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Mass Concrete with EAF Steel Slag Aggregate: Workability, Strength, Temperature Rise, and Environmental Performance

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Abstract: Temperature control is the primary concern during the design and construction process of mass concrete structures. As the concrete production has an enormous negative environmental impact, the development of green mass concretes will eventually become as important as the thermal characteristics. Therefore, this paper investigates the use of Electric Arc Furnace (EAF) steel slag aggregate for the partial replacement of the natural aggregate in the production of mass concrete. The impact of EAF steel aggregate on mass concrete workability, strength, and thermal behaviour was analysed. In addition, a cradle-to-gate LCA study was conducted to evaluate the environmental footprint and sustainability potential of the tested mass concrete mixtures. The study results suggest that the use of EAF steel slag aggregate in combination with a low-heat cement with a high content of blast furnace slag can significantly lower the temperature, reduce the environmental impact, and increase the sustainability potential of mass concrete, while at the same time providing sufficient workability and compressive strength. The study results indicate that EAF steel slag can be upcycled into an aggregate for the production of green mass concrete mixtures.

Keywords: mass concrete; thermal stress; EAF steel slag; green concrete; LCA; sustainability

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1. Introduction

Mass concrete has been used extensively over the past decades for the construction of vital infrastructure, such as nuclear power plants, long-span bridges, coastal structures, and hydroelectric dams. The design and construction of mass concrete structures are primarily concerned with the problem of thermal stresses and temperature control [1]. During the hardening of mass concrete, a large amount of heat is released due to the cement hydration. This often results in the formation of cracks, which can have a severe negative impact on quality, functionality, and durability of mass concrete structures [2,3]. Therefore, the main challenge regarding the design of mass concrete is to reduce the thermal stress and thus the formation of cracks, while at the same time meeting the high strength and durability requirements of mass concrete structures [4].

As concrete is the second most consumed material in the world after water, it has an enormous impact on the environment due to the massive consumption of natural resources and high carbon emissions during cement production [5,6]. The negative environmental impacts of concrete production can be decreased by considering green concretes, i.e., concretes made from different recycled waste materials that lead to a reduction in the environmental footprint [7,8]. Green concretes are generally developed by using (i) alternative aggregates (i.e., aggregates made from different types of recycled waste) or/and (ii) alternative binders with lower CO_2 emissions (i.e., supplementary cementitious materials from recycled waste or byproducts) [9]. Even though there are numerous waste products or byproducts that can be used in the construction sector, only a handful of alternative materials are generally considered for substituting the natural aggregate in the green concrete mixtures: construction and demolition waste, bottom and fly ash, and iron and steel slags [10].

Electric Arc Furnace (EAF) steel slag is a waste product or byproduct of the steelmaking industry, which is formed during the process of melting scrap steel. The quality of EAF steel slag depends on its chemical, physical, and mechanical properties [11,12]. EAF steel slag can contain high contents of free calcium and magnesium oxides, which expand during the hydration process and usually lead to cracking in confined applications [13]. However, with proper ageing, treatment, and stabilisation, the potential expansion phenomenon can be avoided, and the EAF steel slag can be used as a manufactured aggregate for substituting the natural aggregate in concrete mixtures [14,15]. The use of EAF steel slag aggregate can improve concrete's mechanical properties [16,17], carbonation and chloride penetration resistance [18,19], water tightness [20], durability [21–23], shielding properties [24,25], and fire resistance [26].

In addition to improving the technical performance of concrete, the use of EAF steel slag aggregate is also environmentally beneficial as it leads to an overall decrease in steel slag landfill quantities, in extraction and depletion of natural resources, and in energy consumption [27–29]. The environmental benefits of the use of EAF steel slag in concrete production can be evaluated with the Life Cycle Assessment (LCA) methodology. LCA is a widely used method for the assessment of environmental impacts associated with all the stages of the life cycle of a product, which is based upon the international standards ISO 14040 and ISO 14044. LCA analysis has been used by various researchers to evaluate the potential environmental benefits and hotspots of concretes made with EAF steel slag aggregate and compare their environmental performance to both conventional concretes and concretes made with other types of recycled waste materials [30–37].

Numerous studies have shown the advantages of the use of EAF steel slag aggregate for concrete manufacturing in terms of the improved technical characteristics and reduced environmental impact. However, there is limited information on the potential benefits of mass concrete made with EAF steel slag aggregate. Therefore, the aim of this study was to evaluate the use of the EAF steel slag aggregate for the partial replacement of the natural aggregate in the production of mass concrete. The main objectives of the study were (i) to investigate the impact of EAF steel slag aggregate on the workability, strength, and thermal behaviour of mass concrete and (ii) to assess the environmental performance of the production of a mass concrete with EAF steel slag aggregate by means of an LCA study. The study results indicate that EAF steel slag can be successfully upcycled into an aggregate for mass concrete and therefore contribute to the development and production of environmentally friendly mass concrete mixtures.

2. Materials and Methods

2.1. Concrete Mixtures

2.1.1. Cement

The basic requirement for the selection of binders for mass concrete is low heat of hydration. The so-called blended cements are most commonly used for the production of mass concretes [38]. Two types of cement were considered in this study, i.e., CEM II/B-M (LL-V) 42.5 N and CEM III/B 32.5 N LH-SR. The considered types of cements differ in (i) composition, i.e., the type and amount of supplementary cementitious materials (SCM) and (ii) the heat released during the hydration in a cement paste of standard consistency after 7 days. The CEM II-type of cement contains between 21 and 35% mineral additives (i.e., limestone and fly ash), with the released heat during the hydration being 185.8 J/g of specimen. The CEM III-type of cement contains between 66 and 80% granulated blast furnace slag, with the released heat during the hydration being 139.8 J/g of specimen. The commercially available cements used in the study were produced in accordance with the standard SIST EN 197-1.

2.1.2. Plasticiser

In addition to the hydration heat of the cement, the total amount of heat in the mass concrete is also affected by the amount of cement per unit volume of concrete. Waterreducing concrete admixtures or superplasticisers are nowadays used to reduce the cement content per unit volume of concrete while maintaining a constant water–cement (w/c) ratio [39]. In mass concrete, the use of efficient superplasticisers allows for the use of smaller amounts of cement with a smaller maximum aggregate grain size. A highly effective new-generation superplasticiser was employed in this study, which meets the SIST EN 934-1 and SIST EN 934-2 standards.

2.1.3. Aggregates

The granulometric composition of aggregate is an important factor in maintaining the quality of mass concrete. To minimise the heat of hydration (i.e., to minimise the amount of cement), slightly larger amounts of fine aggregate are needed. Concretes with larger maximum aggregate grains are more likely to have larger and more numerous microcracks and thus the potential for bleeding cavities to form under the larger aggregate grains. Two different types of aggregates were considered in this study: natural aggregate and EAF steel slag aggregate. The natural aggregate considered in this study was the river gravel obtained from the Savska Loka separation plant, which is located in the city of Kranj, Slovenia. The EAF steel slag aggregate was provided by the steel producer SIJ Acroni from Jesenice, Slovenia. The nominal maximum size for the natural aggregate was 32 mm, while the nominal maximum size for EAF steel slag aggregate was 16 mm. The aggregates considered in this study can be seen in Figure 1.

(a) **(b)**

Figure 1. Natural aggregate (**a**) and the EAF steel slag aggregate (**b**).

2.1.4. Mixtures

Altogether, eight different concrete mixtures were prepared and tested in this study (Table 1). The first four mixtures were prepared with only natural aggregate (i.e., mixtures MB-1 to MB-4), while the other four were prepared with a combination of natural aggregate and EAF steel aggregate (i.e., mixtures MB-5 to MB-8). The mixtures MB-5 to MB-8 were made with 45% natural aggregate and 55% EAF steel slag aggregate. The general properties of the cement, the quantity of cement, and the initial temperature of the concrete have a great influence on the heat release of the fresh mass concrete. Therefore, two different quantities of cement were considered in the designed mixtures, i.e., 320 and 350 kg/m^3 of placed mass concrete.

In order to achieve slightly higher compressive strengths of the mass concrete, we decided to keep the w/c ratio below 0.50. However, the total w/c (i.e., $(w/c)_{tot}$) could increase due to water absorption of the aggregate. The water absorption of the natural aggregate was lower than that of the EAF steel slag aggregate (Table 2). Thus, there was a small increase in the $(w/c)_{tot}$ of the mixtures made with only natural aggregate (i.e., mixtures MB-1 to MB-4), i.e., from the design value of 0.50 to $(w/c)_{tot}$ of 0.51. On the other hand, the $(w/c)_{tot}$ of the mixtures with the EAF steel slag aggregate increased more considerably, ranging between 0.65 and almost 0.68.

Table 1. The mass concrete mixtures (all quantities in kg per m^3 of concrete).

Mixture	CEM II	CEM III	Water	Plasticiser	Natural Aggregate 0/4 (mm)	4/8 (mm)	8/16 (mm)	16/32 (mm)	EAF Steel Slag Aggregate 0/2 (mm)	2/4 (mm)	8/11 (mm)	0/16 (mm)
MB-1	320	/	164	1.92	1192	100	359	339	/	/	/	/
MB-2	/	320	164	1.92	1189	99	358	338	/	/	/	/
MB-3	350	/	178	1.75	1153	96	347	328	/	/	/	/
MB-4	/	350	178	1.75	1149	96	346	327	/	/	/	/
MB-5	320	/	216	1.60	994	/	/	/	372	126	122	608
MB-6	/	320	216	1.60	991	/	/	/	371	125	121	606
MB-7	350	/	227	1.75	960	/	/	/	360	121	117	587
MB-8	/	350	227	1.75	926	/	/	/	359	121	117	586

Table 2. The physical and geometrical properties of the natural and EAF steel slag aggregates.

