The Effect of Additional Byproducts on the Environmental Impact of the Production Stage of Concretes Containing Bottom Ash Instead of Sand

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Abstract: This study aims to assess whether using byproducts as additional binders can reduce the environmental damage of concretes that already contain bottom ash instead of sand. In particular, two concretes in which sand had been replaced by coal bottom ash at varying percentages (from 0 to 100 wt %) were evaluated in which (i) silica fume was an additional binder, and (ii) silica fume and blast furnace slag were additional binders. Consequential life cycle assessment was applied to environmentally evaluate the effect from the production stage of these byproducts. We used the ReCiPe2016 midpoint hierarchist and single-score (six methodologies) methods. A two-stage nested mixed analysis of variance was used to simultaneously evaluate the results of six ReCiPe2016 methodologies. The ReCiPe2016 midpoint hierarchist results indicate that using additional binders in both bottom ash-based concretes decreases global warming potential, terrestrial ecotoxicity, water consumption, and especially, fossil resource scarcity environmental impacts. The bottom ash-based concrete with silica fume and blast furnace slag as additional binders shows more environmental benefits than the bottom ash-based concrete with only silica fume. The ReCiPe2016 single-score method results indicate that the bottom ash-based alternatives with 40–100 wt % (with silica fume as an additional binder) and 75–100 wt % (with silica fume and blast furnace slag as additional binders) of sand replacement seem to cause the least environmental damage.

Keywords: concrete; coal bottom ash; silica fume; blast furnace slag; life cycle assessment

1. Introduction

To solve the problem of high CO\textsubscript{2} emissions steamed from cement production in the concrete industry and waste steamed from byproducts such as furnace coal bottom ash (BA), silica fume (SF), and blast furnace slag (BFS) in coal-powered plants, the ferrosilicon industry, and the steel industry, respectively, a common worldwide approach is to replace part of the cement with these pozzolanic byproducts [1]. It should be noted that replacing cement with byproducts has been reported to have environmental benefits. For example, Crossin [2] studied the use of 30% cement replacement with BFS and reported a decrease in greenhouse gases of 47.5% compared with conventional concrete. Hossain et al. [1] studied 25% cement replacement with fly ash (FA) and reported decreases in respiratory inorganics, global warming potential (GWP), nonrenewable energy, and acidification, compared with conventional concrete.

However, concrete production also requires a huge quantity of gravel and sand, thereby creating an environmental problem by depleting natural aggregates [3]. Therefore, environmental evaluations of concrete, in which sand was replaced with industrial byproducts, have been presented in the literature. For example, Kua [4] studied the replacement of 10 vol % of sand with copper slag (CS) in high-performance concrete and reported increased CO\textsubscript{2} emissions compared with conventional concrete.
In contrast, Lim et al. [5] studied the replacement of 75 and 100 wt % sand with quarry dust in lightweight foamed concrete and reported decreased CO₂ emissions compared with conventional concrete.

This difference in environmental results by replacing cement and sand with byproducts can be explained by the different environmental contributions from cement (74–93%) and sand (0.3–2%) to the total life cycle assessment (LCA) of byproduct-based concretes [6,7]. The small contribution of sand to the total environmental evaluation of concrete makes this issue very sensitive to different factors related to concrete design. For example, Pushkar [8] studied the influence of the concrete design method (i.e., the fixed slump or fixed water/cement (W/C) ratio methods) on the LCAs of byproduct-based concretes in which sand had been substituted with BA in the amounts of 0, 30, 50, 70, and 100 wt % and reported a decreased environmental impact of the concretes with fixed slump ranges and an increased environmental impact of the concretes with fixed W/C ratios.

This means that the environmental effect of sand replacement in the production of concrete is not fully clear and requires additional LCAs. A key issue of the LCA of structural concrete is the correct definition of a functional unit (FU) that must be unique in all of the compared concrete mixtures because all inputs and outputs of the raw materials and emissions should refer to it [9]. This concrete FU (usually 1 m³ of concrete mixture) requires all of the compared structural concretes to have comparable fresh and hard properties, while compressive strength is the most important property of hard concrete [10].

