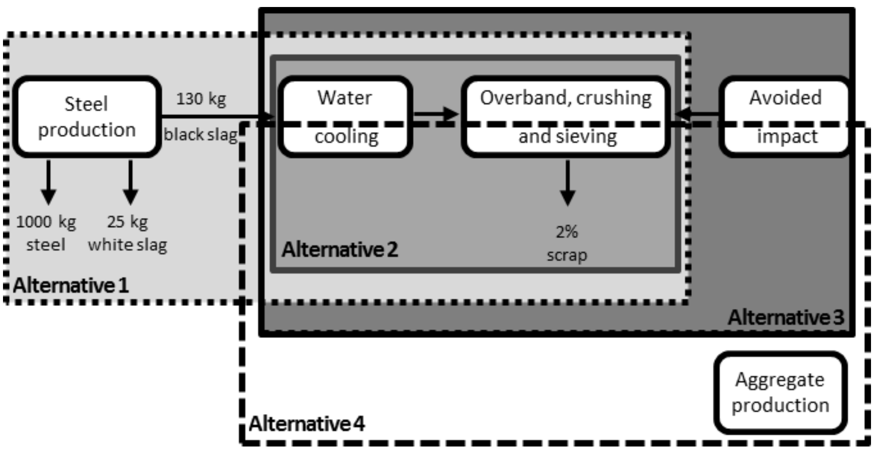


***Figure 2. EAF slag allocation alternatives.***

Alternative 1 consists on assigning part of the steel production impact to slags, in addition to that generated during their processing (cooling, scrap separation, crushing and sieving). For this aim, an allocation based on the process economic profit, what is to say, combining the mass and economic values of the materials, was applied. LCAs are commonly performed using either one or the other separately. Nevertheless, if one of the materials was produced in a very small quantity but had a very high price, it would not be contemplated. Black slag cost varies upon demand, according to the supplier. When a lot of slag is available, it is practically given away. However, in order to cover the expenses, the slag price should be similar to that of limestone. Conservatively, it has been assumed that it costs 10 €. In this way, if the allocation were made by mass, slag would receive 11% of the steel production impact, while doing it by cost it would receive 1.39%. As can be seen in Table 4, with the chosen allocation method slag would assume 0.23% of the steel impact. Therefore, even assuming a high price, slag assignation used in this work is lower than the other two options.

***Table 4. Allocation coefficients.***

| Material | Price (€/tn) | Mass (tn) | Allocation |
|---|---|---|---|
| Steel | 550.00 | 1.000 | 99.70% |
| Black slag | 10.00 | 0.127 | 0.23% |
| White slag | 0.00 | 0.025 | 0.00% |
| Scrap | 150.00 | 0.003 | 0.07% |

In Alternative 2, only those processes that are exclusively performed on slags have been included. In this way, slag would be considered as a waste of the steel making industry that will continue to be produced as long as the need for steel remains.

Alternative 3 expands the system boundaries to include the impact that is being avoided by not extracting natural aggregates. The benefit of recycling would only be received by slags to encourage their use. Otherwise steel would have to assume the impact of landfilling.

Finally, alternative 4 applies the 50/50 method proposed by Martin et al. (2015) to distribute the benefits between steel and slag but paying attention to the mass balance.

The inventory used in each of the alternatives as well as in the processes which allow their calculation is shown in the Table 5. The steel production values are a simplification of the inventory available in the GaBi v9.1. Regarding those of natural aggregates, they were calculated in a previous work by combining several studies (Lizasoain-Arteaga et al., 2019). Slags processing was calculated based on the machinery described in Arenal (2016). Finally, although not included in the table, the inventory of bitumen was obtained from Eurobitume (2012).

***Table 5. Aggregates inventory.***

| Inventory | Steel | Aggregates | Alternat. 1 | Alternat. 2 | Alternat. 3 | Alternat. 4 |
|---|---|---|---|---|---|---|
| Fossil fuels (MJ/tn) | 4,745.03 | 22.06 | 108.91 | 22.64 | 0.58 | 22.35 |
| Electricity (MJ/tn) | 1,648.25 | 19.08 | 30.22 | 0.25 | -18.83 | 9.67 |

### 3.1.3. Asphalt mixture production

The specific heat capacity of each material affects the asphalt mixture manufacture energy. This is why the differential scanning calorimetry (DSC) technique was used to characterize the three coarse aggregates employed in this work: ophite, slag 1 and slag 2. The analysis was performed to different material fractions to determine whether the aggregate size influenced the specific heat because of the presence of different compounds in the big and small particles. However, this premise was discarded based on the results shown in Figure 3, according to which, the biggest and the smallest material almost need the same energy to increase 1ºC the temperature. The specific heat capacity mean and standard deviation of each material can be seen in Figure 4. Ophite is the material which requires more energy to be heated, followed by slag 1 and slag 2. Nevertheless, ophite is also the material with the highest standard deviation. In fact, the smallest ophite specific heat is smaller than the biggest slag 1 specific heat. Therefore, three specific heat capacity values were considered for each material to evaluate these circumstances (see Table 6).

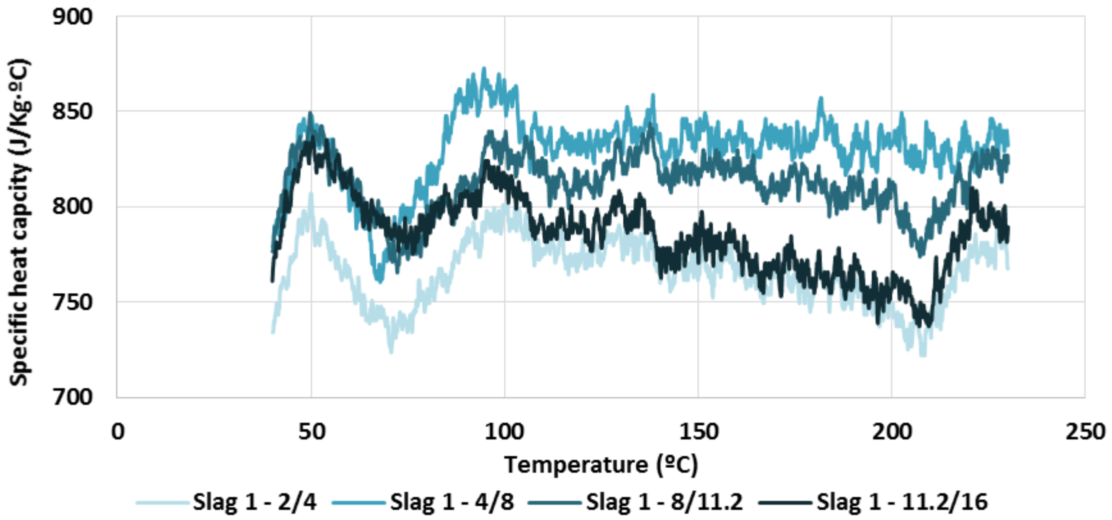


*Figure 3. Specific heat capacity of slag 1 distinguishing between different sizes.*