Parameter	Natural Aggregate 0/2 (mm)	0/4 (mm)	4/8 (mm)	8/16 (mm)	16/32 (mm)	EAF Steel Aggregate 0/2 (mm)	0/4 (mm)	4/8 (mm)	8/16 (mm)	16/32 (mm)
Shape index (%)	-	-	11	7	8	-	-	3	3	2
Apparent specific density ρ_a (kg/m^3)	-	2780	2780	2780	2780	-	3710	3720	3720	3720
Bulk-specific gravity of samples dried in the oven ρ_{rd} (kg/m^3)	-	2710	2740	2740	2730	-	3150	3290	3290	3290
Bulk-specific gravity ρ_{ssd} (kg/m^3)	-	2740	2750	2750	2750	-	3300	3410	3410	3410
Water absorption (24 h) WA_{24} (%)	-	0.9	0.6	0.6	0.6	-	4.7	3.5	3.5	3.5
Resistance to fragmentation (%)	-	-	-	18	-	-	-	-	20	-
Resistance to abrasion (%)	-	-	-	10	-	-	-	-	14	-
Resistance to salt crystallisation (%)	-	-	-	1	-	-	-	-	3	-
Resistance to freezing and thawing (%)	-	-	-	0.1	-	-	-	-	0.5	-
Sand equivalent (%)	77	-	-	-	-	83	-	-	-	-
Fine content (%)	5.4	-	-	-	-	2.8	-	-	-	-

2.2. Life Cycle Assessment (LCA)

2.2.1. Goal and Scope of the Study

The aim of the LCA study was to analyse the environmental impacts associated with the production of conventional and green mass concrete. The main difference between the two sets of concrete mixtures was in the used aggregate: the conventional mass concrete was made with natural aggregate, while the green mass concrete was made with a mixture of natural aggregate and EAF steel slag aggregate. The main goal of the LCA study was to evaluate the potential environmental benefits of the production of green mass concrete where EAF steel slag aggregate was used to replace a portion of natural aggregate in the concrete mixture. The functional unit was specified as the production of 1 m^3 of mass concrete.

The "cradle-to-gate" approach was adopted in this LCA study, with the concrete production stage being the most relevant life cycle stage when assessing the environmental impacts of concretes [40,41]. Hence, this LCA study considered the extraction and processing of raw and alternative materials, consumption of energy and water, and transport of materials to the concrete production plant. The transfer of upstream environmental burdens of alternative materials (e.g., EAF steel slag aggregate) into the LCA model was avoided by following the consequential modelling principle (i.e., system expansion) [42]. The schematic representation of the system boundaries is presented in Figure 2.

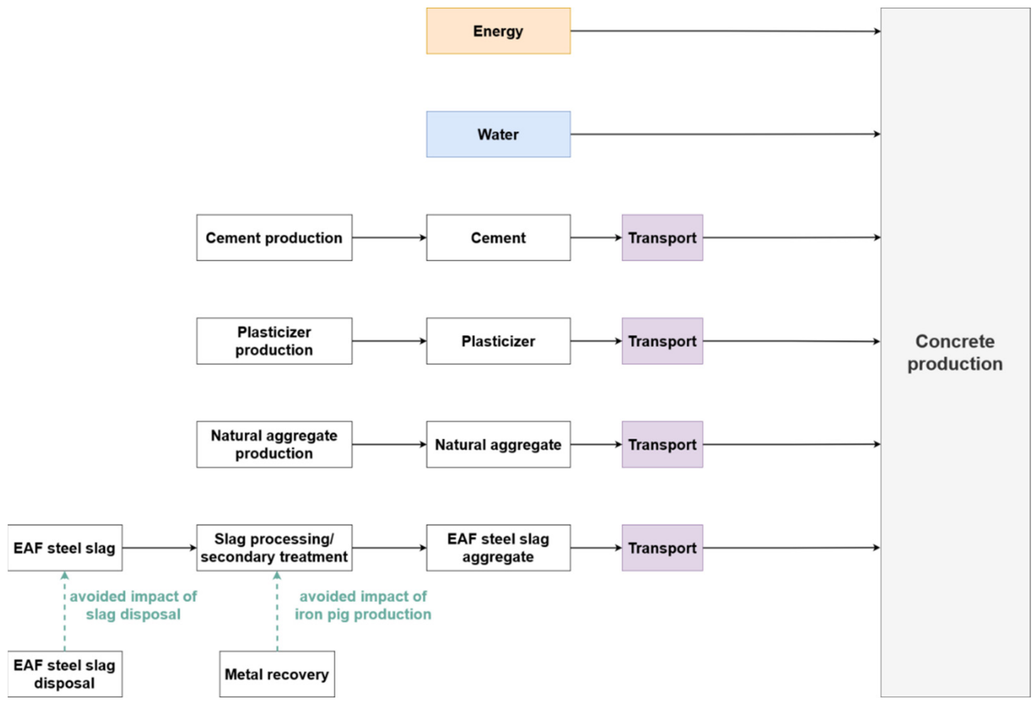

Figure 2. The schematic representation of system boundaries.

The avoided disposal of slag in a landfill and the recovery of metals from the slag were also included within the system boundaries due to the system expansion. The avoided disposal of the EAF steel slag and the process of metal recovery were treated as environmental credits. The recovery of metals from the EAF steel slag reduced the demand for the primary production of metals, while the avoided disposal of the steel slag led to a reduction in the amount of material that needed to be landfilled. Therefore, the environmental burden relating to slag landfilling and the production of metals was considered as an avoided impact, with the avoided impact being subtracted from the total impact associated with the production of green mass concrete [33].

2.2.2. Life Cycle Inventory (LCI)

The production of cement and plasticiser, the production and supply of energy and water, and the transport processes were evaluated based on the LCI data given in the GaBi Professional Database. The modelling of transport in GaBi considered only the emissions that resulted from the operation of the transportation vehicles [43]. Two-way transport distances were considered; i.e., the trucks were fully loaded heading towards the production facility and empty when leaving the production facility. The full life cycle inventory can be seen in the Supplementary Materials.

The data on the energy requirements and emissions associated with the production and processing of natural aggregate (i.e., river aggregate) were obtained from the literature [44]. The data on the energy and water required for processing of EAF steel slag (i.e., cooling, quenching, ageing, crushing, and sieving) were provided by the steel producer SIJ Acroni from Jesenice, Slovenia. On average, 2.9 kWh of electricity, 0.2 L of diesel, and 22 kg of water were consumed for processing 1 tonne of EAF steel slag.

The content of metal in the EAF steel slag was about 8%. The energy requirements for the recovery of metal were provided by SIJ Acroni, with 28 kWh of electricity and 1 L of diesel needed for the extraction of approximately 8 kg of metal from 1 tonne of EAF steel slag. The environmental credit due to the metal recovery was evaluated as an avoided pig iron production [33], with the pig iron production being modelled based on the LCI data given in the Ecoinvent 3.8 database. The environmental benefits due to the avoided disposal of the EAF steel slag were evaluated as an avoided landfill for inert material [33], which was modelled based on the LCI data given in the GaBi Professional Database.

2.2.3. Life Cycle Impact Assessment (LCIA)

The environmental impacts were evaluated with CML 2001 (version August 2016) life cycle impact assessment (LCIA) method. CML 2001 is an LCIA method that restricts quantitative modelling to early stages in the cause–effect chain to limit uncertainties, with results being grouped in midpoint categories according to commonly accepted groupings [45]. CML 2001 is one of the most commonly used impact assessment methods when evaluating and comparing the environmental performance of traditional and green concretes [46–48].

The results of the CML 2001 LCIA were presented in terms of the following impact potentials: Abiotic Depletion Potential for nonfossil resources (ADP el., unit: kg Sb equiv.); Abiotic Depletion Potential for fossil resources (ADP fos., unit: MJ); Acidification Potential (AP, unit: kg SO_2 equiv.); Eutrophication Potential (EP, unit: kg ${PO_4}^{-3}$ equiv.); Freshwater Aquatic Ecotoxicity Potential (FAETP, unit: kg DCB equiv.); Global Warming Potential (GWP, unit: kg CO_2 equiv.); Human Toxicity Potential (HTP, unit: kg DCB equiv.); Ozone Depletion Potential (ODP, unit: kg R11 equiv.); Photochemical Ozone Creation Potential (POCP, unit: kg Ethene equiv.); and Terrestrial Ecotoxicity Potential (TETP, unit: kg DCB equiv.).

2.2.4. Life Cycle Interpretation

The interpretation phase of an LCA study generally consists of different types of numerical analysis, such as contribution, comparative, and sensitivity analyses [49]. The contribution analysis is used to decompose LCA results into several contributions that provide an overview of specific contributing factors. The comparative analysis is used to simultaneously look at different product alternatives, which enables a systematic overview of environmental impacts of different product alternatives or processes.

The sensitivity analysis can be performed by means of a perturbation analysis. The perturbation analysis is used to determine the effect of a small variation of single parameter values on the overall model result. The general idea is that small perturbations of the input parameters propagate as deviations of the resulting output and that useful information can be obtained by indicating which parameters lead to large and which to small deviations [49].

First, the effect of an arbitrary change of a single parameter was assessed, while keeping all the other parameters constant. Second, the sensitivity ratios (SR) were calculated for all relevant parameters for each scenario. The sensitivity ratio is defined as the ratio between the relative change of the result and the relative change of the parameter:

$$\mathrm{SR} = \frac{\frac{\Delta\mathrm{result}}{\mathrm{initial\ result}}}{\frac{\Delta\mathrm{parameter}}{\mathrm{initial\ parameter}}} \tag{1}$$

The SR values larger than 1 or smaller than −1 indicate sensitive parameters, whereas SR values close to 0 indicate insensitive parameters. The rationale for using a perturbation analysis with or instead of an uncertainty analysis is to analyse inherent sensitivities by indicating which parameter variations can have the greatest effect on the overall results of the LCA study [50].