To reach the same compressive strength of FU in conventional and byproduct-based concretes (in which sand is replaced with byproducts), different attempts have been undertaken. For example, Turk et al. [11] used 1 m³ as an FU for the design of conventional and byproduct-based concretes (in which sand was partially replaced by foundry sand or steel slag) with a fixed slump range of 185–205 mm and reported that the range of 28-day compressive strength was 30.1–45.3 MPa. Prem et al. [12] used 1 m³ as an FU for studying conventional and byproduct-based concretes using the absolute volume method for replacing sand with CS and reported that this method limited the addition of any additional water and, as a result, the CS-based concretes demonstrated improved compressive strength. Gursel and Ostertag [13] analyzed high-strength conventional and CS-based concretes designed with fixed W/C ratios of 0.37, 0.47, and 0.57 (in which sand had been replaced by CS at an incremental rate of 20 wt %, CS0:CS20:CS100) and reported that the range of 28-day compressive strength was 65–98 MPa. Due to the wide range of compressive strength values, the authors [13] suggested that a normalized FU should be used, namely, 1 m³ of concrete was normalized to the 28-day compressive strength.

Kim and Lee [14] and Kadam and Patil [15] studied BA-based concretes (in which sand was replaced with BA in different proportions) with a high binder content provided by using the additional byproducts SF and BFS to achieve comparable compressive strength for conventional and BA-based concretes. Kim and Lee [14] studied high-strength BA-based concretes (in which sand was replaced with BA in the following proportions: 40–100 wt %) with 15 and 20 wt % SF and BFS, respectively, of the total binder (cement, SF, and BFS) and reported a 28-day compressive strength of 62–72 MPa. Kadam and Patil [15] studied normal-strength BA-based concretes (in which sand was replaced with BA in the following proportions: 25–100 wt %) with a maximum SF content of 8 wt % of the total binder (cement and SF) and reported a 28-day compressive strength of 41.52–45.76 MPa. However, the environmental effect of increasing the binder content of these additional byproducts in a concrete which already contains byproduct instead of sand has not yet been considered.

The purpose of this study is to assess the environmental impacts of the use of additional byproducts (SF and BFS) in the production of BA-based concretes. According to this purpose, BA-based concretes (in which sand was replaced with BA in different proportions: 25–100 wt %) with a high binder content provided by using additional byproducts were studied due to the fact that such concretes have similar mechanical properties to conventional concrete [14,15].
2. Materials and Methods

2.1. Concrete Mixture Designs

The LCAs of two BA-based concretes (in which sand was replaced with BA in different proportions) were evaluated: (i) with SF as an additional binder and (ii) with SF and BFS as additional binders. The components of the concrete alternatives of the BA-based concretes with SF as an additional binder were based on those described by Kadam and Patil [15] (Table 1), and the components of the concrete alternatives to BA-based concrete with SF and BFS as additional binders were based on those described by Kim and Lee [14] (Table 2).

| Material | BA0SF | BA40SF | BA60SF | BA80SF | BA100SF |
|----------|-------|--------|--------|--------|---------|
| Portland cement (kg/m³) | 438 | 438 | 438 | 438 | 438 |
| SF (kg/m³) | 0 | 35.36 | 35.36 | 35.36 | 35.36 |
| Water content (kg/m³) | 197 | 197 | 197 | 197 | 197 |
| Sand (kg/m³) | 678.47 | 407.08 | 271.39 | 135.69 | 0 |
| BA (kg/m³) | 0 | 199.92 | 299.88 | 399.83 | 499.79 |
| Coarse aggregate (kg/m³) | 1097 | 1097 | 1097 | 1097 | 0.795 |
| Superplastificator (kg/m³) | 0 | 0 | 0 | 0.884 |

1 Replacements of sand with coal bottom ash (BA) were performed based on mass (the specific gravity was 2.67 and 1.93 for sand and BA, respectively).
2 BA0SF, BA40SF, BA60SF, BA80SF, and BA100SF: 0, 40, 60, 80, and 100 wt % of sand replaced with BA, respectively.

| Material | BA0SF-BFS | BA25SF-BFS | BA50SF-BFS | BA75SF-BFS | BA100SF-BFS |
|----------|-----------|------------|------------|------------|-------------|
| Portland cement (kg/m³) | 607 | 607 | 607 | 607 | 607 |
| SF (kg/m³) | 0 | 143 | 143 | 143 | 143 |
| BFS (kg/m³) | 0 | 186 | 186 | 186 | 186 |
| Water content (kg/m³) | 187 | 187 | 187 | 187 | 187 |
| Sand (kg/m³) | 437 | 328 | 219 | 109 | 0 |
| BA (kg/m³) | 0 | 76 | 152 | 227 | 303 |
| Coarse aggregate (kg/m³) | 824 | 824 | 824 | 824 | 824 |
| Superplastificator (kg/m³) | 14 | 14 | 14 | 14 | 14 |

1 Replacements of sand with coal bottom ash (BA) were performed based on mass (the specific gravity was 2.55 and 1.87 for sand and BA, respectively).
2 BA0SF-BFS, BA25SF-BFS, BA50SF-BFS, BA75SF-BFS, and BA100SF-BFS: 0, 25, 50, 75, and 100 wt % of sand replaced with BA, respectively.