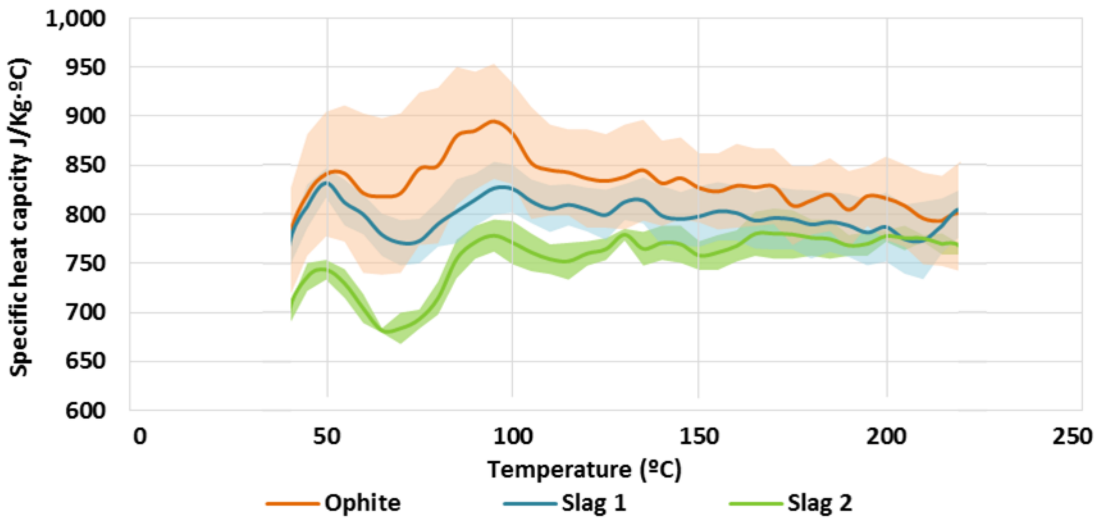


*Figure 4. Coarse aggregates specific heat capacity.*

*Table 6. Specific heat capacity employed.*

| Material | C Mean (kJ/kg·ºC) | C Min (kJ/kg·ºC) | C Max (kJ/kg·ºC) |
|---|---|---|---|
| Slag 1 | 0.798 | 0.768 | 0.829 |
| Slag 2 | 0.757 | 0.726 | 0.788 |
| Ophite | 0.831 | 0.772 | 0.889 |

The water content of the aggregates is another aspect that affects the energy of producing the asphalt mix. This water content depends on the ambient humidity, on whether the aggregate is covered as well as on its porosity. Moreover, different void geometries could also affect the aggregates drying process since the larger the specific surface area, the greater the heat transfer. To evaluate this aspect, a test was developed in the laboratory. An aggregate sample was saturated for 24 hours and was then placed in a sieve to drain the excess of water but without drying the aggregate surface, thus simulating the worst scenario. The aggregate was then introduced into an oven at 60ºC and the water content was evaluated every 5 minutes to monitor the drying process. The humidity evolution of the aggregates over time can be seen in Figure 5. These results are consistent with the aggregate absorption data (see Table 1). Slag 2, the aggregate with the highest absorption value, requires more drying time than slag 1 and ophite (which have very similar absorption). However, the fact that the three lines are parallel shows that the drying speed is practically the same for all the aggregates. Therefore, at least in this case, the drying time only depends on the amount of water retained in the aggregate. For this reason, three moisture contents were taken into account to evaluate their influence of the asphalt mixture energy consumption: the maximum calculated in the test, 50% of the maximum and 1% in all the materials)

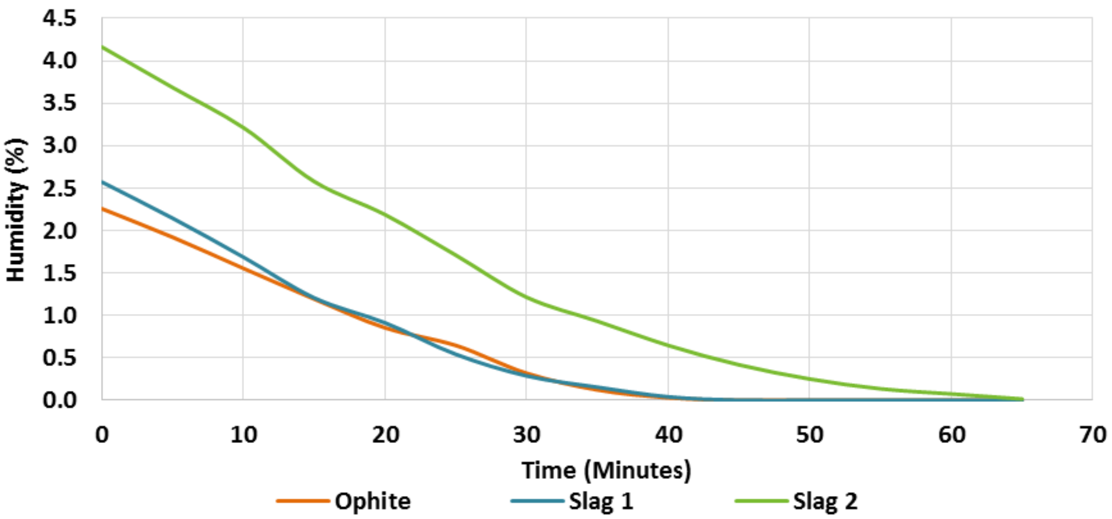


***Figure 5. Loss of aggregate moisture over time.***

The energy consumed in the asphalt plant was calculated based on the thermodynamic study of an asphalt plant's rotatory dryer developed by Peinado et al. (2011). However, the model was modified to take into account different types of aggregates. Furthermore, unlike the heavy fuel oil employed in the asphalt plant modelled by Peinado et al. (2011) natural gas was assumed for this work. In addition to this energy, which accounts for 85% of total consumption of the asphalt plant according to Stotko (2011), 12% of electricity and 3% of diesel have to be added to include other sources of energy consumption such us the bitumen heaters or the drum dryer motor. The parameters needed to feed the model can be seen in Table 7 and the achieved results in Table 8. As the moisture of the aggregate affects the results at least 3 times more than the variation of the specific heat capacity and evaluating all the options would result in a large number of alternatives, the LCA was performed considering only the average specific heat capacity of each aggregate but several moisture contents.