2.3. Sustainability Index

In addition to the LCA, the sustainability potential of the considered mass concrete mixtures can be further evaluated based on the calculation of the sustainability indexes (SI). The sustainability index concept was initially developed to compare different concrete mixtures in terms of their CO_2 emissions, i.e., the amount of CO_2 emitted to deliver one unit of performance (usually compressive strength) [51]. The concept can be adapted to consider other parameters (e.g., resources use, fossil fuel consumption, and toxicity potential) and has been used in several studies [36,52,53]. In this study, we considered three different sustainability indexes: $SI_{\mathrm{climate\ change}}$, $SI_{\mathrm{fossil\ energy}}$, and $SI_{\mathrm{natural\ resources}}$.

The $SI_{\text{climate change}}$ indicates the amount of greenhouse gasses emitted during the production of 1 m^3 of the considered mass concrete mixtures (i.e., raw material production and transport and concrete manufacturing) in relation to the compressive strength at 28 days. The value of the $SI_{\text{climate change}}$ indicator was calculated as follows:

$$SI_{\text{climate change}} = \frac{\text{GHG emissions}}{f_c} \quad (2)$$

where the GHG emissions indicator represents the total amount of greenhouse gases emitted during the production of 1 m^3 of the considered mass concrete mixtures (kg CO_2 equiv.), and f_c is the concrete compressive strength at 28 days (MPa).

The $SI_{\text{fossil energy}}$ indicates the amount of energy obtained from fossil fuels that was consumed during the production of 1 m^3 of the considered mass concrete mixtures (i.e., raw material production and transport and concrete manufacturing) in relation to the compressive strength at 28 days. The value of the $SI_{\text{fossil energy}}$ indicator was calculated as follows:

$$SI_{\text{fossil energy}} = \frac{\text{fossil energy}}{f_c} \quad (3)$$

where the fossil energy indicator represents the amount of fossil energy (fossil fuels) consumed during the production of 1 m^3 of the considered mass concrete mixtures (MJ), and f_c is the concrete compressive strength at 28 days (MPa).

The $SI_{\text{natural aggregate}}$ indicates the amount of natural aggregate used to produce 1 m^3 of the considered mass concrete mixtures in relation to the compressive strength at 28 days. The value of the $SI_{\text{natural aggregate}}$ indicator was calculated as follows:

$$SI_{\text{natural aggregate}} = \frac{NA}{f_c} \quad (4)$$

where NA is the amount of natural aggregate in 1 m^3 of the considered mass concrete mixtures (kg), and f_c is the concrete compressive strength at 28 days (MPa).

The proposed sustainability indexes aimed to identify the concrete mixtures that had the optimal balance between environmental impact and technical performance, i.e., the lowest possible environmental footprint and the highest possible functionality and durability. Thus, the lower the value of the sustainability index, the higher the degree of sustainability of the considered mass concrete mixture.

3. Results and Discussion

3.1. Aggregates

The physical and geometrical properties of the considered aggregates are summarised in Table 2, while the chemical properties of the aggregates are presented in Table 3. Table 2 shows that the natural and EAF steel aggregates exhibited similar physical and geometrical properties, with comparable fragmentation, abrasion, salt crystallisation, and freezing and thawing resistance. The EAF steel slag had lower shape index values compared to the natural aggregate, which can potentially ensure higher stability of the concrete [15]. Table 3 shows that the EAF steel slag aggregate sulphate content was slightly higher compared to the natural aggregate. However, these values were within the acceptable levels, with the low sulphate content resulting in a lower risk of long-term loss of mechanical properties, durability, and dimensional instability [54,55].

Table 3 also shows that the water-soluble chloride content was negligible for both types of aggregates, which prevented the occurrence of the phenomenon of corrosion in the case of employing steel reinforcement in the concrete [15]. Finally, the expansion of the aged EAF steel slag aggregate was sufficiently low in order to avoid a potential negative impact due to concrete cracking [13]. All in all, the physical, geometrical, and chemical properties of the EAF steel slag aggregate indicated that it can be used for the partial replacement of natural aggregate in mass concrete mixtures.

Table 3. The chemical properties of the natural and EAF steel slag aggregates.

Parameter	Fraction	Natural Aggregate	EAF Steel Slag Aggregate
Water-soluble chloride content (%)	0/2 mm	<0.001	<0.001
Total sulphur content (%)	below 0.125 mm	0.03	0.05
Acid-soluble sulphate (%)	below 0.125 mm	0.03	0.12
Expansion of steel slag (vol%)	0/32 mm	-	1.1 ± 0.3

3.2. Concrete Mixtures

3.2.1. Workability

Figure 3 shows the results of the slump and bulk density tests for the considered mass concrete mixtures 30 min after mixing, with the tests being conducted in accordance with the standards SIST EN 12350-2 (slump) and SIST EN 12350-6 (bulk density). Figure 3 shows that concretes with EAF steel slag aggregate (i.e., mixtures MB-5 to MB-8) displayed a significantly lower workability performance when compared to the mixtures made with only the natural aggregate (i.e., mixtures MB-1 to MB-4). However, this was as expected, because the majority of the other relevant studies confirmed the negative effect of EAF steel slag on the workability [56]. EAF steel slags have higher specific gravity/relative density and higher absorption properties and are more angular compared to the natural aggregate, which can contribute to the reduced mobility of the fresh concrete mixtures [12,57,58]. Nonetheless, the workability of the concretes made with a mixture of natural and EAF steel slag aggregates (i.e., mixtures MB-5 to MB-8) is still of an acceptable level to be used for the application in mass concrete structures [59].

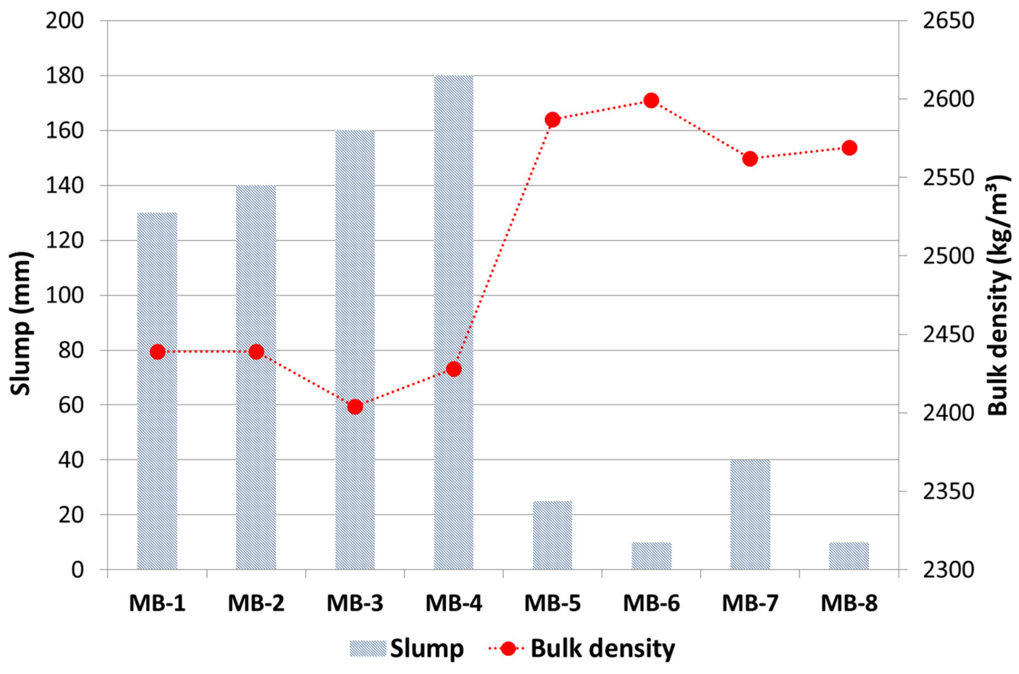

Figure 3. The results of slump and bulk density tests.

3.2.2. Compressive Strength

Figure 4 shows the results of compressive strength tests for the considered mass concrete mixtures at 3, 7, and 28 days, with the compressive strength test being conducted in accordance with standard SIST EN 12390-3. Figure 4 shows that the compressive strength increased with age, with mass concretes made with only natural aggregate (i.e., mixtures MB-1 to MB-4) having higher compressive strengths than the mass concretes made with a mixture of natural and EAF steel slag aggregates (i.e., mixtures MB-5 to MB-8).

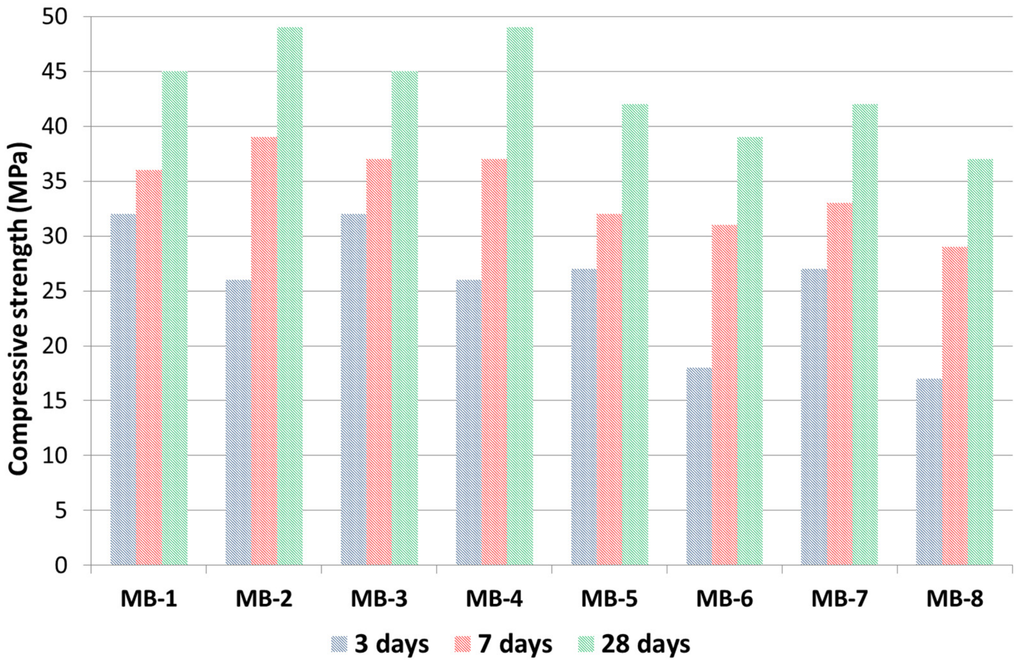

Figure 4. The results of compressive strength tests at different curing stages.

