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# Comparative "from Cradle to Gate" Life Cycle Assessments of Hot Mix Asphalt (HMA) Materials

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**Abstract:** The objective of this work is to compare the environmental impact of two different hot mix asphalt (HMA) materials used for road construction in Italy. The analyses used a "from cradle to gate" Life Cycle Assessment (LCA) boundary system and the methodology included considerations about raw materials and fuel supply, as well as transport and manufacturing processes. Primary data provided by the producers and secondary data available in the literature were used as part of the analyses. The results suggest that the proposed method offers rigorous criteria for a comprehensive assessment of the environmental impact of HMA materials, which could be used, among others, as an evaluation parameter in public bids.

**Keywords:** pavements; HMA; from cradle to gate; EPD®; EN 15804; LCA

## 1. Introduction

On 19 April 2016 came into force the new Italian Public Procurement Code [1], which implements the European Directives 2014/23/EU, 2014/24/EU and 2014/25/EU [2–4]. This code provides guidelines and specifications for three different design levels for infrastructure projects:

- the technical and economic feasibility design stage (i.e., the best cost-benefit ratio among different alternatives);
- the selected or final design stage (i.e., the works that should be performed); and
- the executive project design stage (i.e., the description of the works and of the life cycle of the project).

Among the various principles of this new Code, it is stated that the contracting authorities have the ability and responsibility to adopt a policy inspired by social needs, as well as by the protection of health, environment and cultural heritage, and/or by the promotion of sustainable development. The concept of including environmental aspects into public procurement administration was addressed for the first time in the "Green Paper on the modernization of EU public procurement policy towards a more efficient European Procurement Market" [5]. This document introduced the possibility of integrating environmental aspects as part of the procedures used for purchasing goods, works and services. Accordingly, the European Community legislature has pointed out that the Member States should use public procurement to promote products and services that are respectful to the environment and, consequently, that they should also contribute to the implementation of the National Action Plans for Green Public Procurement (NAP GPP).

Unfortunately, the Green Public Procurement (GPP) has been poorly applied in contracts related to construction works, mainly due to two reasons [6]:

- difficulties in obtaining services/green products suppliers; and
- procedural difficulties in the implementation of GPP.

Despite this situation, the new Italian Public Procurement Code requires the administrative authorities to effectively contribute to the achievement of the environmental objectives set out in the Italian NAP GPP. These action plans, adopted by the Interministerial Decree of 11 April 2008 [7], aim at maximizing the use of GPP among public bodies in order to improve environmental, economic and industrial efficiency. The Italian GPP NAP, that was updated through the Decree of 10 April 2013, issued by the Italian Ministry of the Environment and the Protection of Natural Resources [8], contains the Minimum Environmental Criteria (MEC) requirements that should be included as part of public bids. Specifically, the Italian GPP NAP has identified a set of MEC for contracts related to the following "product categories": furniture; construction (construction and renovation of buildings with a focus on building materials); waste management; urban and energy services; electronic equipment; textiles and footwear; office furniture; food and catering services; building management services; and transport. For building materials, the MEC does not currently provide any formal requirement applicable to bitumen bounded road materials, which is the topic of this work, since it only stipulates regulations for cement concrete. At the international level, the Environmental Declaration of Building Products, which makes part of the Sustainability in Building Construction Specification ISO 21930:2007 [9], does not either include regulations for road materials.

As can be observed, the achievement of ambitious environmentally friendly road projects in Italy, as in any other European country, is still an on-going effort. Indeed, there are several gaps and challenges in current regulations that need to be faced, especially in some of the most complex processes which include many materials and works [10]. Thus far, for example, the assessment of road sustainability is limited to the evaluation of the environmental impact assessment that should be carried out in the case of major projects. These assessments focus on the principle of environmental compatibility, which is the ability of a system or structure to get integrated into the environment without negatively affecting or damaging it [11]. Nevertheless, the fact that this approach is only applicable when the infrastructure project under consideration has national significance, restricts the possibility of having a more comprehensive vision of an Italian environmental strategy for public construction projects [12].

The implementation of such an integral vision, however, should consider that the environmental criteria go beyond the environmental performance of materials and/or construction products. The selection of specific materials and products for a specific project, for example, should never overlook their geographical location and local availability, or the structural and functional performances that have to be provided [13]. In this sense, current practices in road infrastructure projects demonstrate that there is a need for a rigorous methodology that combines unbiased and comparable environmental criteria. This methodology should recognize that a proper environmental approach should avoid choosing a low cost material with higher environmental burden, balancing often conflicting objectives [14]. Furthermore, it should also recognize that the production chain significantly affects the environmental impact of any product [15] and, therefore, that each environmental analysis is only valid under its own boundary system and operational conditions [16]. Consequently, a more inclusive environmental approach for road projects should involve direct and indirect costs, both environmental and monetary, during the whole life cycle of the infrastructure system [17–20]. This perspective makes it possible to pursue the aim of sustainability, i.e., the integration of economic [21–23] and environmental aspects [24]. It is noteworthy that an approach of this nature could be applied not only to road infrastructure projects and related facilities [25], but also to railway [26,27], airports [28] and sidewalk infrastructure [29].