***Table 7. Parameters of the asphalt plant thermodynamic study.***

| Parameter | Value |
|---|---|
| Filler fraction in the solid entrance (%) | 0.08 |
| Filler fraction retained with solids (%) | 0.01 |
| Ambient temperature (ºC) | 15 |
| Solid temperature in the outlet | 170 |

| | |
|---|---|
| Filler temperature in fluent gases | Air temperature in the outlet |
| Air temperature in the outlet | 0.8 * Solid temperature in the outlet (Bueche, n.d.) |
| Reference temperature (ªC) | 25 |
| Solid humidity at the inlet | Several |
| Solid humidity at the outlet (%) | 0.5 |
| Stoichiometric ratio | 2.25 |
| Humidity ratio, or mass basis absolute humidity | 0,0038 |
| Thermal losses (%) | 20 (Gillespie, 2012) |

*Table 8. Asphalt plant energy consumption per ton of asphalt mix.*

| Energy | Ref | | | Slag 1 | | | Slag 2 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | Min | Max | Mean | Min | Max | Mean | Min | Max |
| **100% of the humidity** | | | | | | | | | |
| E. burned (MJ/tn) | 239.55 | 231.92 | 247.05 | 246.36 | 242.05 | 250.81 | 277.57 | 273.2 | 281.95 |
| Electricity (MJ/tn) | 33.82 | 32.74 | 34.88 | 34.78 | 34.17 | 35.41 | 39.19 | 38.57 | 39.81 |
| Diesel (MJ/tn) | 8.45 | 8.19 | 8.72 | 8.69 | 8.54 | 8.85 | 9.8 | 9.64 | 9.95 |
| **50 % of the humidity** | | | | | | | | | |
| E. burned (MJ/tn) | 198.09 | 190.46 | 205.59 | 200.64 | 196.34 | 205.28 | 212.2 | 207.83 | 216.58 |
| Electricity (MJ/tn) | 27.97 | 26.89 | 29.03 | 28.33 | 27.72 | 28.95 | 29.96 | 29.34 | 30.58 |
| Diesel (MJ/tn) | 6.99 | 6.72 | 7.26 | 7.08 | 6.93 | 7.24 | 7.49 | 7.34 | 7.64 |

#### 3.1.4. Transport distances

The transport distances employed in this work are shown in Table 9. It should be noted that either limestone or slags are supposed to be locally used. However, a variable distance was assigned to ophite in order to calculate when replacing natural coarse aggregates by slags is preferable.

*Table 9. Transport distances.*

| Material | Transport distance (km) |
|---|---|
| Ophite | Variable |
| Limestone | 30 |
| Slag | 30 |
| Binder | 100 |

### 3.2. Construction stage

This stage includes the transportation of the asphalt mix from the plant to the roadwork (which is assumed to be 30 km away), as well as the construction of the road. In a previous work (Lizasoain-Arteaga et al., 2019), an industrial partner indicated that 1.56 l of diesel was required to pave and compact 1 ton of conventional asphalt mix. However, the compaction energy can be affected with the addition of slags. To determine this, the rotatory machine was used to perform compaction tests to the three mixtures (see Figure 6). Results revealed that ophite mixtures needs more compaction energy than slag 1 and slag 2. However, the energy achieved in this test cannot be directly correlated to the energy consumed onsite. For this reason, the relationship between the energies obtained were applied to the consumption data available (see Table 10). It should be mentioned that this is a conservative assumption since in addition to an increase in the compaction diesel consumption, an increase of paving consumption is also assumed.

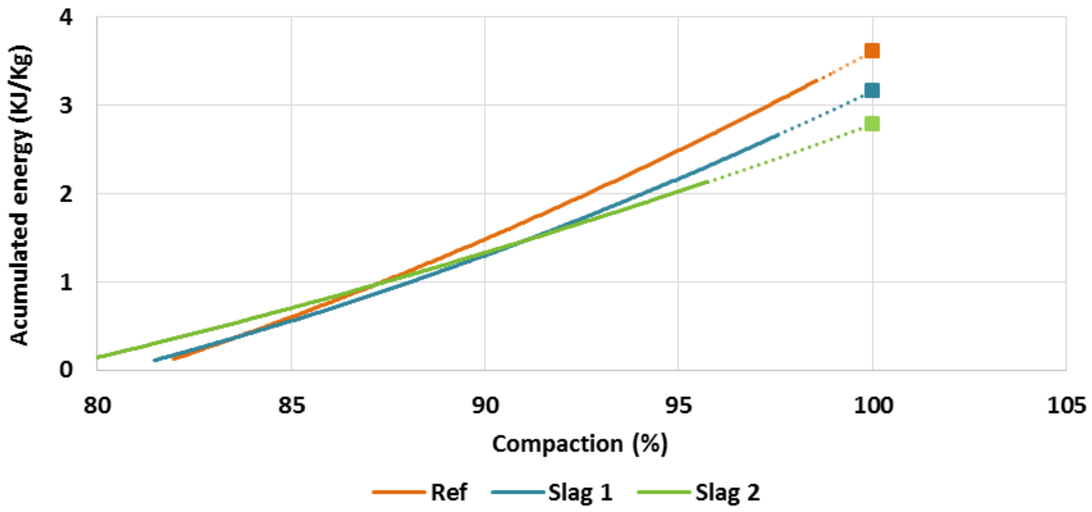


*Figure 6. Compaction energy.*

*Table 10. Paving and compaction diesel consumption.*

| Results | Ref | Slag 1 | Slag 2 |
|---|---|---|---|
| Density (t/m$^3$) | 2.43 | 2.95 | 2.94 |
| Compaction energy (KJ/kg) | 3.62 | 3.17 | 2.78 |
| Fuel consumption (l/t) | 1.56 | 1.37 | 1.20 |

## 3.3. Use stage

### 3.3.1. Leaching

One potential hazard that can arise from the replacement of natural aggregates by slags is an increase in the chemical elements or compounds released to the environment because of the contact with rainwater. However, when they are used as aggregates in asphalt mixtures this contact could decrease because of the coating that bitumen provides. To take this effect into account, the test defined in the standard EN 12457-4:2002 (UNE-EN, 2002), was used. This test is commonly used to analyse the environmental behaviour of granular waste materials. Nevertheless, in this case it was also applied to the loose asphalt mixtures in order to evaluate their leachability in a more realistic way.

Figure 7 shows the relationship between the leachate generated by slag 1 when analysed as a granular material and embedded within the asphalt mixture. In general, the chemical elements released to the environment decrease due to bitumen and only those below the detection limit remains unchanged. Still, 3 of the 18 substances analysed increase: dissolved organic carbon (DOC), nitrates ($NO3^-$) and copper (Cu). However, this increase could be caused by the limestone and/or the bitumen contained in the mixture. In fact, the amount of these compounds is higher in the reference mixture than in those containing EAF slags (see Table 11). The leachate values used for each of the mixtures are shown in Table 11. It should be noted that beryllium (Be), cobalt (Co), cadmium (Cd) and mercury (Hg) were considered to be zero since they were below the detection limit in all the samples despite the high accuracy of the equipment employed to perform the tests.