The decrease in the compressive strength of the mixtures made with EAF steel slag was probably due to the higher $(w/c)_{tot}$ ratio and/or the partial replacement of fine particle sizes [14,60,61]. In addition, the impacts associated with the limestone particles and the general quality of the slag can also contribute to the reduced compressive strengths [62,63]. Figure 4 shows that the compressive strengths at 28 days exceeded 35 MPa for all the considered mass concrete mixtures. However, high compressive strengths (e.g., higher than 30 MPa) were usually not required for mass concrete applications [59]. Therefore, we concluded that all mixtures can ensure sufficient mechanical strength for the application in mass concrete structures.

3.2.3. Temperature Rise

Figure 5 shows the temperature rise during the first five days after the mixing of the considered mass concrete mixtures. A semiadiabatic curing test with the heat-loss compensation method was applied for measuring and evaluating the temperature rise [64]. In the first phase of the test, the semiadiabatic test was carried out using the classical method of placing thermocouples on individual characteristic points of a cuboid (50/50/50 cm) specimen. In the second phase of the test, the fibre-optic cable method was used. This method offered a much more accurate determination of the adiabatic curve, because in this case, the temperature of the concrete during the hydration process was measured linearly, which meant a significantly higher number of measurement points.

Figure 5 shows that the temperatures were lower in the mass concrete mixtures that included the CEM III-type of cement (i.e., mixtures MB-2, MB-4, MB-6, and MB-8) when compared to the mass concrete mixtures that included the CEM II-type of cement (i.e., mixtures MB-1, MB-3, MB-5, and MB-7). In addition, the temperature gradient in the initial phases of the concrete curing was much steeper for the mass concrete mixtures with the CEM II-type of cement when compared to a more gradual heat release for mass concrete mixtures with the CEM III-type of cement. For example, the concrete temperature doubled in the first day of curing for mixtures MB-1, MB-3, MB-5, and MB-7. However, these results were as expected due to the higher heat release during the hydration in the cement paste for CEM II when compared to CEM III.

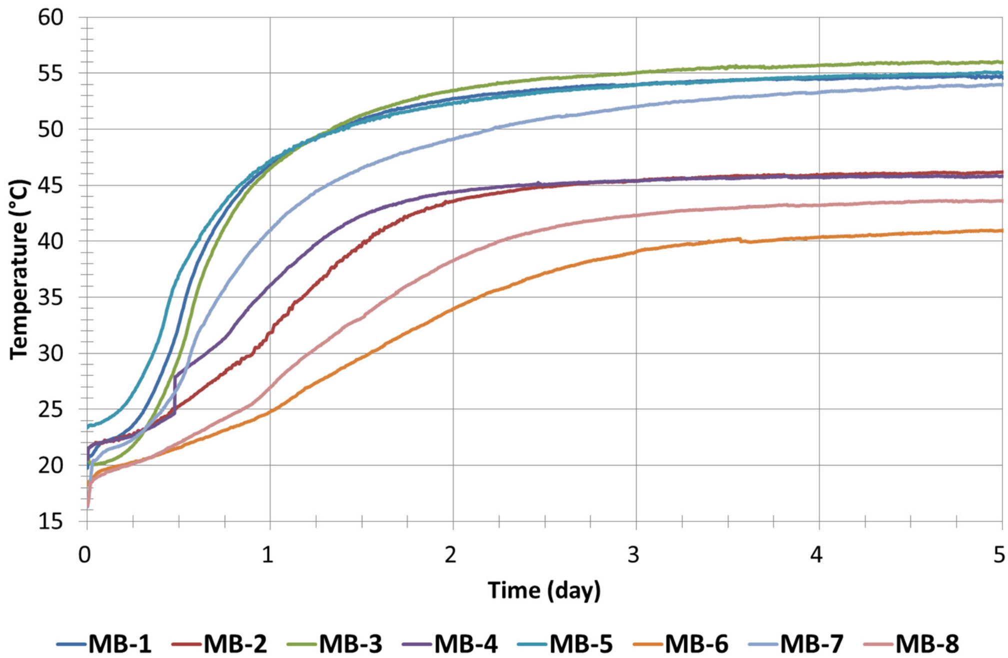

Figure 5. The temperature rise during the first five days after the mixing of mass concrete mixtures.

Figure 5 also shows that the lowest temperatures were measured for mixture MB-6, which was followed by mixtures MB-8 and MB-4. The maximum measured temperatures of the considered mass concrete mixtures and the temperature difference between the maximum and the initial concrete temperatures (ΔT) are summarised in Table 4. Table 4 shows that the smallest temperature difference was obtained for mixture MB-6, which was followed by mixtures MB-2 and MB-4. It appears that the impact of CEM III on the temperature control was far more significant than the impact of the EAF steel. For example, the difference in ΔT between MB-6 and MB-5 (i.e., mixtures with the EAF steel slag with the same amount but different type of cement) was nearly 10 °C, whereas the difference in ΔT between MB-6 and MB-4 was only 1.5 °C. All in all, the results indicate that the use of the EAF steel slag can improve the thermal characteristics of mass concrete mixtures and therefore contribute to increasing the durability and safety of mass concrete structures.

Table 4. The maximum measured temperatures and the temperature difference between maximum and initial concrete temperatures.

Mixture	Max Temperature (°C)	ΔT (°C)
MB-1	54.8	34.1
MB-2	46.7	23.3
MB-3	56.3	35.9
MB-4	45.9	24.4
MB-5	55.6	32.2
MB-6	41.4	22.9
MB-7	54.9	38.2
MB-8	43.8	27.2

3.3. LCA

3.3.1. Contribution Analysis

Figure 6 shows the contributions of the constituent materials and processes to the environmental footprint of the production of mass concrete made by the natural aggregate (i.e., mixtures MB-1 to MB-4) and the mixture of natural and EAF steel slag aggregates (i.e., mixtures MB-5 to MB-8). Figure 6 shows that cement is the greatest contributor to the total environmental impact of the production of mass concrete made with natural aggregate. Cement represents between 60 and 95% of the total impact in the vast majority of the considered impact categories for mixtures MB-1 to MB-4. However, we noticed that the type and the quantity of the used cement had an impact on the environmental performance. Other materials and processes that had a more noticeable environmental impact were transport, natural aggregate, and concrete admixture (i.e., superplasticiser).

For example, for mixtures MB-1 and MB-3, transport contributed more noticeably in terms of the ADP fos. and FAETP impact categories; natural aggregate in terms of the AP, EP, and POCP impact categories; and concrete admixture primarily in terms of the ODP impact category. When the results for mixtures MB-2 and MB-4 were compared to the results for mixtures MB-1 and MB-3, we observed that transport and concrete admixtures contributed more noticeably also in terms of the ADP el. impact category. As mentioned, the cement used in mixtures MB-2 and MB-4 contained between 66 and 80% blast furnace slag (i.e., CEM III), while the cement used in mixtures MB-1 and MB-3 contained between 21 and 35% mineral additions (i.e., CEM II). Therefore, the higher content of secondary materials in CEM III resulted in a lower impact in terms of the depletion of natural resources and thus to a better environmental performance.

Figure 6 further shows that cement is also the greatest contributor to the total environmental impact of the production of mass concretes made with a mixture of natural and EAF steel slag aggregates (i.e., mixtures MB-5 to MB-8). Other materials and processes that had a more noticeable environmental impact were metal recovery and transport. The main difference between the mixtures made with and without the EAF steel slag was in the avoided impacts (i.e., the negative values on the graphs). The avoided pig iron production and landfilling decreased the environmental impact of mixtures MB-5 to MB-8 in all impact categories.

In particular, the largest decrease was observed in terms of the FAETP and ODP impact categories due to the avoided landfilling and in terms of the TETP impact category due to the avoided pig iron production. As with mixtures MB-1 to MB-4, the type and the quantity of the used cement also had an impact on the environmental performance of the mixtures with EAF steel slag aggregate. Mixtures MB-6 and MB-8 that were made with CEM III had a lower impact in terms of resource depletion when compared to mixtures made with CEM II (i.e., MB-5 and MB-7).