In the present study, the BA-based concretes with SF as an additional binder are denoted as BA0SF, BA40SF, BA60SF, BA80SF, and BA100SF, which represent 0, 40, 60, 80, and 100 wt % of sand replaced with BA, respectively (Table 1), while the BA-based concretes with SF and BFS as additional binders are denoted as BA0SF-BFS, BA25SF-BFS, BA50SF-BFS, BA75SF-BFS, and BA100SF-BFS, which represent 0, 25, 50, 75, and 100 wt % of sand replaced with BA, respectively (Table 2).

2.2. Life Cycle Assessment

The LCAs of the BA-based concretes were conducted by defining the FU and system boundaries, analyzing the life cycle inventory (LCI), and evaluating the life cycle impact assessment (LCIA) [9]. With respect to the LCA of concretes, (i) the design stage, (ii) the production/execution stage, (iii) the usage stage, and (iv) the end-of-life stage needed to be considered [16]. However, structural concretes have different usage stages for different building elements, such as beams, pillars, and walls [17]. In particular, different building elements differ in lifetimes (50–300 years for foundational and load-bearing elements and 20–50 years for exterior walls) [18]. Thus, the usage stage is usually excluded from LCAs of
concrete [19]. Moreover, the end-of-life stage of structural concretes is uncertain because it is highly influenced by the applied disposal practices [20]. As a result, in this study, only a “cradle-to-gate” LCA, which evaluated the production of (i) the BA-based concretes with SF as an additional binder and (ii) the BA-based concretes with SF and BFS as additional binders, was conducted.

2.2.1. FU, System Boundary, and LCI

The FU is a reference to which the inputs and outputs need to be connected [9]. The FU used in this study was 1 m$^3$ of a concrete mixture. This FU can be considered appropriate in the case of concretes with additional binders (as in our cases) due to the very similar compressive strengths of such concretes. In particular, for the alternatives of BA-based concretes with SF as an additional binder, Kadam and Patil [15] reported a 28-day compressive strength of 41.52–45.76 MPa, and for the alternatives of BA-based concretes with SF and BFS as additional binders, Kim and Lee [14] reported a 28-day compressive strength of 62–72 MPa. Thus, both concretes have concrete mixtures with comparable compressive strengths, which is a necessary condition for performing comparable LCAs of these alternatives.

Figure 1 presents the system boundaries of the cradle-to-gate LCAs conducted in this study, which included the production of the concrete components with the relevant raw materials and the transport of the concrete components to the concrete batching plant. To model the concretes’ LCIs, the Ecoinvent v3.5 database, which is based on the SimaPro v9.0 software platform [21], was used (Table 3). The Ecoinvent v3.5 database (secondary data) was used due to the absence of local Israeli data. However, using such data was acceptable given the aim of the study, namely, to compare BA-based concrete alternatives with high binder contents.

According to Ecoinvent v3.5, the cement production included the supply, mixing, packing, and storage of raw materials; the aggregate (gravel and sand) extraction included their excavation; and the water treatment included its treatment. The transportation of the cements and aggregates to the batching plant was modeled in SimaPro using the local transportation distances. A short distance of 50 km was assumed for the transportation of aggregates from an aggregate quarry to a concrete plant. A longer distance of 100 km was assumed for the transportation of cement and byproducts (BA, SF, and BFS) from their industries (a cement plant, a ferrosilicon plant, and a steel mill, respectively) to a concrete plant.

In this study, BA, SF, and BFS were modeled using a consequential approach to byproducts (Figure 1). This approach involved system expansion; that is, boundary consequences of using byproducts from other industries in the concrete industry were included in the studied system [22]. In particular, both BA-based concrete mixtures with SF as an additional binder and BA-based concrete mixtures with SF and BFS as additional binders avoided the need to transport BA, SF, and BFS to the disposal site, and the avoided need to put these byproducts in a landfill was subtracted from the total impact of concrete production. Moreover, BA-based concrete mixtures with SF and BFS as additional binders avoided the need to produce steel by using BFS recovery (up to 8 kg of metal can be extracted from BFS). This was also subtracted from the total impact of concrete production.
Table 3. The EcoInvent v3.5 database [21] references used to model the life cycle of the bottom ash (BA)-based concrete mixtures with silica fume (SF) as an additional binder and the BA-based concrete mixtures with SF and blast furnace slag (BFS) as additional components.