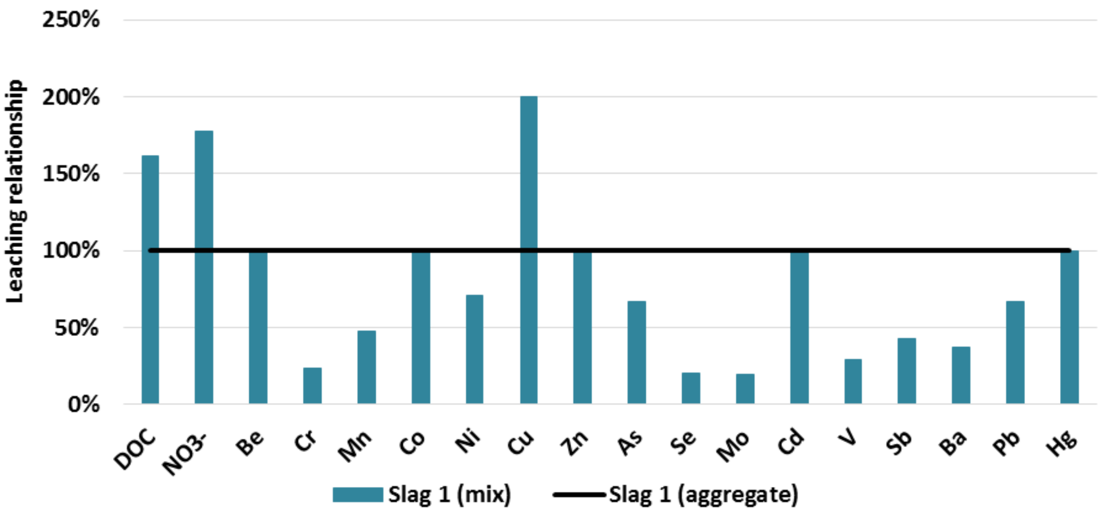


***Figure 7. Effect of bitumen in asphalt mixture leachates.***

| Mix | DOC | NO3- | Cr | Mn | Ni | Cu | Zn | As | Se | Mo | V | Sb | Ba | Pb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ref | 31.6 | 1.3 | 0.009 | 0.001 | 0.003 | 0.005 | 0.066 | 0.001 | 0.006 | 0.022 | 0.033 | 0.002 | 0.025 | 0.001 |
| Slag 1 | 25.1 | 0.6 | 0.01 | 0.002 | 0.002 | 0.002 | 0.001 | 0.001 | 0.002 | 0.018 | 1.246 | 0.001 | 0.218 | 0.001 |
| Slag 2 | 19.2 | 0.25 | 0.016 | 0.002 | 0.001 | 0.001 | 0.001 | 0.001 | 0.004 | 0.048 | 1.006 | 0.005 | 0.312 | 0.001 |

***Table 11. Leaching results per kg of loose asphalt mixture.***

#### 3.3.2. Maintenance

Maintenance activities involve milling the deteriorated layer (which consumes 0.41 l/t (Lizasoain-Arteaga et al., 2019)), transporting the reclaimed asphalt to the recovery centre (located 30 km away) and producing and constructing a new layer. According to experience, 15 years durability can be expected for an AC mix (EAPA, 2007; Nicholls et al., 2010). Therefore, taking into account the 30 years analysis period selected for this work, only 1 mill and overlay actions would be performed. Furthermore, the same durability was assumed for all mixes.

### 3.4. End-of-life stage

This stage includes the milling of the asphalt layer and the transportation of the reclaimed asphalt to the recovery centre. The same consumption and distances assumed in the maintenance modulus were applied.

## 4. Life Cycle Impact Assessment

To convert emissions into impacts, the ReCiPe 2016 Hierarchical characterization method was selected (RIVM, 2016). This method enables the transformation of the 18 midpoint impacts, which are focused on single environmental problems, into 3 endpoint impacts which represents the damage to the three areas of protection (damage to human health, HH; damage to ecosystem diversity, ED; and damage to resource availability, RA) based on cause-effect pathway.

An LCA of the 3 mixtures was carried out taking into account the 4 allocation procedures and different ophite transport distances. In addition, the aggregates were considered to have the highest moisture content (2.26%, 2.57% and 4.16% the ophite, slag 1 and slag 2, respectively). The results of comparing the impacts of slag mixtures with the reference mixture are shown in Figure 8. The x-axis represents the transport distance of ophite while the y-axis represents the increase or decrease of the slag mixtures environmental impact with respect to the reference mix.

Results show that alternatives 2 and 4 provide very similar values for HH and ED impacts. In fact, for the same ophite transport distance, alternative 2 provides only around 1.3% more environmental impact than alternative 4. Alternative 1, assuming part of the environmental loads associated with the steel manufacturing process, provides 13.0% more environmental impact than alternative 2. However, as alternative 3 benefits from the credit received for the avoided impact without taking into account the conservation of mass, 7.8% reduction is achieved. However, these relationships are not maintained in the RA impact, which is clearly affected by the consideration or not of the avoided impact as well as by the conservation of mass. This makes alternative 4 the most detrimental allocation method and alternative 3 the most beneficial, leaving alternative 1 and 2 with very similar results. Therefore, it seems that alternative 2 always remains in a middle position between the other methods. Moreover, this alternative has the advantage of directly fulfilling the mass conservation and not needing to debate about future potential uses or the product which should receive the credit. Consequently, alternative 2 was selected for the rest of the work.

When comparing the two slags, the better performance of slag 1 can be seen due to the higher absorption rate of slag 2, what increases the amount of bitumen needed as well as the aggregates water content. In fact, while slag 1 could replace ophite aggregate located 177 km away achieving improvements in the HH and ED impacts, slag 2 could replace those located more than 296 km away. Regarding the RA impact, the results do not seem to vary too much despite changing the ophite transport distance. In fact, slag 1 always proves to be a good alternative to ophite while slag 2 always produces a greater impact.