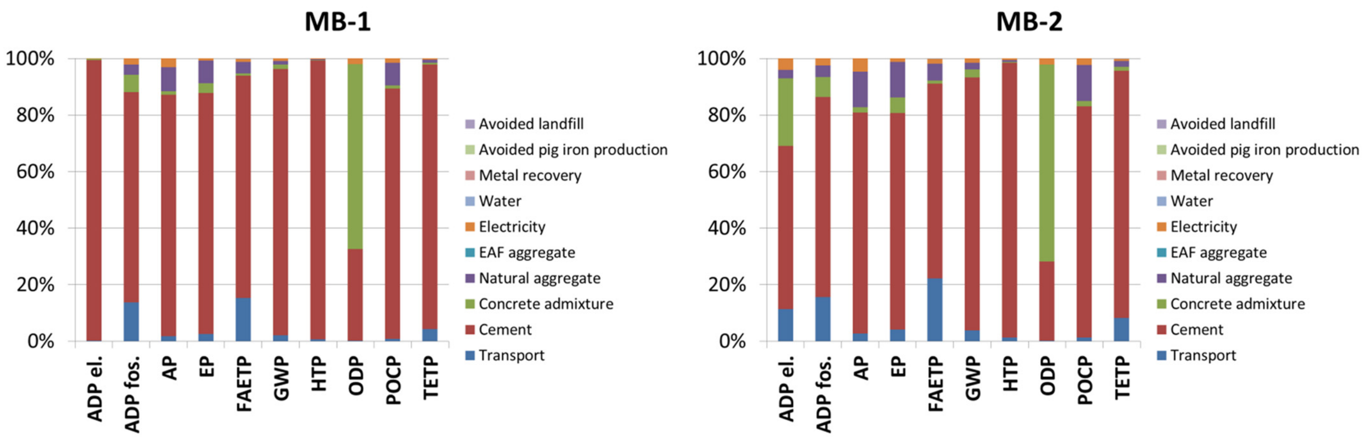

Figure 6. *Cont.*

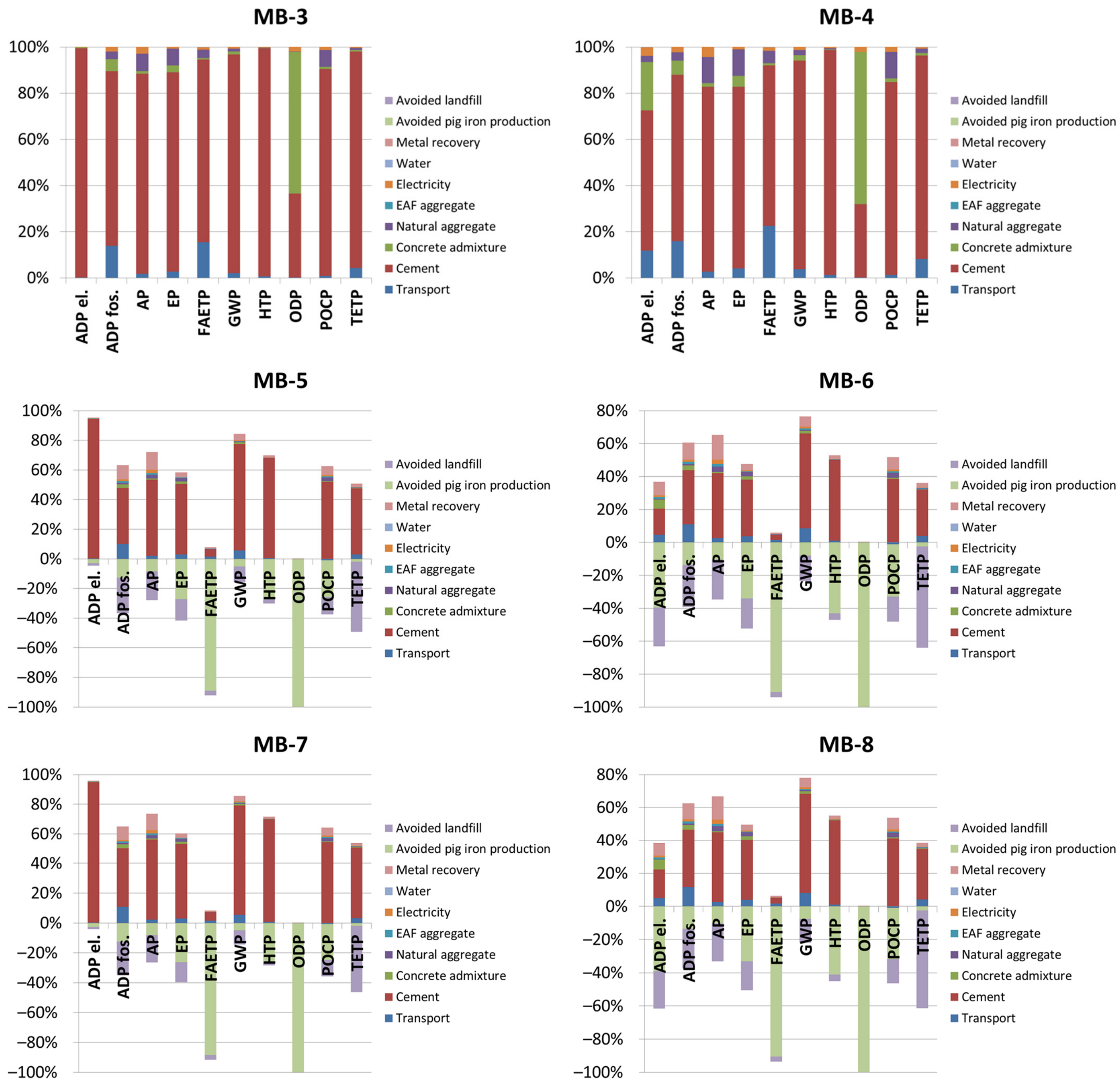

Figure 6. The contribution analyses for the considered mass concrete mixtures.

3.3.2. Sensitivity Analysis

The results of the perturbation analysis for variation ±10% of an individual parameter are summarised in Table 5. Table 5 shows that the variation of 10% in the cement led to the variation between 7.4 and 8% of the total results for the mass concretes made with the natural aggregate (i.e., mixtures MB-1 to MB-4), while the variation of the total results increased up to nearly 15% for concretes made with a mixture of natural and EAF steel aggregates (i.e., mixtures MB-5 to MB-8). Other parameters that led to a noticeable variation of the total results were avoided pig iron production, avoided slag landfilling, transport, and metal recovery.

The influence of the individual parameter variation was highlighted by graphically representing the calculated sensitivity ratios SR, which can be seen in Figure 7. Figure 7 shows that the highest SR were calculated for cement, which was followed by avoided slag landfilling, avoided iron pig production, and metal recovery. For example, the highest SR value of 1.48 was calculated for cement for mixture MB-6, meaning that a variation of 20% in cement quantity led to an increase in the total results of nearly 30%. On the other hand, the SR value of −0.8 for avoided landfill impact for mixture MB-8 meant that a variation of 20% in landfill quantity led to a decrease in the total results of 16%.

Table 5. The perturbation analysis for variation ±10%.

Mixture	Transport	Cement	Concrete Admixture	Natural Aggregate	EAF Aggregate	Electricity	Water	Metal Recovery	Avoided Pig Iron Production
MB-1	±1.1%	±7.9%	±0.5%	±0.3%	/	±0.2%	±0%	/	/
MB-2	±1.4%	±7.4%	±0.6%	±0.4%	/	±0.2%	±0%	/	/
MB-3	±1.1%	±8.0%	±0.4%	±0.3%	/	±0.2%	±0%	/	/
MB-4	±1.4%	±7.5%	±0.5%	±0.3%	/	±0.2%	±0%	/	/
MB-5	±2.8%	±13.2%	±0.7%	±0.2%	±0.3%	±0.3%	±0%	±2.7%	±3.7%
MB-6	±4.3%	±14.8%	±1.1%	±0.4%	±0.5%	±0.5%	±0%	±4.1%	±5.7%
MB-7	±2.6%	±12.2%	±0.6%	±0.2%	±0.3%	±0.3%	±0%	±2.2%	±3.3%
MB-8	±3.9%	±13.3%	±1.0%	±0.3%	±0.4%	±0.4%	±0%	±3.2%	±4.8%

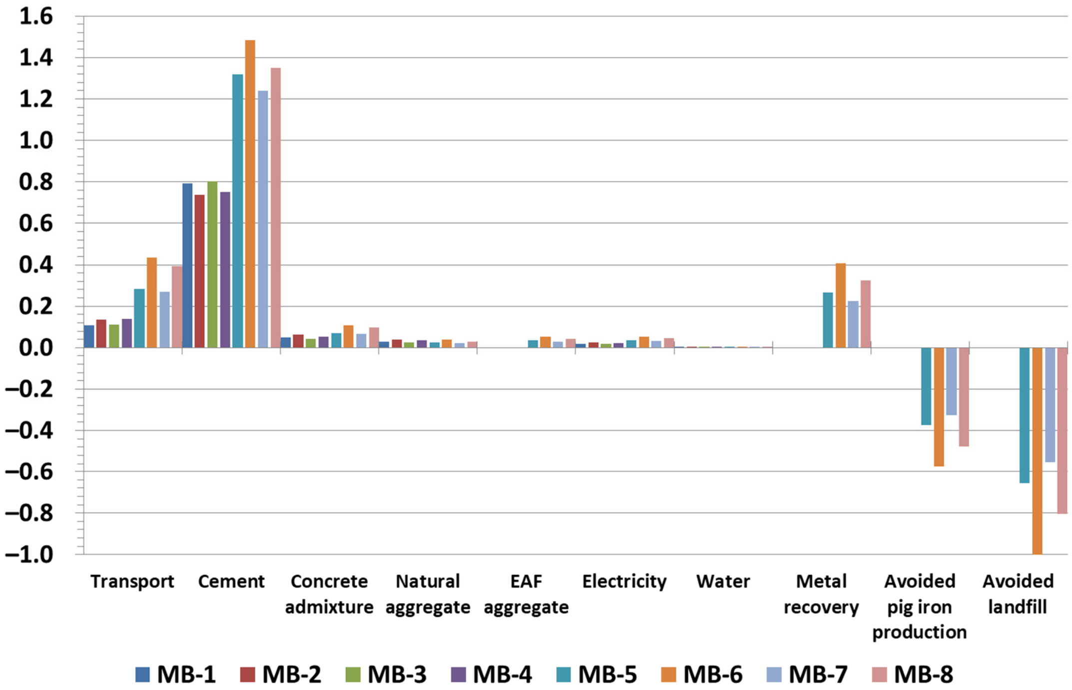

Figure 7. The sensitivity ratios.

Figure 7 shows that LCA results for mixtures with EAF steel slag (i.e., mixtures MB-5 to MB-8) were more sensitive to the influence of cement on the model results than mixtures made with only natural aggregate (i.e., mixtures MB-1 to MB-4). For example, the SR values for cement for mixtures MB-5 to MB-8 were greater than 1.2, while the SR values for cement for mixtures MB-1 to MB-4 were lower than 0.8. This means that the variation in the cement quantities would lead to a larger variation in the model results for mixtures made with a mixture of natural and EAF steel slag aggregates when compared to mixtures made with only natural aggregate. Figure 7 also shows that the cement type had an indirect impact on the sensitivity of the model results for mixtures made with EAF steel slag.