| Process                  | Reference                                                                 |
|--------------------------|---------------------------------------------------------------------------|
| Water treatment          | Tap water, at user/CH U                                                   |
| Cement production        | Cement mortar, at plant/CH U                                              |
| Aggregate extraction     | Gravel, crushed, at mine/CH U                                             |
| Sand extraction          | Sand, at mine/CH U                                                        |
| Transport                | Lorry transport, Euro 0, 1, 2, 3, 4 mix, 22 t total weight, 17.3 t         |
| BA landﬁlling            | Disposal, concrete, 5% water, to inert material landﬁll/CH U              |
| SF landﬁlling            | Disposal, slag from silicon production, 0% water, to inert landﬁll/CH U  |
| BFS landﬁlling           | Disposal, steel, % water, to inert material landﬁll/CH U                  |
| Steel production         | Reinforcing steel, at plant/RER U                                         |

2.2.2. LCIA Method

In this study, the ReCiPe2016 LCIA method was used to convert the LCIs of the concretes to their LCIA results. This LCIA method was used because it includes three different perspectives from cultural theory [23]: individualist (I), which evaluates all of the short-term damaging effects; egalitarian (E), which evaluates all of the possible long-term damaging effects; and hierarchist (H), which evaluates the balance between the short- and long-term damaging effects [24]. By applying ReCiPe2016, these perspectives can be evaluated using the midpoint and single-score methods [21]. As a
result, by applying the ReCiPe2016 midpoint method, I, H, and E evaluations can be obtained. However, the ReCiPe2016 single-score method evaluates I, H, and E perspectives through the application of both average and particular weighting sets of the damage to human health, ecosystem quality, and resources. Thus, the average weighting set includes the individualist/average (I/A), hierarchist/average (H/A), and egalitarian/average (E/A) methodological options, and the particular weighting set includes the individualist/individualist (I/I), hierarchist/hierarchist (H/H), and egalitarian/egalitarian (E/E) methodological options.

The midpoint H (default) and single-score methods of ReCiPe2016 have different inherent advantages and disadvantages. The application of the midpoint method is related to less uncertainty in environmental evaluations; however, the interpretation of its results is more difficult. The application of the single-score method is related to high uncertainty in environmental evaluations; however, the interpretation of its results is less difficult [24].

Therefore, the environmental impacts of the BA-based concrete mixtures with SF as an additional binder and BA-based concrete mixtures with SF and BFS as additional binders were evaluated using both the midpoint method and the single-score methods of the ReCiPe2016. The midpoint H method was used to evaluate only the four most significant environmental impacts: GWP, terrestrial ecotoxicity, fossil resource scarcity, and water consumption. The single-score method was used to evaluate the six methodological options: I/A, H/A, E/A, I/I, H/H, and E/E. In addition, to simultaneously evaluate the results of the six methodological options, a two-stage nested (hierarchical) mixed analysis of variance (ANOVA) was used [8].

2.2.3. The Two-stage Nested (Hierarchical) ANOVA Design Structure

If the design of the study is a hierarchical design, then Picquelle and Mier [25] recommend using a two-stage nested ANOVA design structure. Consequently, a two-stage nested ANOVA design structure was used to environmentally evaluate both the BA-based concrete mixtures with SF as an additional binder and the BA-based concrete mixtures with SF and BFS as additional binders. According to Picquelle and Mier [25], this ANOVA design structure has the following statistical terminology: sampling frame, primary sampling unit, subunits, and individual subunits. The sampling frame is a collection of all elements (primary sampling units) that are accessible for sampling in the population of interest. A primary sampling unit contains two or more subunits. A subunit contains two or more individual subunits. Measurements were collected from the individual subunits.