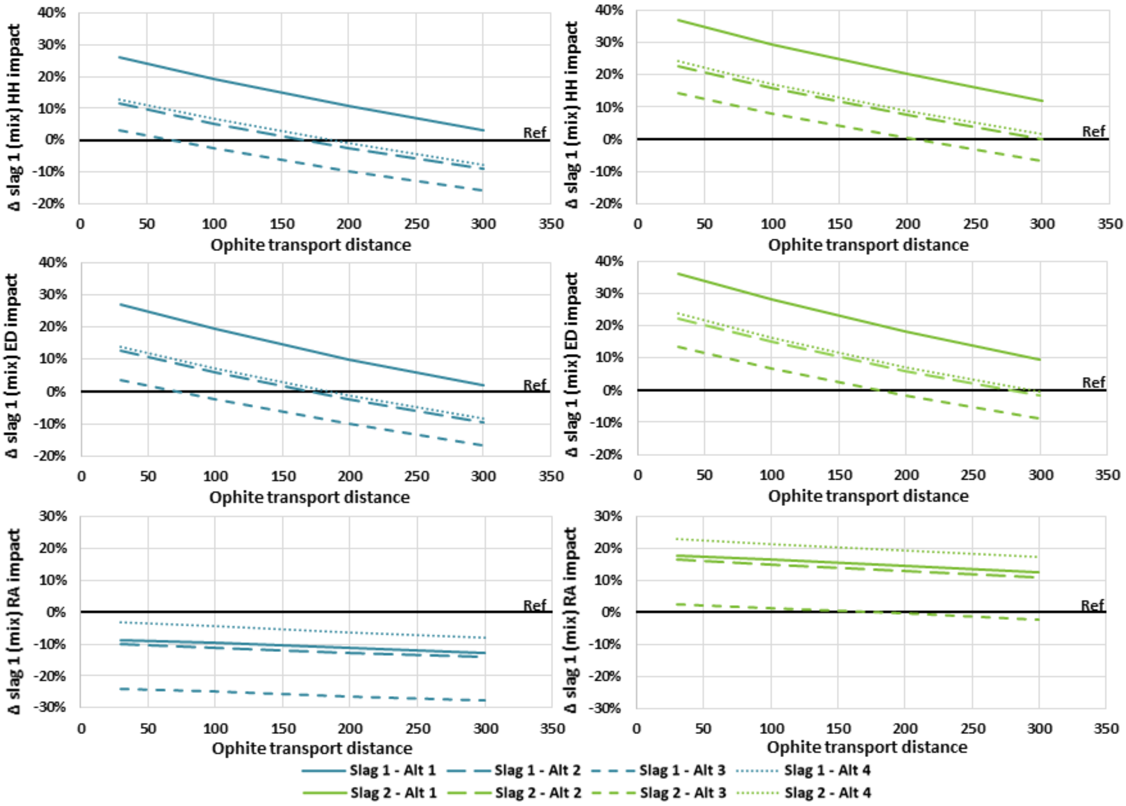


***Figure 8. LCA considering 4 allocation procedures and maximum aggregates' humidity.***

To further understand these results, the processes contribution to the LCA results were evaluated focussing in a specific case in which the ophite transportation distance was assumed to be 200 km (see Figure 9).

As expected, the asphalt mixture production is the process that contributes most to the HH and ED impacts, its relevance being higher in slag 2 due to the higher aggregate humidity. This process is followed by the bitumen production in slag 2 mixture and the construction activities in slag 1 mixture. It should be remembered that slag 2 mixture needs greater percentage of bitumen. Furthermore, the selection of 200 km as the ophite transportation distance increases transport relevance in the reference mix up to 24% of the total impact.

Regarding RA impact, the transportation activities barely affect the results. In fact, in the reference mix it only accounts for 6% of the total impact. In contrast, bitumen is the most important process meaning 67%, 73% and 79% in the reference, slag 1 and slag 2 mixes, respectively. This explains the results observed in Figure 8. Slag 1, needing the least bitumen, always produces less RA impact than ophite. However, slag 2, containing more bitumen, always produces more RA impact.

Finally, leachate is negligible in all the three endpoint categories, representing less than 0.2%.

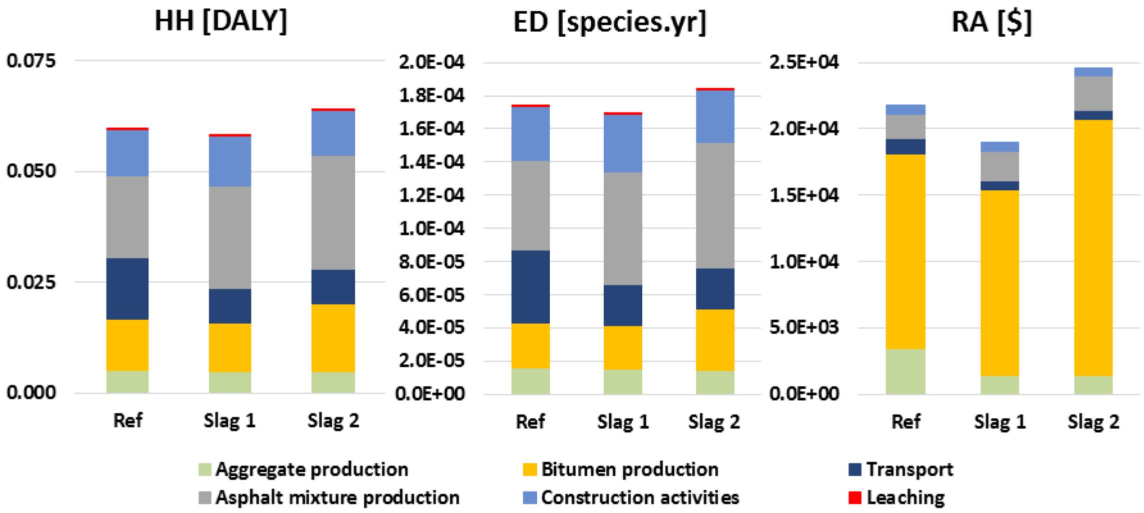


***Figure 9. Process contribution to the LCA results. Allocation method: Alternative 2. Transport distance: 200 km.***

Considering the great importance of the asphalt mix production in the HH and ED impacts and the possible reduction of the aggregates' moisture with their covering, the distance from which using slag is beneficial was re-evaluated. In this sense, the analysis was repeated considering 50% of the humidity employed before (1.13%, 1.29% and 2.08%). Results show that slag 1 and slag 2 could replace natural aggregates located 149 km and 235 km away, respectively, what implies a reduction of around 30 km and 60 km. However, despite this 50% decrement, slag 2 would still have much more water than slag 1 and ophite. In fact, even considering the same percentage of moisture for all the aggregates, slag would still have more amount of water than ophite due to their high specific weight. Therefore, to evaluate the results under more similar conditions, 1% moisture in all the aggregates was also assumed. This percentage, which is similar to their absorption rate, is only slightly lower than that already considered for ophite and slag 1, so the distance is practically unaffected. However, it is a big change for slag 2, which could even replace ophite that are 190 km away. Nevertheless, it would still produce between 9% and 14% more RA impact than the reference mix due to its higher bitumen content (see Figure 10).