Mixtures made with EAF steel slag and CEM III (i.e., MB-6 and MB-8) were more sensitive to the influence of the parameter representing the impact of the avoided steel slag landfilling than mixtures made with CEM II (i.e., MB-5 and MB-7). For example, the SR value for the parameter avoided landfilling was −1 for mixture MB-6, while the corresponding SR values for mixtures MB-5 and MB-7 were −0.66 and −0.55, respectively. In addition to being sensitive to the variations in the cement quantity, it seems that the model results for mixtures MB-5 to MB-8 were also sensitive to the type of cement. Hence, the perturbation analysis highlighted the importance of the inclusion of slag in the mass concrete (directly as aggregate and/or indirectly as cement additive) in terms of the environmental performance.

3.3.3. Comparative Analysis

Figure 8 shows the comparison of the environmental performances of the considered mass concrete mixtures. The environmental impacts for an individual mass concrete mixture are presented in relation to the total impact of all the considered mixtures, i.e., as a percentage of the total impact of all mixtures in terms of the different impact categories. Figure 8 shows that the mass concretes made with a mixture of natural and EAF steel slag aggregates (i.e., mixtures MB-5 to MB-8) generally had a lower environmental impact than mass concretes made with only natural aggregate (i.e., mixtures MB-5 to MB-8). The exception was the impact in terms of the ADP el. for mixtures MB-5 and MB-7, which was similar to that of MB-1 and MB-3. This was due to the impact associated with the production of CEM II, which was higher than the impact related to the production of CEM III used in mixtures MB-2, MB-4, MB-6, and MB-8. As mentioned, CEM III contains a higher content of waste materials (i.e., blast furnace slag) when compared to CEM II, which was reflected in a lower environmental burden in terms of the natural resource depletion potential.

Figure 8 also shows that mixtures made with EAF steel slag aggregate exhibited an environmental benefit (i.e., negative values on the graph) in terms of the FAETP and ODP impact categories. This was due to the positive environmental impacts associated with the avoided pig iron production and avoided slag landfilling, which significantly reduced the amount of emissions to the air and soil. In addition, mixtures MB-6 and MB-8 exhibited an environmental benefit also in terms of the TETP impact category. This could be attributed to the lower environmental burden of CEM III used in mixtures MB-6 and MB-8 when compared to CEM II used in mixtures MB-5 and MB-7. All in all, the results presented in Figure 8 indicate that the use of EAF steel slag aggregate can significantly reduce the total environmental impact of the mass concrete mixture.

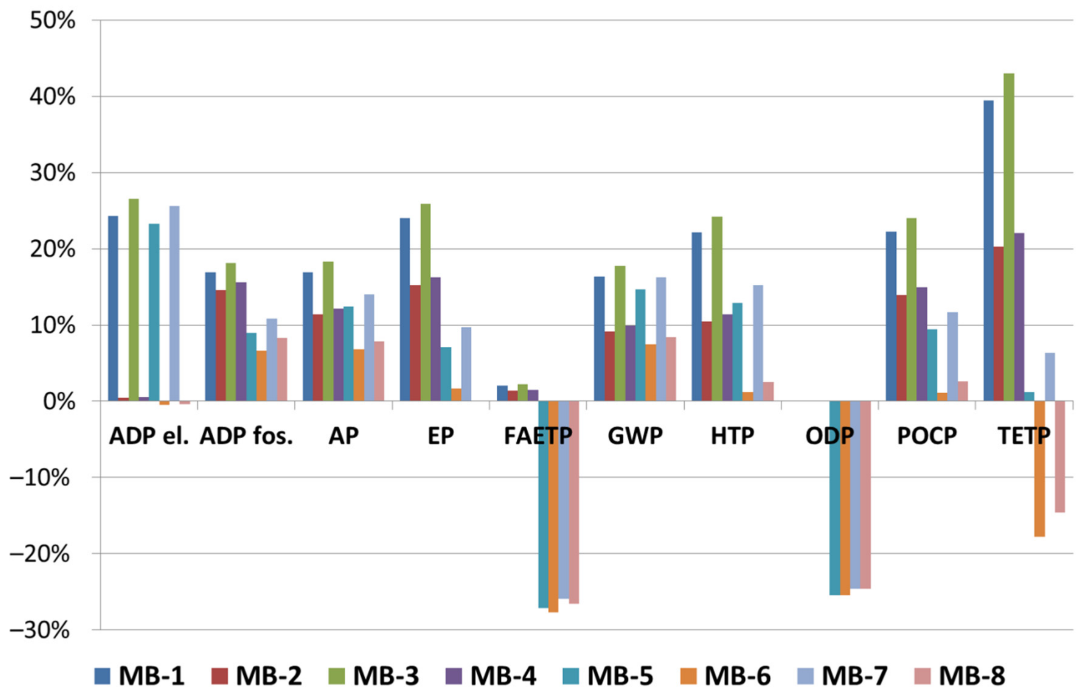

Figure 8. The comparison of the environmental performance of the considered mass concrete mixtures.

3.3.4. Critical Assessment of LCA Results

Cement was the greatest contributor to the total environmental impact of the production of mass concrete made with the EAF steel slag aggregate, with similar observations being reported in other studies [30,33,35,65]. The environmental impact of concretes made with a mixture of natural and EAF steel slag aggregates was lower compared to the concretes made with only the natural aggregate. However, the main reason for the improved environmental performance was due to the environmental credit associated with the avoided pig iron production and avoided slag landfilling, with similar conclusions being drawn by other authors [33]. Therefore, the type of the aggregate alone had a small direct impact on the overall environmental performance of the mass concrete. Nonetheless, the use of the EAF steel aggregate was still more ecofriendly compared to the natural aggregate due to the reduced need for natural resources.

The sensitivity analysis highlighted the dominant impact of the type (and quantity) of cement and the benefits related to the avoided burden on the environmental performance of green mass concretes. This means that the variation in the cement type (and quantity) and the benefits associated with the use of EAF steel slag (i.e., avoided landfilling and pig iron production) will lead to the largest variation in the model results. In addition, several studies have highlighted the impact of transportation distances of different natural and waste materials on the overall environmental performance of common and green concretes [33,44,47,66]. However, the use of alternative aggregates (e.g., EAF steel slag aggregate) is generally more environmentally friendly even in cases of long transport distances [35]. All in all, the type of cement, the potential environmental credit due to the avoided burden, and the impact of transportation modes and distances should be generally evaluated more in detail when assessing the impacts of green mass concretes in order ensure the best environmental performance. When comparing conventional and alternative (green) concretes, several factors should be thoroughly considered, such as the selection of the functional unit, LCI data, LCIA method, and potential allocation methods [47]. However, all these factors are highly dependent on the focus of the LCA user, which can lead to inconsistencies and a subjective evaluation of the results [48]. For example, a common practice when comparing regular and green concretes is to specify a simple functional unit based on the unit of mass or volume [67]. However, model results could differ quite significantly if a more complex functional unit based on the concrete's functional performance metrics (e.g., strength and durability) were considered [9,30,67,68]. As there is no systematic LCA framework that addresses green mass concrete mixtures, the environmental performance related to the functional parameters of the mass concrete mixtures was evaluated with the calculation of the sustainability indexes (Section 3.4). Even though these sustainability indicators are highly informative, a multicriteria LCA framework is needed that would specify the evaluation procedure based on the relationship between the main functionally parameters of the mass concrete (e.g., thermal behaviour) and environmental indicators.

3.4. Sustainability Index

Table 6 shows the calculated sustainability indexes per 1 m^3 of the considered mass concrete mixtures. As mentioned, low sustainability index values indicated a high sustainability potential of the considered mass concrete mixtures. Table 6 shows that the lowest sustainability index in terms of the impact on climate change (i.e., greenhouse gas emissions in CO_2 equivalent) was calculated for mixture MB-2, which was closely followed by mixtures MB-6 and MB-4. In terms of the impact on the depletion of fossil resources, the lowest sustainability index was calculated for mixture MB-6, which was followed by mixtures MB-5 and MB-8. Finally, the results summarised in Table 6 also show that in terms of the depletion of natural resources (i.e., natural aggregates), the lowest value of the sustainability index was calculated for mixture MB-7, which was followed by mixtures MB-5 and MB-8.

Table 6. The sustainability indexes per 1 m^3 of the considered mass concrete mixtures.

Mixture	$SI_{climate\ change}$	$SI_{fossil\ energy}$	$SI_{natural\ aggregate}$
MB-1	5.1	19.6	44.2
MB-2	2.6	15.5	40.5
MB-3	5.5	21.0	42.8
MB-4	2.8	16.6	39.1
MB-5	4.9	11.1	23.7
MB-6	2.7	8.9	25.4
MB-7	5.4	13.4	22.9
MB-8	3.1	11.6	25.0

Based on the values of all three sustainability indexes presented in Table 6, we concluded that mixture MB-6 is the most sustainable, with mixtures MB-8 and MB-5 being second and third best. The high sustainability potential of mixture MB-6 was related to the synergistic effect of the positive impact of the use of CEM III (i.e., lower environmental burden due to the higher content of waste materials in the cement) and the benefits associated with the use of EAF steel aggregates (i.e., environmental benefit due to the avoided pig iron production and avoided slag landfilling).

4. Conclusions

This paper investigates the use of EAF steel slag aggregate for the partial replacement of the natural aggregate in the production of mass concrete. Eight different mass concrete mixtures were prepared and tested in this study, i.e., four mixtures with only natural aggregate and four mixtures with a combination of natural aggregate and EAF steel aggregate. Two different cement types were considered, i.e., CEM II and CEM III. We analysed the effect of the EAF steel aggregate on the mass concrete's workability, strength, and thermal behaviour. In addition, we conducted a cradle-to-gate LCA study to assess the environmental impact of the production of mass concrete with the EAF steel slag aggregate and evaluated the sustainability potential of the considered mass concrete mixtures.