In the specific case of bituminous materials used in pavement engineering projects, there exist some limited recent efforts that have conducted comparative Life Cycle Assessments (LCA) of bituminous products (e.g., [30,31]). Nevertheless, these works do not analyze the impact related to the characteristics of the used fuels during the production of the materials and the adopted production processes. Furthermore, these results have regional specificity and are dependent on the adopted methodologies [32]. For example, it is common that only $CO_2$ emissions are considered as part of the environmental analysis (e.g., [33,34]), even though the best environmental solution does not necessarily correspond to that providing the lowest $CO_2$ emissions due to the complexity of the environmental problem.

The aim of this paper is to assess the environmental impact of two hot mix asphalt (HMA) materials that are currently used in the Italian road industry. The proposed evaluation consists of a series of environmental indicators that, according to existing international standards, are defined to have a type III label [35]. This label is a document that quantifies the environmental impact of a product based on LCA, which is verified by a qualified third party. The methodology used to accomplish the objectives of this work is the LCA of the asphalt mixes, considering both the Life Cycle Inventory analysis (LCI) and the Life Cycle Impact Assessment (LCIA) of the materials [36–38]. The study uses a "from cradle to gate" boundary approach (i.e., the analysis considers the product life cycle from the resource extraction processes to the moment at which the material is ready to be transported at the factory gate), including upstream and downstream processes, as specified in the International Environmental Product Declaration, or EPD® system. The interpretation of the results [39] permits to compare the environmental impact of the materials, and identifying the strengths and weaknesses of the processes evaluated. This, in turn, permits to improve and update the technology used as part of the processes studied and boost competitiveness.

As observed, this work overcomes some of the main limitations of existing LCA conducted on bituminous materials, which makes it a relevant contribution to the current state of knowledge on this topic. It is also important to highlight that the methodology herein used could be efficiently replicated to conduct similar analysis for other road materials and, consequently, it constitutes a useful tool for the achievement of the environmental policies stipulated by the Italian and European Community legislature.

## 2. Data and Methods

The authors calculated the environmental impact of two HMA produced by two different Italian asphalt mix companies (Company 1 and Company 2) that are located near Rome. The declared unit for the analysis is 1 Mg of bituminous concrete for binder layer used in flexible pavements. To compute the product declaration of this declared unit of material, which is a necessary step in the LCA analyses, the authors considered the methodological requirements stated in the ISO 14025:2006 standard [40], as well as those stipulated in the "General Programme Instructions of the International EPD System 2.5" [41], and in the Product Category Rules in the European standard 15804:2012+A1:2013 [42]. The standard EN 15804 "Sustainability of construction works, environmental product declarations, core rules for the product category of construction products" [42] provides guidelines to elaborate an unbiased set of data useful to examine and improve the environmental performance of a building material. For conducting the LCA of the two HMA considered in the study, some pre-specified minimum requirements are stated by the Product Category Rules (PCR)—which were developed and proposed by the Norwegian Environmental Product Declaration (EPD) Foundation [43]—for preparing an environmental declaration (EPD) for a product group consisting of asphalt and crushed stone. Indeed, the cited documents can be used to develop a type III label EPD of these materials [35]. This methodological approach was selected to conduct the environmental impact assessment of these mixtures because several experts consider that it offers the most comprehensive strategy currently available to perform these types of analyzes.

The bituminous mixes evaluated, which volumetric properties are summarized in Table 1, satisfy the Italian standards for road materials [44,45]. As observed in this Table, the composition of both mixes is identical. In fact, their only difference is the source or origin of the materials, as explained in a later section.

**Table 1.** Mixes composition.

| Component | Volume (%) | Density (kg/m$^3$) | Weight * (kg) |
|---|---|---|---|
| Bitumen | 10 | 1020 | 44.1 |
| Aggregates (limestone) | 85 | 2600 | 955.9 |
| Air void content | 5 | - | - |

* These values refer to the declared unit.

The selected boundary of the system is a "from cradle to gate", which means that the life cycle analysis requires data for the raw materials and fuel sources, as well as for transport and manufacturing processes. This means that the LCA study considered A1, A2 and A3 stages (upstream and core processes), as explained in Figure 1. Modules from A4 to D (i.e., construction process, use, end-of-life stages and benefits and loads beyond the system boundary) were considered to be beyond the scope of this work and, therefore, they were not included as part of the analysis (Figure 1).