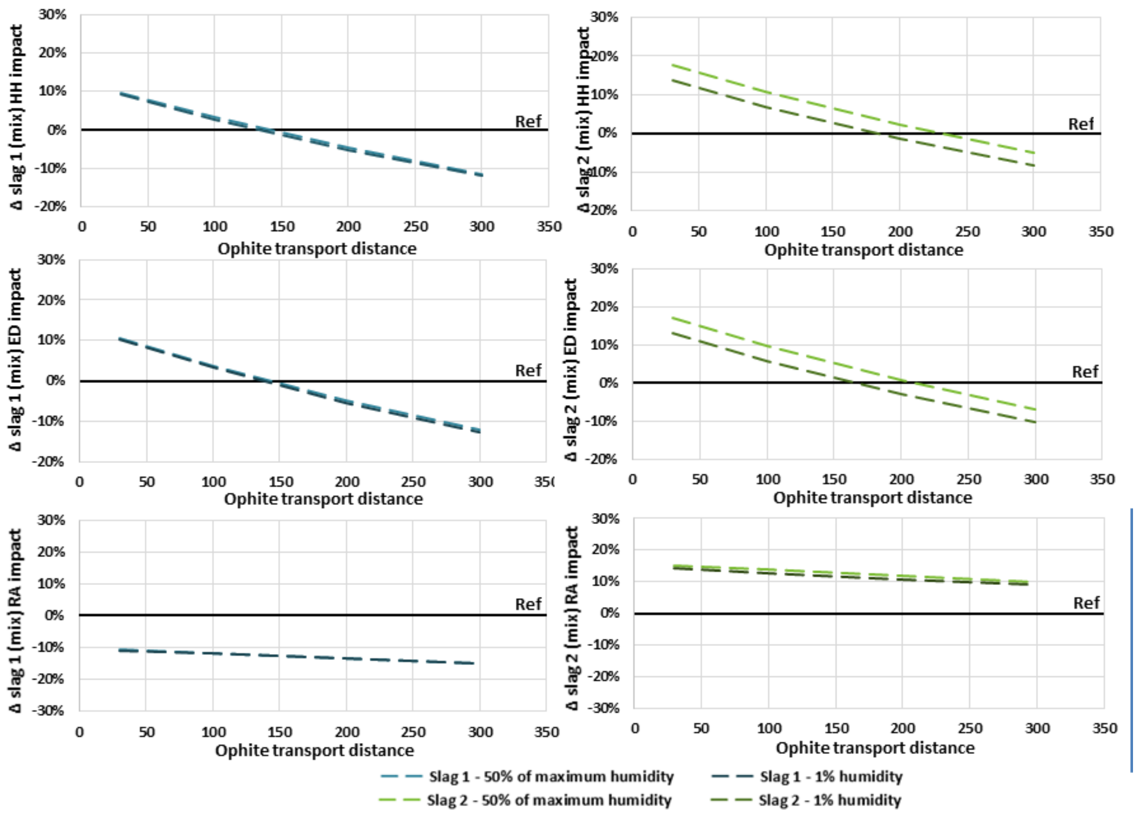


***Figure 10. LCA considering alternative 2 allocation procedure and 2 moisture content.***

Finally, the sensitivity of the analysis was studied by applying the CML 2001 characterization method (January 2016 update). This method is recommended to develop Environmental Product Declarations of construction products, services and processes and enables the calculation of mid-point impacts. However, to obtain a single value for every mix, a normalization and a weighting processes are required, what do not have a scientific basis and it is not recommended in the ISO 14044 (ISO, 2006b) in comparative assertions intended to be disclosed to the public. The analysis was performed to the specific case described above where the maximum humidity of the aggregates and 200 km transport distance was selected. Furthermore, the impacts where normalized by dividing the scores by the impact produced by the 28 member states of the European Union in 2000 and they were weighted using the factors described in Lizasoain-Arteaga et al. (2019).

Table 11 shows the relationship between the impacts produced by the slag and the reference mixtures when both characterisation methods are applied. ReCiPe studies more environmental impacts than CML and of those shared by both methods, the former provides a greater difference in the metal depletion impacts while CML calculates grater freshwater ecotoxicity, human toxicity and photochemical ozone formation potential. However, the greatest differences occur when comparing ReCiPe's end-point impacts with the normalized and weighted impacts of CML: while ReCiPe calculates similar impacts for slag and reference mixtures, CML predicts 145% and 137% higher impacts for slag 1 and 2 mixtures, respectively.

***Figure 11. Slag and reference mixture impacts relationship using ReCiPe and CML characterization methods.***

| Impact | Abbr. | ReCiPe | | CML | |
|---|---|---|---|---|---|
| | | Slag 1 | Slag 2 | Slag 1 | Slag 2 |
| | | Mid-point impacts | | | |
| Climate change, excl biogenic carbon | GWP | -1% | 10% | -1% | 10% |
| Fine Particulate Matter Formation | PMFP | -6% | 3% | | |
| Fossil depletion | FD | -3% | 26% | -3% | 26% |
| Freshwater Consumption | WCP | 89% | 94% | | |
| Freshwater ecotoxicity | FETP | 936% | 745% | 2715% | 2178% |
| Freshwater Eutrophication | FEP | -7% | 24% | | |
| Human toxicity, cancer | HTPc | -7% | -7% | 110% | 100% |
| Human toxicity, non-cancer | HTPnc | 2% | -5% | | |
| Ionizing Radiation | IRP | -6% | 3% | | |
| Land use | LU | -17% | -17% | | |
| Marine ecotoxicity | METP | 787% | 626% | 815% | 670% |
| Marine Eutrophication | MEP | -18% | -18% | -5% | -3% |
| Metal depletion | MD | -63% | -63% | -6% | 0% |
| Photochemical Ozone Formation, Ecos. | EOFP | -5% | -3% | -245% | -294% |
| Photochemical Ozone Formation, HH | HOFP | -5% | -3% | | |
| Stratospheric Ozone Depletion | ODP | -8% | -4% | -6% | 3% |
| Terrestrial Acidification | TAP | -5% | 4% | -5% | 4% |
| Terrestrial ecotoxicity | TETP | -8% | -2% | -16% | -16% |
| **Impact** | **Abbr.** | **End-point impacts** | | **Normalized and weighted** | |
| Damage to human health | HH | -2% | 7% | | |
| Damage to ecosystem diversity | ED | -2% | 6% | 145% | 137% |
| Damage to resource availability | RA | -13% | 13% | | |

When the contribution of each process to the total LCA impact is analysed, the difference of both methods can be seen. Leaching, which was negligible according to the ReCiPe method, accounts for 61% and 53% of the total impact in slag 1 and 2 mixtures. Over 90% of this impact is caused by vanadium, a chemical element that is only included in the leaching limit standards for waste-derived aggregates of 4 of the 10 countries studied in Saveyn et al. (2014). And in fact, the asphalt mixtures under study fulfil those 4 legislations. Therefore, taking into account that when comparing the midpoint impacts with both methods the results are not so different, the variation of the final results may be caused by the way these impacts are aggregated, in other words, by the normalization and weighting.