Based on the study results, the following conclusion can be drawn:

- The physical, geometrical, and chemical properties of the considered EAF steel slag aggregate were comparable to those of the considered natural aggregate; therefore, the results suggest that the EAF steel aggregate can be used for partial replacement of the natural aggregate in mass concrete mixtures.
- The higher specific gravity/relative density and absorption properties of the EAF steel slag aggregate compared to the natural aggregate reduced the workability performance, while the higher $(w/c)_{tot}$ ratios and the partial replacement of fine particles in the mixtures made with the EAF steel slag aggregate probably contributed to lower compressive strengths. However, the workability and compressive strength of the concretes made with a mixture of natural and EAF steel slag aggregates were still of an acceptable level to be used for the application in mass concrete structures.
- The temperature rise was smaller in the mass concrete mixtures that included the CEM III-type of cement compared to the mass concrete mixtures that included the CEM II-type of cement due to the lower heat release during the hydration in a cement paste. On the other hand, the impact of the EAF steel aggregate on the overall thermal performance was less significant compared to the impact of the low-heat cement. Nonetheless, the use of the EAF steel slag contributed to better temperature control and thus to the improved durability and safety of mass concrete structures.
- Cement was the greatest contributor to the total environmental impact of all the considered mass concrete mixtures, while the type of the aggregate alone had a noticeably smaller environmental impact. However, the use of the EAF steel aggregate was still more environmentally advantageous due to the reduced consumption of natural resources. The environmental impact of concretes made with a mixture of natural and EAF steel slag aggregates was lower compared to the concretes made with

only the natural aggregate in the vast majority of the considered impact categories. This was primarily due to the environmental credit associated with the avoided pig iron production and avoided slag landfilling.

- The highest sustainability potential was observed in the concretes that were made with a mixture of natural and EAF steel slag aggregates and CEM III cement due to the synergistic effect of the positive impact of the use of CEM III compared to CEM II (i.e., lower environmental burden due to the higher content of SCMs in the cement) and the benefits associated with the use of EAF steel slag aggregate (i.e., environmental benefit due to the avoided pig iron production and avoided slag landfilling).

All in all, the study results indicate that the EAF steel slag can be successfully upcycled into an aggregate that can be used to manufacture a green mass concrete. In general, there should be no restrictions for the use of the EAF steel slag aggregate in practical concrete production and application. However, it should be investigated in the future whether there are any practical and/or technical limitations when mass concrete with EAF steel aggregate is produced and placed in large volumes. In addition, an economic analysis is needed to evaluate the financial viability of the production of mass concrete with the EAF steel slag aggregate, e.g., the impact of higher-density EAF steel slag on transportation costs and the impact of the adaptations of the technological process on the production costs. Finally, the durability of EAF steel slag mass concrete must be thoroughly investigated in order to evaluate the impact of the EAF steel slag aggregate on the mass concrete's long-term performance and resistance to weathering processes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142315502/s1, Figure S1: Grain size distribution curves of natural and EAF steel slag aggregates; Table S1: The materials and processes included in the LCA study.

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References

1. Wu, Y.; Luna, R. Numerical implementation of temperature and creep in mass concrete. *Finite Elem. Anal. Des.* **2001**, *37*, 97–106. [CrossRef]
2. Cha, S.-L.; Jin, S.-S. Prediction of thermal stresses in mass concrete structures with experimental and analytical results. *Constr. Build. Mater.* **2020**, *258*, 120367. [CrossRef]
3. Hamid, H.; Chorzepa, M.G. Quantifying maximum temperature in 17 mass concrete cube specimens made with mixtures including metakaolin and/or slag. *Constr. Build. Mater.* **2020**, *252*, 118950. [CrossRef]
4. El-Mir, A.; Assaad, J.J.; Nehme, S.G.; El-Hassan, H. Correlating strength and durability to time-temperature profiles of high-performance mass concrete. *Case Stud. Constr. Mater.* **2022**, *16*, e01055. [CrossRef]
5. Akhtar, A.; Sarmah, A.K. Construction and demolition waste generation and properties of recycled aggregate concrete: A global perspective. *J. Clean. Prod.* **2018**, *186*, 262–281. [CrossRef]

6. Sousa, V.; Bogas, J.A. Comparison of energy consumption and carbon emissions from clinker and recycled cement production. *J. Clean. Prod.* **2021**, *306*, 127277. [CrossRef]
7. Sivakrishna, A.; Adesina, A.; Awoyera, P.O.; Rajesh Kumar, K. Green concrete: A review of recent developments. *Mater. Today Proc.* **2020**, *27*, 54–58. [CrossRef]
8. Chen, H.; Chow, C.L.; Laua, D. Developing green and sustainable concrete in integrating with different urban wastes. *J. Clean. Prod.* **2022**, *368*, 133057. [CrossRef]
9. Marinković, S.; Carević, V.; Dragaš, J. The role of service life in Life Cycle Assessment of concrete structures. *J. Clean. Prod.* **2021**, *290*, 125610. [CrossRef]
10. Santamaría, A.; Romera, J.M.; Marcos, I.; Revilla-Cuesta, V.; Ortega-López, V. Shear strength assessment of reinforced concrete components containing EAF steel slag aggregates. *J. Build. Eng.* **2022**, *46*, 103730. [CrossRef]
11. Muhmood, L.; Vitta, S.; Venkateswaran, D. Cementitious and pozzolanic behavior of electric arc furnace steel slags. *Cem. Concr. Res.* **2009**, *39*, 102–109. [CrossRef]
12. Pellegrino, C.; Gaddo, V. Mechanical and durability characteristics of concrete containing EAF slag as aggregate. *Cem. Concr. Compos.* **2009**, *31*, 663–671. [CrossRef]
13. Brand, A.S.; Roesler, J.R. Steel furnace slag aggregate expansion and hardened concrete properties. *Cem. Concr. Compos.* **2015**, *60*, 1–9. [CrossRef]
14. Monosi, S.; Ruello, M.L.; Sani, D. Electric arc furnace slag as natural aggregate replacement in concrete production. *Cem. Concr. Compos.* **2016**, *66*, 66–72. [CrossRef]
15. Rondi, L.; Bregoli, G.; Sorlini, S.; Cominoli, L.; Collivignarelli, C.; Plizzari, G. Concrete with EAF steel slag as aggregate: A comprehensive technical and environmental characterisation. *Compos. Part B Eng.* **2016**, *90*, 195–202. [CrossRef]
16. Adegoloye, G.; Beaucour, A.L.; Ortola, S.; Noumowé, A. Concretes made of EAF slag and AOD slag aggregates from stainless steel process: Mechanical properties and durability. *Constr. Build. Mater.* **2015**, *76*, 313–321. [CrossRef]
17. Faleschini, F.; Brunelli, K.; Zanini, M.A.; Dabalà, M.; Pellegrino, C. Electric Arc Furnace Slag as Coarse Recycled Aggregate for Concrete Production. *J. Sustain. Metall.* **2016**, *2*, 44–50. [CrossRef]
18. Faleschini, F.; Alejandro Fernández-Ruíz, M.; Zanini, M.A.; Brunelli, K.; Pellegrino, C.; Hernández-Montes, E. High performance concrete with electric arc furnace slag as aggregate: Mechanical and durability properties. *Constr. Build. Mater.* **2015**, *101*, 113–121. [CrossRef]
19. Andrade, H.D.; de Carvalho, J.M.F.; Costa, L.C.B.; Elói, F.P.D.F.; e Silva, K.D.D.C.; Peixoto, R.A.F. Mechanical performance and resistance to carbonation of steel slag reinforced concrete. *Constr. Build. Mater.* **2021**, *298*, 123910. [CrossRef]
20. Roslan, N.H.; Ismail, M.; Khalid, N.H.A.; Muhammad, B. Properties of concrete containing electric arc furnace steel slag and steel sludge. *J. Build. Eng.* **2020**, *28*, 101060. [CrossRef]
21. Kolawole, J.T.; Babafemi, A.J.; Paul, S.C.; du Plessis, A. Performance of concrete containing Nigerian electric arc furnace steel slag aggregate towards sustainable production. *Sustain. Mater. Technol.* **2020**, *25*, e00174. [CrossRef]
22. Papachristoforou, M.; Anastasiou, E.K.; Papayianni, I. Durability of steel fiber reinforced concrete with coarse steel slag aggregates including performance at elevated temperatures. *Constr. Build. Mater.* **2020**, *262*, 120569. [CrossRef]
23. Sosa, I.; Thomas, C.; Polanco, J.A.; Setién, J.; Sainz-Aja, J.A.; Tamayo, P. Durability of high-performance self-compacted concrete using electric arc furnace slag aggregate and cupola slag powder. *Cem. Concr. Compos.* **2022**, *127*, 104399. [CrossRef]
24. Maharaj, D.; Mwasha, A. Comparative analysis of the transmission factors of lead and concrete manufactured with electric arc furnace slag aggregates. *Constr. Build. Mater.* **2016**, *112*, 1141–1146. [CrossRef]
25. Pomaro, B.; Gramegna, F.; Cherubini, R.; De Nadal, V.; Salomoni, V.; Faleschini, F. Gamma-ray shielding properties of heavyweight concrete with Electric Arc Furnace slag as aggregate: An experimental and numerical study. *Constr. Build. Mater.* **2019**, *200*, 188–197. [CrossRef]
26. Roy, S.; Miura, T.; Nakamura, H.; Yamamoto, Y. High temperature influence on concrete produced by spherical shaped EAF slag fine aggregate—Physical and mechanical properties. *Constr. Build. Mater.* **2020**, *231*, 117153. [CrossRef]
27. Hossain, M.U.; Poon, C.S.; Lo, I.M.C.; Cheng, J.C.P. Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. *Resour. Conserv. Recycl.* **2016**, *109*, 67–77. [CrossRef]
28. Dong, Q.; Wang, G.; Chen, X.; Tan, J.; Gu, X. Recycling of steel slag aggregate in portland cement concrete: An overview. *J. Clean. Prod.* **2021**, *282*, 124447. [CrossRef]
29. Kirthika, S.K.; Singh, S.K.; Chourasia, A. Alternative fine aggregates in production of sustainable concrete—A review. *J. Clean. Prod.* **2020**, *268*, 122089. [CrossRef]
30. Faleschini, F.; De Marzi, P.; Pellegrino, C. Recycled concrete containing EAF slag: Environmental assessment through LCA. *Eur. J. Environ. Civil Eng.* **2014**, *18*, 1009–1024. [CrossRef]
31. Anastasiou, E.K.; Liapis, A.; Papayianni, I. Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials. *Resour. Conserv. Recycl.* **2015**, *101*, 1–8. [CrossRef]
32. Kua, H.W. Integrated policies to promote sustainable use of steel slag for construction—A consequential life cycle embodied energy and greenhouse gas emission perspective. *Energy Build.* **2015**, *101*, 133–143. [CrossRef]
33. Turk, J.; Cotič, Z.; Mladenovič, A.; Šajna, A. Environmental evaluation of green concretes versus conventional concrete by means of LCA. *Waste Manag.* **2015**, *45*, 194–205. [CrossRef] [PubMed]