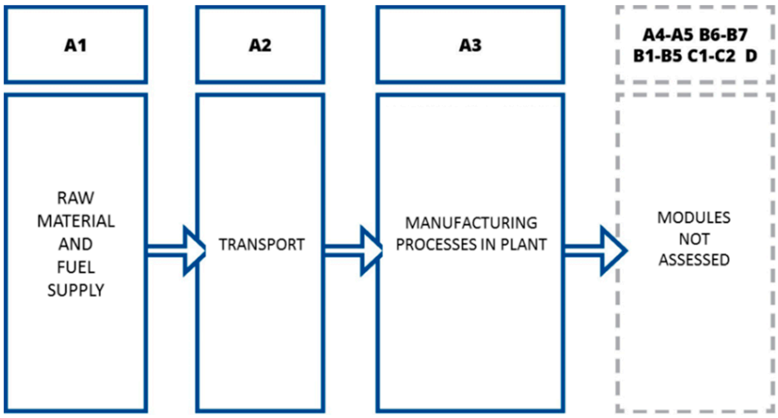


**Figure 1.** System boundaries.

The EPD® system defines three data categories for the inventory analysis phase [41]:

- primary data, obtained through on-site surveys and carried out by the producers;
- secondary data, available in the literature;
- tertiary data (also defined as other generic data), obtained through statistical averages.

In this study, primary data include:

- the composition of the mix;
- the performance of the vehicles used for aggregates and bitumen transport;
- the annual fuel consumption of the asphalt mix plants; and
- the distance of the asphalt plant from the quarries and the refinery.

Secondary data are related to the environmental impact of raw materials, fuels and transport, and they were obtained from existing environmental databases available in the literature [46–48]. Finally, tertiary data were not used in this study.

## *2.1. Inventory Analysis Phase: Primary Data*

As explained previously, in the LCI phase, the authors collected primary data directly from the two mix plants, named Company 1 and Company 2. The year 2014 was selected as the reference for the analysis. Information for both companies for this year is presented next.

Company 1 includes aggregates that are both natural (purchased from the quarries) and recycled (from recycling plants), and 20% of the total aggregates used in the binder mixes belong to the second group. The bitumen used in the production of the HMA comes from two refineries located in Falconara and Livorno (Italy), and the limestone material is extracted from a quarry in Riofreddo (Figure 2, obtained from Google Earth, and Table 2). In terms of transportation, bitumen and fuels are transported from the refineries to the plant by tankers with a capacity of 30 $m^3$, and aggregates are transported from the quarry to the plant by trucks with a capacity of 20 $m^3$. Regarding the energy sources used in the plant, the burner and the thermal oil boiler work with methane gas, and the annual consumption of natural gas is 730,835 $m^3$, while the annual electricity consumption is 392,020 kW. Finally, the annual production of asphalt concrete in this plant is 49,758 $m^3$ (the average hourly production is 80 $m^3$).


**Figure 2.** Company 1 geographical data.

**Table 2.** Geographical data of Company 1.

| Primary Data—Company 1 | Place | Distance (km) |
|---|---|---|
| Aggregates | Riofreddo | 73 |
| Bitumen | Falconara | 322 |
| | Livorno | 325 |

Table 2 lists the distances of the raw products to the mix plant of Company 1.

Similar to Company 1, aggregates in Company 2 are both natural (purchased from the quarries) and recycled (from recycling plants), and 20% of the total aggregates in the binder mixes are recycled. In this case, the bitumen is obtained from two refineries located in Falconara and Livorno (Italy) and limestone is extracted from a quarry in the city of Anagni (Figure 3, obtained from Google Earth). Regarding the transportation of raw materials, bitumen and fuels are transported from the refineries to the plant by tankers with a capacity of 20 $m^3$, while aggregates are transported from the quarries to the plant by trucks with a capacity of 20 $m^3$. Energy sources in this plant include low-sulfur crude oil, which is used to feed the oven in the plant mix, and gasoil, which feeds the diathermic oil boiler. The annual consumption of gasoil is 107,640 kg and the annual consumption of low-sulfur crude oil is 533,073 kg. In terms of production, this plant manufactures 51,257 $m^3$ of asphalt concrete per year (the average hourly production is 101 $m^3$).


**Figure 3.** Company 2 geographical data.

Table 3 lists the distances of the raw products to the mix plant of Company 2.

**Table 3.** Geographical data of Company 2.

| Primary Data—Company 2 | Place | Distance (km) |
|---|---|---|
| Aggregates | Anagni | 40.2 |
| Bitumen | Falconara | 322 |
| | Livorno | 325 |

Tables 4 and 5 show the smokestacks emissions in both mix plants. The data presented in these tables were obtained following the UNI EN ISO 16911-1:2013 standard [49], which regulates the methods for sampling and analyzing the control of emissions. It is noteworthy that a third party certified these data. The oxygen content by volume in the waste gas corresponds to 17% for Company 1 and to 16% for Company 2.