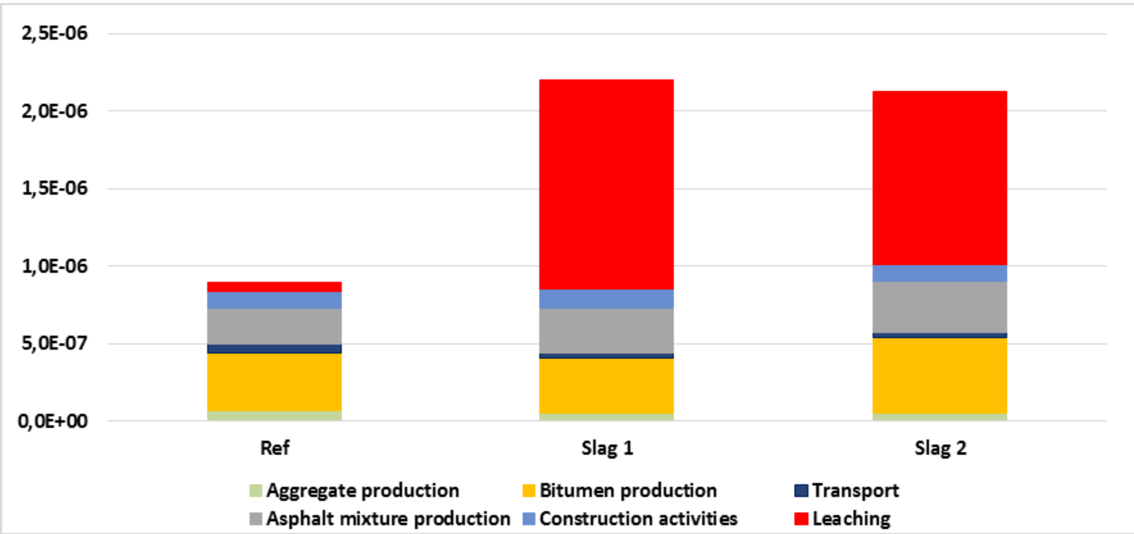


***Figure 12. Process contribution to the LCA results. Transport distance: 200 km. CML characterization method.***

## 5. Conclusions

In this study, the environmental impact of replacing high quality coarse aggregates by EAF steel slag was assessed. A 30-years LCA was performed on three different asphalt mixture (reference, slag 1 and slag 2) considering several aggregates' moisture content, ophite transport distances and allocation methods. After the analysis, the following conclusions can be drawn:

- Alternative 2, which only takes into account those processes that are exclusively performed on slags, is the most reasonable allocation method. Assigning part of the steelmaking process impact to slags makes this material unattractive while including a credit for the avoided impact creates problems regarding the mass conservation and the industry that should receive the benefit.
- The absorption rate of slags strongly affect the LCA results, increasing the binder content of the mixture as well as the aggregates' humidity. However, depending on the production process it is possible to find slags with a porosity similar to natural aggregates.
- The aggregate moisture is crucial in the LCA of a road. Slags with low absorption rate can replace high quality aggregates located more than 144 km away when they are covered, this distance increasing to 177 km when the humidity is higher. Similarly, slags with high absorption rate can replace aggregates located between 190 km and 296 km away depending on their moisture content. However, if the water absorption is too high as in the case of slag 2, the higher binder content could impede slags to improve the RA impact.
- Bitumen coating reduces most of the chemical elements leached by the asphalt mixtures, thus, making this stage negligible when the ReCiPe characterization method is employed.
- Although similar trends are observed between ReCiPe and CML mid-point impact categories, results calculated by normalising and weighting the CML impacts differ greatly from those obtained applying ReCiPe. Considering the high subjectivity and variability of the normalisation and weighting processes, using ReCiPE's endpoint impacts is recommended when it is necessary to reduce the number of impacts to make comparative assertions.

## Acknowledgements

This work has been funded by the doctoral CVE-2006-11670 studentship program from the University of Cantabria, co-financed by the Government of Cantabria.

## References

Ameri, M., Hesami, S., Goli, H., 2013. Laboratory evaluation of warm mix asphalt mixtures containing electric arc furnace (EAF) steel slag. Constr. Build. Mater. 49, 611–617. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2013.08.034

Arenal, J.R., 2016. Estudio, análisis y diseño de aplicaciones de áridos procedentes de la valorización de residuos industriales : firmes de carreteras y hormigones.

Bueche, N., n.d. Évaluation des performances et des impacts des enrobés bitumineux tièdes. EPFL PP - Lausanne. https://doi.org/10.5075/epfl-thesis-5169

Chen, C., Habert, G., Bouzidi, Y., Jullien, A., Ventura, A., 2010. LCA allocation procedure used as an incitative method for waste recycling: An application to mineral additions in concrete. Resour.

Conserv. Recycl. 54, 1231–1240. https://doi.org/10.1016/j.resconrec.2010.04.001
Di Maria, A., Salman, M., Dubois, M., Van Acker, K., 2018. Life cycle assessment to evaluate the environmental performance of new construction material from stainless steel slag. Int. J. Life Cycle Assess. 23, 2091–2109. https://doi.org/10.1007/s11367-018-1440-1
Dirección General de Carreteras, 2017. Pliego de Prescripciones Técnicas Generales para Obras de Carreteras y Puentes (PG-3) (Spanish General Technical Specifications for Roads and Bridge Works, PG-3).
EAPA, 2007. Long-Life Asphalt Pavements. Technical version.
ERF, 2017. Road [WWW Document]. Road Netw. 2017. URL http://erf.be/statistics/road-network-2017/
EU, 2008. Directive 2008/98/EC of the European parliament and of the council on waste and repealing certain directives.
Eurobitume, 2012. The bitumen industry in Europe [WWW Document]. URL http://www.eurobitume.eu/bitumen/industry/ (accessed 12.30.17).
EUROSLAG, EUROFER, 2012. Position paper on the status of ferrous slag complying with the Waste Framework Directive (Articles 5/6) and the REACH Regulation.
Ferreira, V.J., Sáez-De-Guinoa Vilaplana, A., García-Armingol, T., Aranda-Usón, A., Lausín-González, C., López-Sabirón, A.M., Ferreira, G., 2016. Evaluation of the steel slag incorporation as coarse aggregate for road construction: technical requirements and environmental impact assessment. J. Clean. Prod. 130, 175–186. https://doi.org/https://doi.org/10.1016/j.jclepro.2015.08.094
Gillespie, I., 2012. Quantifying the Energy Used in an Asphalt Coating Plant 164.
Habert, G., 2013. A method for allocation according to the economic behaviour in the EU-ETS for by-products used in cement industry. Int. J. Life Cycle Assess. 18, 113–126. https://doi.org/10.1007/s11367-012-0464-1
Huang, Y., Spray, A., Parry, T., 2013. Sensitivity analysis of methodological choices in road pavement LCA. Int. J. Life Cycle Assess. 18, 93–101. https://doi.org/10.1007/s11367-012-0450-7
Iacobescu, R.I., Angelopoulos, G.N., Jones, P.T., Blanpain, B., Pontikes, Y., 2016. Ladle metallurgy stainless steel slag as a raw material in Ordinary Portland Cement production: a possibility for industrial symbiosis. J. Clean. Prod. 112, 872–881. https://doi.org/https://doi.org/10.1016/j.jclepro.2015.06.006
IISD, n.d. International Institure for Sustainable Development [WWW Document]. URL https://www.iisd.org/topic/sustainable-development
ISO, 2006a. ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework, 2 nd. International Organization for Standardization.
ISO, 2006b. ISO 14044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines, 1 edn. International Organization for Standardization.
Jullien, A., Proust, C., Martaud, T., Rayssac, E., Ropert, C., 2012. Variability in the environmental impacts of aggregate production. Resour. Conserv. Recycl. 62, 1–13. https://doi.org/https://doi.org/10.1016/j.resconrec.2012.02.002
Kavussi, A., Qazizadeh, M.J., 2014. Fatigue characterization of asphalt mixes containing electric arc furnace (EAF) steel slag subjected to long term aging. Constr. Build. Mater. 72, 158–166. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2014.08.052
Lizasoain-Arteaga, E., Indacoechea-Vega, I., Alonso, B., Castro-Fresno, D., 2020. Influence of traffic delay produced during maintenance activities on the life cycle assessment of a road. J. Clean. Prod. 253. https://doi.org/10.1016/j.jclepro.2020.120050
Lizasoain-Arteaga, E., Indacoechea-Vega, I., Pascual-Muñoz, P., Castro-Fresno, D., 2019. Environmental