34. Anastasiou, E.K.; Liapis, A.; Papachristoforou, M. Life Cycle Assessment of Concrete Products for Special Applications Containing EAF Slag. *Procedia Environ. Sci.* **2017**, *38*, 469–476. [CrossRef]
35. Evangelista, B.L.; Rosado, L.P.; Penteado, C.S.G. Life cycle assessment of concrete paving blocks using electric arc furnace slag as natural coarse aggregate substitute. *J. Clean. Prod.* **2018**, *178*, 176–185. [CrossRef]
36. Václavík, V.; Ondová, M.; Dvorský, T.; Eštoková, A.; Fabiánová, M.; Gola, L. Sustainability Potential Evaluation of Concrete with Steel Slag Aggregates by the LCA Method. *Sustainability* **2020**, *12*, 9873. [CrossRef]
37. Hafez, H.; Kassim, D.; Kurda, R.; Silva, R.V.; de Brito, J. Assessing the sustainability potential of alkali-activated concrete from electric arc furnace slag using the ECO2 framework. *Constr. Build. Mater.* **2021**, *281*, 122559. [CrossRef]
38. Moranville-Regourd, M.; Kamali-Bernard, S. 10—Cements Made From Blastfurnace Slag. In *Lea's Chemistry of Cement and Concrete*, 5th ed.; Hewlett, P.C., Liska, M., Eds.; Butterworth-Heinemann: Oxford, UK, 2019; pp. 469–507. [CrossRef]
39. Flatt, R.; Schober, I. 7—Superplasticizers and the rheology of concrete. In *Understanding the Rheology of Concrete*; Roussel, N., Ed.; Woodhead Publishing: Cambridge, UK, 2012; pp. 144–208. [CrossRef]
40. Hossain, M.U.; Dong, Y.; Ng, S.T. Influence of supplementary cementitious materials in sustainability performance of concrete industry: A case study in Hong Kong. *Case Stud. Constr. Mater.* **2021**, *15*, e00659. [CrossRef]
41. Delnavaz, M.; Sahraei, A.; Delnavaz, A.; Farokhzad, R.; Amiri, S.; Bozorgmehrnia, S. Production of concrete using reclaimed water from a ready-mix concrete batching plant: Life cycle assessment (LCA), mechanical and durability properties. *J. Build. Eng.* **2022**, *45*, 103560. [CrossRef]
42. Li, L.; Ling, T.-C.; Pan, S.-Y. Environmental benefit assessment of steel slag utilization and carbonation: A systematic review. *Sci. Total Environ.* **2022**, *806*, 150280. [CrossRef]
43. Sphera. GaBi Databases & Modelling Principles 2022. Available online: https://sphera.com/wp-content/uploads/2022/02/MODELING-PRINCIPLES-GaBi-Databases-2022.pdf (accessed on 22 May 2022).
44. Marinković, S.; Radonjanin, V.; Malešev, M.; Ignjatović, I. Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Manag.* **2010**, *30*, 2255–2264. [CrossRef] [PubMed]
45. Guinée, J.B. Handbook on life cycle assessment: Operational guide to the ISO standards. *Int. J. Life Cycle Assess.* **2002**, *7*, 311–313. [CrossRef]
46. Van den Heede, P.; De Belie, N. Environmental impact and life cycle assessment (LCA) of traditional and 'green' concretes: Literature review and theoretical calculations. *Cem. Concr. Compos.* **2012**, *34*, 431–442. [CrossRef]
47. Vieira, D.R.; Calmon, J.L.; Coelho, F.Z. Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: A review. *Constr. Build. Mater.* **2016**, *124*, 656–666. [CrossRef]
48. Xing, W.; Tam, V.W.Y.; Le, K.N.; Hao, J.L.; Wang, J. Life cycle assessment of recycled aggregate concrete on its environmental impacts: A critical review. *Constr. Build. Mater.* **2022**, *317*, 125950. [CrossRef]
49. Heijungs, R.; Kleijn, R. Numerical approaches towards life cycle interpretation five examples. *Int. J. Life Cycle Assess.* **2001**, *6*, 141–148. [CrossRef]
50. Heijungs, R.; Suh, S.; Kleijn, R. Numerical Approaches to Life Cycle Interpretation—The case of the Ecoinvent'96 database (10 pp). *Int. J. Life Cycle Assess.* **2005**, *10*, 103–112. [CrossRef]
51. Damineli, B.L.; Kemeid, F.M.; Aguiar, P.S.; John, V.M. Measuring the eco-efficiency of cement use. *Cem. Concr. Compos.* **2010**, *32*, 555–562. [CrossRef]
52. Yang, K.-H.; Jung, Y.-B.; Cho, M.-S.; Tae, S.-H. Effect of supplementary cementitious materials on reduction of CO_2 emissions from concrete. *J. Clean. Prod.* **2015**, *103*, 774–783. [CrossRef]
53. Lee, J.; Lee, T.; Jeong, J.; Jeong, J. Engineering, Durability, and Sustainability Properties Analysis of High-Volume, PCC Ash-Based Concrete. *Sustainability* **2020**, *12*, 3520. [CrossRef]
54. Agrela, F.; Cabrera, M.; Galvín, A.P.; Barbudo, A.; Ramirez, A. Influence of the sulphate content of recycled aggregates on the properties of cement-treated granular materials using Sulphate-Resistant Portland Cement. *Constr. Build. Mater.* **2014**, *68*, 127–134. [CrossRef]
55. Thomas, C.; Cimentada, A.; Rico, J.; Setién, J. 17—Sulphur content of recycled aggregates applied in concrete production. In *New Trends in Eco-Efficient and Recycled Concrete*; de Brito, J., Agrela, F., Eds.; Woodhead Publishing: Cambridge, UK, 2019; pp. 499–508. [CrossRef]
56. Rashad, A.M. Behavior of steel slag aggregate in mortar and concrete—A comprehensive overview. *J. Build. Eng.* **2022**, *53*, 104536. [CrossRef]
57. Qasrawi, H.; Shalabi, F.; Asi, I. Use of low CaO unprocessed steel slag in concrete as fine aggregate. *Constr. Build. Mater.* **2009**, *23*, 1118–1125. [CrossRef]
58. Pellegrino, C.; Cavagnis, P.; Faleschini, F.; Brunelli, K. Properties of concretes with Black/Oxidizing Electric Arc Furnace slag aggregate. *Cem. Concr. Compos.* **2013**, *37*, 232–240. [CrossRef]
59. ACI. *Mass Concrete—Guide*; ACI PRC-207.1-21; American Concrete Institute: Farmington Hills, MI, USA, 2022; p. 34.
60. Manso Juan, M.; Gonzalez Javier, J.; Polanco Juan, A. Electric Arc Furnace Slag in Concrete. *J. Mater. Civil Eng.* **2004**, *16*, 639–645. [CrossRef]
61. Rooholamini, H.; Sedghi, R.; Ghobadipour, B.; Adresi, M. Effect of electric arc furnace steel slag on the mechanical and fracture properties of roller-compacted concrete. *Constr. Build. Mater.* **2019**, *211*, 88–98. [CrossRef]

62. Yu, X.; Tao, Z.; Song, T.-Y.; Pan, Z. Performance of concrete made with steel slag and waste glass. *Constr. Build. Mater.* **2016**, *114*, 737–746. [CrossRef]
63. Lam, M.N.-T.; Le, D.-H.; Jaritngam, S. Compressive strength and durability properties of roller-compacted concrete pavement containing electric arc furnace slag aggregate and fly ash. *Constr. Build. Mater.* **2018**, *191*, 912–922. [CrossRef]
64. Ng, P.L.; Ng, I.Y.T.; Kwan, A.K.H. Heat Loss Compensation in Semi-Adiabatic Curing Test of Concrete. *ACI Mater. J.* **2008**, *105*, 52–61. [CrossRef]
65. Marinković, S.; Dragaš, J.; Ignjatović, I.; Tošić, N. Environmental assessment of green concretes for structural use. *J. Clean. Prod.* **2017**, *154*, 633–649. [CrossRef]
66. Pradhan, S.; Tiwari, B.R.; Kumar, S.; Barai, S.V. Comparative LCA of recycled and natural aggregate concrete using Particle Packing Method and conventional method of design mix. *J. Clean. Prod.* **2019**, *228*, 679–691. [CrossRef]
67. Panesar, D.K.; Seto, K.E.; Churchill, C.J. Impact of the selection of functional unit on the life cycle assessment of green concrete. *Int. J. Life Cycle Assess.* **2017**, *22*, 1969–1986. [CrossRef]
68. Petek Gursel, A.; Masanet, E.; Horvath, A.; Stadel, A. Life-cycle inventory analysis of concrete production: A critical review. *Cem. Concr. Compos.* **2014**, *51*, 38–48. [CrossRef]