**Table 4.** Emissions generated by Company 1.

| Substance | Concentration (mg/Nm$^3$) | Mass Flow (g/h) |
|---|---|---|
| Particulates | 11.12 | 274.98 |
| Volatile Organic Compounds | 1.43 | 35.36 |
| Carbon monoxide (CO) | 98 | 2423 |
| Nitrogen oxides ($NO_x$) | 39 | 964.27 |
| Sulfur oxides ($SO_x$) | <1 | <24.72 |
| Hydrogen chloride (HCl) | 0.1323 | 3.27 |
| Hydrogen fluoride (HF) | 0.0226 | 0.56 |
| Cadmium (Cd) + Thallium (Tl) | <0.0005 | <0.012 |
| Mercury (Hg) | 0.00004 | <0.0001 |
| Antimony (Sb) + Arsenic (As) + Lead (Pb) + Chrome (Cr) + Cobalt (Co) + Copper (Cu) + Manganese (Mn) + Nickel (Ni) + Vanadium (V) + Tin (Sn) | <0.04879 | <1.21 |
| Polycyclic aromatic hydrocarbons | <0.005 | <0.12 |

**Table 5.** Emissions generated by Company 2.

| Substance | Concentration ($mg/Nm^3$) | Mass Flow (g/h) |
|---|---|---|
| Particulates | 2.6 | 95.66 |
| Volatile Organic Compounds | <1 | <36.79 |
| Nitrogen oxides ($NO_x$) | 75 | 2759.33 |
| Sulfur oxides ($SO_x$) | 48 | 1765.97 |
| Hydrogen chloride (HCl) | <1 | <36.79 |
| Hydrogen fluoride (HF) | <0.1 | <3.68 |
| Cadmium (Cd) + Thallium (Tl) | <0.01 | <0.37 |
| Mercury (Hg) | <0.01 | <0.37 |
| Antimony (Sb) + Arsenic (As) + Lead (Pb) + Chrome (Cr) + Cobalt (Co) + Copper (Cu) + Manganese (Mn) + Nickel (Ni) + Vanadium (V) + Tin (Sn) | <0.002 | <0.07 |
| Polycyclic aromatic hydrocarbons | <0.002 | <0.07 |

### *2.2. Inventory Analysis Phase: Secondary Data*

After reviewing several LCI databases available in the literature for LCIA, the following information was selected for the analyses:

- For aggregates, the Environmental Impact Categories of "from cradle to gate" analysis defined by the Union Nationale des Producteurs de Granulats [46,47] were used.
- For bitumen and fuels, the Life Cycle Inventory of Bitumen published by Eurobitume [48] was selected.
- For transport, the data of exhaust gas emission standards were obtained from the current Italian and European regulations [50–52]. Specifically, the data included information of the European and Italian standards and limits for the emissions of carbon dioxide, carbon oxide, hydrocarbon, and mono-nitrogen oxides.
- For earth-moving machines, data published by Vermeer [53] were considered.

In this phase, the LCI does not provide $CO_2$ emissions from the manufacturing process. However, the annual consumption of methane gas allows calculating the emissions of carbon dioxide that results from burning methane gas for Company 1. The stoichiometric combustion reaction of methane is (Equation (1)).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{1}$$

Considering the following molecular mass of the substances, it is then possible to calculate the corresponding $CO_2$ emissions, as follow (Equation (2)).

$$1\text{ kg } CH_4 + 4\text{ kg } O_2 \rightarrow 2.75\text{ kg } CO_2 + 2.25\text{ kg } H_2O \tag{2}$$

Similarly, the annual consumption of low-sulfur oil and gasoil for Company 2 allows calculating the emissions of carbon dioxide resulting from the burning processes. According to the Italian Ministry of the Environment [54], the $CO_2$ emissions for each ton of asphalt mix produced are (Equation (3)).

$$C_e = Q \cdot EF \cdot NCV \cdot O_f \tag{3}$$

where $C_e$ is the quantity of $CO_2$ emission due to fuel combustion, $Q$ is the quantity of fuel consumed, $EF$ is the emission factor, $NCV$ is the net calorific value of fuel and $O_f$ is the oxidation factor, representing the fraction of carbon oxidized during combustion. Table 6 lists the values used for this calculation.

**Table 6.** Parameters used for calculating $CO_2$ emissions of Company 2 [54].

| Low-Sulfur Crude Oil | | | |
|---|---|---|---|
| *Q* (kg) | *NCV* (GJ/t) | *EF* ($tCO_2$/TJ) | $O_f$ |
| 4.50 | 41 | 76.4 | 0.99 |
| **Gasoil** | | | |
| *Q* (kg) | *NCV* (GJ/t) | *EF* [$tCO_2$/TJ) | $O_f$ |
| 0.91 | 46 | 65.5 | 0.99 |

The obtained values of $CO_2$, which do not contain biogenic $CO_2$ emissions, refer to the declared unit of asphalt concrete.