impact assessment of induction-healed asphalt mixtures. J. Clean. Prod. 208. https://doi.org/10.1016/j.jclepro.2018.10.223

Martin, M., Svensson, N., Eklund, M., 2015. Who gets the benefits? An approach for assessing the environmental performance of industrial symbiosis. J. Clean. Prod. 98, 263–271. https://doi.org/10.1016/j.jclepro.2013.06.024

Mladenovič, A., Turk, J., Kovač, J., Mauko, A., Cotič, Z., 2015. Environmental evaluation of two scenarios for the selection of materials for asphalt wearing courses. J. Clean. Prod. 87, 683–691. https://doi.org/https://doi.org/10.1016/j.jclepro.2014.10.013

Mroueh, U.-M., Eskola, P., Laine-Ylijoki, J., 2001. Life-cycle impacts of the use of industrial by-products in road and earth construction. Waste Manag. 21, 271–277. https://doi.org/https://doi.org/10.1016/S0956-053X(00)00100-8

Nicholls, J.., Carswell, I., Thomas, C., Sexton, B., 2010. Durability of thin asphalt surfacing systems. Part 4: Final report after nine years' monitoring. 674 TRL Rep.

NREL [WWW Document], 2012. . U.S. Life Cycle Invent. Database. URL https://www.lcacommons.gov/nrel/search (accessed 11.19.12).

OECD, 20109. TF Transport Outlook 2019.

Pasetto, M., Baldo, N., 2010. Experimental evaluation of high performance base course and road base asphalt concrete with electric arc furnace steel slags. J. Hazard. Mater. 181, 938–948. https://doi.org/https://doi.org/10.1016/j.jhazmat.2010.05.104

PE International, 2014. Harmonization of LCA Methodologies for Metals.

Peinado, D., de Vega, M., García-Hernando, N., Marugán-Cruz, C., 2011. Energy and exergy analysis in an asphalt plant's rotary dryer. Appl. Therm. Eng. 31, 1039–1049. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2010.11.029

RIVM, 2016. ReCiPe 2016 V1.1.

Saade, M., Silva, M., Silva, V., 2013. Environmental impact allocation methods and their reflection on the attractiveness of blast furnace slag in cement industry.

Saveyn, H., Eder, P., Garbarino, E., Muchova, L., Hjelmar, O., van der Sloot, H., Comans, R., van Zomeren, A., Hyks, J., Oberender, A., 2014. Study on methodological aspects regarding limit values for pollutants in aggregates in the context of the possible development of end-of-waste criteria under the EU Waste Framework Directive, Report EUR 26769 EN. https://doi.org/10.2791/1125

Sayagh, S., Ventura, A., Hoang, T., François, D., Jullien, A., 2010. Sensitivity of the LCA allocation procedure for BFS recycled into pavement structures. Resour. Conserv. Recycl. 54, 348–358. https://doi.org/https://doi.org/10.1016/j.resconrec.2009.08.011

Sorlini, S., Sanzeni, A., Rondi, L., 2012. Reuse of steel slag in bituminous paving mixtures. J. Hazard. Mater. 209–210, 84–91. https://doi.org/https://doi.org/10.1016/j.jhazmat.2011.12.066

Stotko, O., 2011. Energy and Related Carbon Emission Reduction Technologies for Hot Mix Asphalt Plants. 10th Conf. Asph. Pavements South. Africa - CAPSA 8000, 1–9.

Stripple, H., 2001. Life Cycle Assessment of Road. A Pilot Study for Inventory Analysis.

UEPG, 2017. European Aggregates Association. A Sustainable Industry for a Sustainable Europe.

UNE-EN, 2002. UNE-EN 12457-4:2002 Characterisation of waste. Leaching. Compliance test for leaching of granular waste materials and sludges. One stage batch test at a liquid to solid ratio of 10 l/kg for materials with particle size below 10 mm (without or with size re.

United Nations, n.d. Sustainable Development Goals [WWW Document]. URL https://www.un.org/sustainabledevelopment/sustainable-development-goals/

Weidema, B., 2001. Avoiding Co-Product Allocation in Life-Cycle Assessment 4.

Worldsteel Association, 2018. World Steel in Figures 2018.

*Title Page
Click here to download Title Page: Title page information.docx

**Title**

Comprehensive analysis of the environmental impact of electric arc furnace steel slag in asphalt mixtures

**Authors**

Lizasoain-Arteaga, Esther[1]*; Lastra-González, Pedro[1]; Indacoechea-Vega, Irune[1]; Flintsch, Gerardo[2]

**Affiliations**

[1]GITECO Research Group, Universidad de Cantabria, Av. de los Castros 44, 39005, Santander, Spain

[2]Center for Sustainable Transportation Infrastructure, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

**Email addresses**

lizasoaine@unican.es (E. Lizasoain-Arteaga); pedro.lastragonzalez@unican.es (P. Lastra-González); indacoecheai@unican.es (I. Indacoechea-Vega); flintsch@vt.edu (G. Flintsch)

*Corresponding author. Tel +34942203943; Fax: +34942201703

***Declaration of Interest Statement**

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

**Highlights (for review)**

LCA of replacing high quality coarse aggregates by EAF steel slag

The inventory gaps were filled by laboratory tests and theoretical models

The absorption rate strongly affects the binder content and the aggregates humidity

Slags can replace aggregates located more than 144 km away