The environmental analysis also requires using available data for the construction of homogeneous environmental profiles for the considered materials, machines and processes. According to the defined system boundaries, the authors collected six types of environmental profiles for the different elements considered in the analysis, as follows:

- limestone [46];
- recycled aggregate [47];
- bitumen [48];
- asphalt plant (smokestacks emissions);
- articulated lorry [51]; and
- earth-moving machine [53].

As an example of these profiles, Table 7 presents the air emissions of 1 Mg of limestone material.

**Table 7.** Air emissions for limestone at the quarry.

| Emissions | Quantity (g) |
|---|---|
| Carbon monoxide (CO) | 18.6 |
| Hydrocarbons (HC) | 0.43 |
| Nitrogen oxides ($NO_x$) | 61.9 |
| Particulates (PM) | 20.3 |
| Volatile Organic Compounds | 10.3 |
| Sulfur oxides ($SO_x$) | 4.8 |
| Hydrogen chloride (HCl) | $3.71 \times 10^{-2}$ |
| Cadmium (Cd) + Thallium (Tl) | $1.24 \times 10^{-4}$ |
| Mercury (Hg) | $1.37 \times 10^{-4}$ |
| Nickel (Ni) | $1.45 \times 10^{-3}$ |
| Selenium (Se) | $8.21 \times 10^{-5}$ |
| Vanadium (V) | $2.19 \times 10^{-3}$ |
| Methane ($CH_4$) | 2.53 |
| Carbon dioxide ($CO_2$) | 2360 |
| Biogenic carbon dioxide | 12.4 |
| Nitrous oxide ($N_2O$) | $4.52 \times 10^{-1}$ |
| Ammonia ($NH_3$) | 7.09 |
| Hydrogen sulfide($H_2S$) | $4.26 \times 10^{-3}$ |
| Arsenic (As) | $3.15 \times 10^{-4}$ |
| Chrome ($Cr^{3+}$) | $6.84 \times 10^{-3}$ |
| Hexavalent chromium ($Cr^{6+}$) | $1.67 \times 10^{-4}$ |
| Copper (Cu) | $2.05 \times 10^{-3}$ |
| Lead (Pb) | $1.5 \times 10^{-3}$ |
| Zinc (Zn) | $1.84 \times 10^{-4}$ |

Tables 8 and 9 list the amount of resources and the produced wastes that should be disposed for this same material. Information in this table corresponds to the same declared unit of 1 Mg of limestone. Equivalent information was collected for the other materials considered in the analysis.

**Table 8.** Use of resources in the process of obtaining limestone at the quarry.

| Resource Use | Quantity | Unit |
|---|---|---|
| Use of natural energy resources | 0.95 | kg |
| Use of natural resources, non-energy | 1040 | kg |
| Total primary energy | 60.9 | MJ |
| Renewable energy | 0.7 | MJ |
| Non-renewable energy | 60.2 | MJ |
| Electricity consumption | 2.54 | kWh |
| Use of fresh water | 27.6 | L |

**Table 9.** Limestone's waste to disposal.

| Waste to Disposal | Quantity (kg) |
|---|---|
| Hazardous waste | $8.82 \times 10^{-3}$ |
| Non-hazardous waste | $2.39 \times 10^{-1}$ |

In addition, these data were collected for each category of fuels, raw materials and machine considered in the study, when available in the literature.

### *2.3. Life Cycle Impact Assessment*

Data collected in the LCI phase are used for the LCIA through the characterization factors defined by EN 15804. These are factors derived from an environmental model that are applied to convert the assigned LCI results to a common unit of a category indicator. Therefore, this procedure reduces the scores of the environmental impact of each category to the same measurement units, expressed as equivalent (eq.) after the "conversion" process. For a given set of substances, the equivalence describes the amount of the reference substance that would have the same environmental effect. Consequently, they allow quantifying the extent to which each pollutant contributes to different environmental impacts.

As an example of the result of this process, Table 10 lists the environmental impact of 1 Mg of limestone, which was obtained using the information presented in Tables 7–9.

**Table 10.** Environmental impacts of 1 Mg limestone.

| Environmental Impact | Quantity | Unit |
|---|---|---|
| Global warming potential, *GWP* | $2.57 \times 10^{0}$ | kg $CO_2$ eq. |
| Depletion potential of the stratospheric ozone layer, *ODP* | $2.71 \times 10^{-7}$ | kg CFC-11 eq. |
| Acidification potential of soil and water, *AP* | $6.15 \times 10^{-2}$ | kg $SO_2$ eq. |
| Eutrophication potential, *EP* | $1.18 \times 10^{-2}$ | kg $(PO_4)^{3-}$ eq. |
| Formation potential of tropospheric ozone, *POCP* | $4.07 \times 10^{-3}$ | kg $C_2H_4$ eq. |
| Abiotic depletion potential for fossil resources, *ADP-fossil fuels* | $6.02 \times 10^{1}$ | MJ |
| Human Toxicity Potential (*HTP*) | $8.53 \times 10^{-1}$ | kg 1,4-DCB eq. |

The resulting data containing information about emissions, use of resources and wastes for each one of the six categories evaluated describe the upstream process and allow calculating the A1–A2 modules of the EPD.

The allocation rules used in the LCIA comply with the EN 15804 regulation [42]. All materials and energy flows were included in the calculation, therefore, energy and mass contributions considered in the analysis were fully allocated into the system. Nevertheless, energy and material contributions related to asphalt production but different from the main object of the present analysis were excluded (e.g., bitumen-bound aggregate mixtures). Finally, the wastes generated directly from the asphalt production, if carried out within the plant, were allocated to the production of asphalt.

The authors obtained the EPD of 1 Mg of asphalt concrete to be used in the construction of binder courses collecting data during the inventory analysis phase and selecting the characterization factors provided by EN 15804 and by Huijbregts [55] for "Human Toxicity Potential" (*HTP*). Although it is not defined by the EN 15804 specification, the additional parameter *HTP* was considered as part of the analysis due to the interest of the European Community on this aspect.

In summary, the product declaration considers parameters describing the environmental impact, the use of resources, the waste categories, the output flow materials, and the potential of human toxicity.

## 3. Results

Data collected in the LCI were modeled using the characterization factors listed in [42] and proposed by Frischknecht et al. [56]. As explained previously, the concept of characterization factors permits to compare the ability of different substances to cause the same environmental consequence. These factors convert the assigned LCI results into a common unit of a category indicator as explained by Equation (4).

$$IC = \sum_{x} CF_{ic}(x) \cdot INV(x) \quad (4)$$

where $IC$ is the Impact Category, obtained from the inventory $INV(x)$ of the substance $x$ and $CF_{ic}(x)$ the characterization factor assigned to the substance $x$ for the calculation of $IC$.

For environmental impacts which have a chemical unit of measure, the unit is expressed as equivalent (eq.) due to the applied "conversion" process.

Table 11 presents the resulting impact categories of 1 Mg of the asphalt concrete produced by both companies.

**Table 11.** Impact categories of 1 Mg of asphalt concrete for the two companies.

| Impact Categories | Company 1 | Company 2 | Unit |
|---|---|---|---|
| Global Warming Potential, *GWP* | 34.48 | 38.04 | kg $CO_2$ eq. |
| Acidification Potential, *AP* | 0.16 | 0.16 | kg $SO_2$ eq. |
| Ozone layer Depletion Potential, *ODP* | $2.55 \times 10^{-7}$ | $2.55 \times 10^{-7}$ | kg CFC-11 eq. |
| Eutrophication Potential, *EP* | 0.78 | 0.78 | kg $(PO_4^{3-})$ eq. |
| Formation potential of tropospheric ozone, *POCP* | 0.01 | 0.01 | kg $C_2H_4$ eq. |
| Abiotic Depletion Potential for fossil resources, *ADP-fossil fuels* | 441.58 | 438.05 | MJ |
| Use of natural energy resources | 9.34 | 10.25 | kg |
| Use of natural resources, non-energy | 1054.75 | 1054.76 | kg |
| Total primary energy | 422.78 | 419.41 | MJ |
| Renewable energy | 0.68 | 0.68 | MJ |
| Non-renewable energy | 422.10 | 418.73 | MJ |
| Electricity consumption | 4.92 | 4.77 | MJ |
| Net use of fresh water | 0.03 | 0.03 | $m^3$ |
| Components for reuse | 0 | 0 | kg |
| Materials for recycling | 0.30 | 0.30 | kg |
| Materials for energy recovery | 0 | 0 | kg |
| Human Toxicity Potential (*HTP*) | 2.97 | 2.54 | kg 1,4-DCB eq. |

As observed, the main differences between the impacts of the two mix materials summarized in Table 11 are related to the fuels and transport and manufacturing modules, while quality and quantity of raw materials are the same for both companies. Except for ADP-fossil fuels, Company 1 has an overall lower environmental impact. The results are compliant with the fact that this company uses methane gas as a fuel source. Out of all fossil fuels, natural gas—which is used by Company 1—has the highest ratio between energy produced by combustion and emitted $CO_2$ and, therefore, it has a low contribution to global warming. Besides, it was found that Company 1 requires more electricity than Company 2 to produce the declared unit of bituminous concrete, and Company 2 has a lower HTP in comparison to Company 1.

The interpretation phase of the results included the analysis of the average percentage contribution of fuels and raw materials (A1 phase), internal and external transport (A2 phase) and manufacturing processes (A3 phase) of the two companies [39]. Table 12 summarizes the results obtained for the analysis conducted for both mix plants.

The values in this table refer to the percentage of contribution of each phase (i.e., A1 to A3), to the total LCA of the environmental impact under evaluation. Consequently, the values in every column always sum up to 100%. The advantage of presenting the LCA results in this way is that it permits to easily identify and analyze the stages that contribute the most to each environmental hazard or impact, as done by Renzulli et al. [57].

**Table 12.** Results of LCA for the two companies (values in percentage).

| | Company 1 | | | | | | | Company 2 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Phase** | ***GWP*** | ***AP*** | ***ODP*** | ***EP*** | ***POCP*** | ***ADP Fossil*** | ***HTP*** | ***GWP*** | ***AP*** | ***ODP*** | ***EP*** | ***POCP*** | ***ADP Fossil*** | ***HTP*** |
| A1 | 43 | 95 | 87 | 90 | 93 | 72 | 70 | 39 | 90 | 92 | 90 | 93 | 72 | 82 |
| A2 | 22 | 3 | 7 | 7 | 6 | 28 | 1 | 20 | 0 | 4 | 3 | 6 | 28 | 0 |
| A3 | 35 | 2 | 7 | 3 | 1 | 0 | 29 | 42 | 10 | 4 | 7 | 1 | 0 | 18 |

Note: *GWP*: global warming potential; *AP*: acidification potential; *ODP*: formation potential of tropospheric ozone; *EP*: eutrophication potential; *POCP*: formation potential of tropospheric ozone; *ADP fossil*: abiotic depletion potential for fossil resources; *HTP*: human toxicity potential.

## 4. Discussion

The obtained results are interesting and they should be examined to highlight the difference in terms of environmental performances.

For the *GWP*, the differences in the results between the two asphalt plants are mainly due to the use of different fuel sources in the manufacturing process. This result was already anticipated based on the differences previously discussed about the LCA of the HMA of both companies. Transport phase (A2) accounts for 22% and 20% of the total *GWP*, while internal transport included in the A2 phase resulted to be negligible, as it represents less than 1% of the total *GWP* emissions. As observed in Table 12, the *GWP* in phase A3 for Company 2 resulted to be 20% greater than that obtained for Company 1. The reason explaining this result lies in the fact that natural gas is the most environmentally friendly fossil fuel, as explained before. Indeed, natural gas is a much cleaner fuel source than crude oil and its derivatives, since its combustion produces 20%–30% less carbon dioxide ($CO_2$) compared to other petroleum-based products [58,59].

In terms of the Acidification Potential (*AP*) emissions, it is observed that more than 90% of the *AP* emissions comes from processes related to raw materials (A1). The third party certified analysis of smokestacks emissions demonstrated strong differences between the two mix plants. Data in Table 12 show that the use of low-sulfur crude oil and gasoil instead of methane makes the A3 *AP* emissions of Company 2 five times higher than the A3 emissions of Company 1. As stated previously, the use of methane instead of gasoil and low-sulfur crude oil explains this result, as confirmed by Chai et al. [60].

Regarding the Ozone layer Depletion Potential (*ODP*) emission, the results show that more than 90% of the total emissions in both companies are related to raw materials and fuel processes (A1 stage). Similar to what was reported for the *AP* emissions, the use of low-sulfur crude oil and gasoil instead of methane also has a significant impact on *ODP* (stage A3 in Table 12). Besides, it was found that the item related to internal transport processes included in the A2 stage represents less than 2% of the total *ODP* results.

The results listed in Table 12 show that the differences in the contribution of the Eutrophication Potential (*EP*) emissions for the A1 phase between the two companies are not appreciable. In this case, the distances from the quarries to the plants, as well as the type of fuel sources used, explain the differences observed in the A2 and A3 results between the two companies (i.e., larger transport-related emissions and lower manufacturing-related emissions for Company 1).

The results of *POCP* are the same for both mixes, suggesting that the use of different fuel sources in the manufacturing process does not influence this environmental impact. The results highlight that more than 90% of the total emissions in both companies are related to raw materials and fuel processes (A1 stage). The item related to internal transport processes included in the A2 stage represents 6% of the total *POCP* results, while the A3 stage contributes to 1%.

In terms of the Abiotic Depletion Potential (*ADP*) for fossil resources, the results for both companies were found to be the same. The contribution of the consumption of fossil resources is about half of the total environmental impact and it is correctly attributed to the A1 phase, according to the EN 15804 [42].

Finally, for the distribution of Human Toxicity Potential (*HTP*) emissions, it was found that the contribution of the A2 phase is negligible, whereas the incidence of raw materials (A1 phase) strongly influences the results. In fact, the analysis showed that the average result for the aggregates-related emissions is 70%, and for the bitumen is 6%. In this case, it is also important to observe that the contribution of the A1 stage to the total *HTP* emissions where 15% lower for Company 1, while the contribution of the A3 stage to the total *HTP* in Company 1 was 1.6 larger than for Company 2. These results could be explained by the chemical composition of fuels: pollutants contained in gasoil and low-sulfur crude oil have higher impact on the *HTP* emissions than the ones contained in natural gas.

As can be observed from the previous analysis, the LCAs herein conducted permitted to identify the contribution of the different stages related to the production of both asphalt mixtures (i.e., from the acquisition of the raw materials and fuel supplies to the final production of the mixes themselves), to a diverse set of environmental impact factors.

The results demonstrate that there are important differences in the environmental performance of the two HMA materials, and that these differences go beyond the specific results obtained for the $CO_2$ emissions. This is an important observation since several documents available in the literature have quantified the environmental impact of asphalt mixes using the computation of greenhouse gas emissions and, particularly, $CO_2$ emissions (e.g., [34,61]). However, as demonstrated in this work, the Global Warming Potential (*GWP*) is only one—though the most famous—of the environmental categories to be considered when evaluating the environmental impact of a product. Indeed, the experience gained in this area suggests that the exclusive consideration of $CO_2$ emissions limits the possibility of conducting an integral LCA, and promotes the chances of selecting of a low $CO_2$ material that could present unacceptable environmental burdens. The Italian Ministry of the Environment is taking measures in this regard, since it is currently discussing the MEC for road construction and maintenance. The implementation of NAP GPP would probably consider the type III label as a rewarding parameter in public bids. This, in turn, will be useful not only for protecting the environment, but also for improving and updating the technology used and boost competitiveness.

## 5. Conclusions

Although the interest in environmental-related construction issues has grown fast in recent years, there is still a need for a comprehensive approach that could be universally applied to different civil works. Often, the environmental analysis is conducted using a qualitative rather than a quantitative approach, providing weak and far from reliable results. In Italy, the new Public Procurement Code requires public authorities to assess the environmental impact of construction projects in public bids.

As a response to this need, this paper presents an application of the Life Cycle Assessment, or LCA, processes on two different hot mix asphalt materials used for the construction of road infrastructure. The method complies with current European standards concerning environmental management, and it consists of four steps: (1) the definition of the goal and scope; (2) an inventory analysis; (3) the impact assessment; and (4) the interpretation of the results.

The presented analysis allows quantifying the environmental impact of a declared unit of 1 Mg of hot asphalt mix for the construction of binder layers in pavement structures produced at two different plant mixes (Company 1 and Company 2), using the "from cradle to gate" boundary system (i.e., including upstream and core production processes). The primary and secondary data used for the study were defined based on the European standard EN 15804.

The examined mix plants differ for the use of methane as a fuel source (Company 1) instead of gasoil and low-sulfur crude oil (Company 2). The results suggest that the environmental impact of Company 1 in terms of *GWP* and use of natural energy resources is lower than the one obtained for Company 2. The LCA of both products demonstrates that Company 2 presents a lower *ADP-fossil fuels*, energy and electricity consumption, and *HTP*. This shows that it is incorrect to consider only one indicator to select the "greenest" process among several alternatives. Indeed, it was found that each indicator had a different incidence in terms of its environmental impact, and that the contribution of each stage related to the LCA of both mixtures (i.e., acquisition of raw materials and fuel supplies, transportation, and manufacturing) was significantly different among indicators. This result is paramount because contracting authorities often consider *GWP* as the only environmental criterion to evaluate or control the impact of a product or process, while the results obtained in this work demonstrate the need for considering a broader panel of environmental indicators.

In conclusion, the "from cradle to gate" Life Cycle Assessment conducted to the production of bituminous concrete demonstrates that it is possible to use an unbiased tool to calculate and examine the environmental performance of a road material. Furthermore, the results from those assessments provide reliable information to identify potential actions that could contribute to reduce the environmental impact related to a construction product. Finally, it is worth mentioning that that the results obtained from this LCA could be used as reliable input data in more comprehensive environmental analyses that include road construction and maintenance or rehabilitation activities (e.g., [62]).

**Author Contributions:** Antonio D'Andrea and Laura Moretti conceived and designed the experiments; Vittorio Mandrone performed the LCI and the LCIA; Laura Moretti analyzed the data; and Silvia Caro wrote the paper.

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## Abbreviations

| | |
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| HMA | Hot Mix Asphalt |
| LCA | Life Cycle Assessment |
| EU | European Union |
| NAP GPP | National Action Plans for Green Public Procurement |
| GPP | Green Public Procurement |
| MEC | Minimum Environmental Criteria |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| EPD | Environmental Product Declaration |
| PCR | Product Category Rule |
| *GWP* | Global warming potential |
| *ODP* | Depletion potential of the stratospheric ozone layer |
| *AP* | Acidification potential of soil and water |
| *EP* | Eutrophication potential |
| *POCP* | Formation potential of tropospheric ozone |
| *ADP-fossil fuels* | Abiotic depletion potential for fossil resources |
| *HTP* | Human Toxicity Potential |

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