Figure 2 shows two primary sampling units: the ReCiPe2016 results of a BA0SF and a BA40SF. The primary sampling unit included two subunits, namely, the particular and average weighting sets, and each subunit included three individual subunits, giving a total of six methodological options. Measurements were collected from the individual subunits. Therefore, four concretes with 40, 60, 80, and 100 wt % of sand replaced with BA were compared with 0 wt % of sand replaced with BA in pairs for the BA-based concrete mixtures with SF as an additional binder, and four concretes with 25, 50, 75, and 100 wt % of sand replaced with BA were compared with 0 wt % of sand replaced with BA in pairs for the BA-based concrete mixtures with SF and BFS as additional binders.
2.2.4. Statistical Analysis

First, the ReCiPe2016 results were multiplied by $10^3$ and were log10-transformed. The differences between the two ReCiPe2016 results were then analyzed using a two-stage nested ANOVA [8]. In the current study, the hybrid of the Paleo–Fisherian and Neyman–Pearsonian paradigms (i.e., null hypothesis significance tests (NHST)) are replaced by neo-Fisherian significance assessments, as recommended by Hurlbert and Lombardi [26]. The neo-Fisherian paradigm (1) does not fix $\alpha$, (2) does not describe $p$-values as “significant” or “nonsignificant”, (3) does not accept null hypotheses based on high $p$-values but only suspends judgment, (4) interprets significance tests according to “three-valued logic”, and (5) presents effect size information if necessary. The $p$-values were evaluated according to the three-valued logic: “appears to be positive”, “appears to be negative”, and “judgment is suspended” [26]. Additionally, Hurlbert and Lombardi [26] cited the recommendation of Gotelli and Ellison [27], noting that “in many cases, it may be more important to report the exact $p$-value and let the readers decide for themselves how important the results are.” Recently, this practical recommendation was applied in green building [28–31]. Also recently, it was shown that two-stage nested mixed ANOVA rather than a $t$-test is recommended as a supplemental method in evaluations of ReCiPe due the hierarchical structure of the methodological options [28].

In this study, the logic values for the BA-based concrete mixtures with SF as an additional binder were “there appears to be a difference between the BA0SF and BA40SF, the BA0SF and BA60SF, the BA0SF and BA80SF, or the BA0SF and BA100SF”; “there does not appear to be a difference between the BA0SF and BA40SF, the BA0SF and BA60SF, the BA0SF and BA80SF, or the BA0SF and BA100SF”; “judgment was suspended with respect to the difference between the BA0SF and BA40SF, the BA0SF and BA60SF, the BA0SF and BA80SF, or the BA0SF and BA100SF”.

The logic values for the BA-based concrete mixtures with SF and BFS as additional binders were “there appears to be a difference between the BA0SF-BFS and BA25SF-BFS, the BA0SF-BFS and BA50SF-BFS, the BA0SF-BFS and BA75SF-BFS, or the BA0SF-BFS and BA100SF-BFS”; “there does not appear to be a difference between the BA0SF-BFS and BA25SF-BFS, the BA0SF-BFS and BA50SF-BFS, the BA0SF-BFS and BA75SF-BFS, or the BA0SF-BFS and BA100SF-BFS”; and “judgment was suspended with respect to the difference between the BA0SF-BFS and BA25SF-BFS, the BA0SF-BFS and BA50SF-BFS, the BA0SF-BFS and BA75SF-BFS, or the BA0SF-BFS and BA100SF-BFS.”

Figure 2. Structure of the two-stage nested hierarchical analysis of variance (ANOVA) that was used for the environmental evaluation of the concretes with silica fume (SF) as an additional binder, i.e., BA0SF and FBA40SF. I/A: individualist/average; H/A: hierarchist/average; E/A: egalitarian/average; I/I: individualist/individualist; H/H: hierarchist/hierarchist; and E/E: egalitarian/egalitarian (the methodological options of the ReCiPe2016 single-score results).
3. Results

Both BA-based concrete mixtures with SF as an additional binder and BA-based concrete mixtures with SF and BFS as additional binders were evaluated via the ReCiPe2016 midpoint H method, and six methodological options of the ReCiPe2016 single-score method and the results are presented in Figures 3–6 and Tables 4 and 5.

Figure 3. The environmental impacts of replacing sand with coal bottom ash (BA) in concretes with silica fume (SF) as an additional binder. A: BA0SF; B: BA40SF; C: BA60SF; D: BA80SF; E: BA100SF. The ReCiPe2016 midpoint hierarchist method was used. Black circles and black dashed lines are average environmental impact and trend of impacts from A to E, respectively.
The environmental impacts of replacing sand with coal bottom ash (BA) in concretes with silica fume (SF) as an additional binder. A: BA0SF; B: BA40SF; C: BA60SF; D: BA80SF; E: BA100SF. The life cycle assessments (LCAs) (production stage) were evaluated via the six methodological options of the ReCiPe2016 single-score method.

Figure 4. The environmental impacts of replacing sand with coal bottom ash (BA) in concretes with silica fume (SF) as an additional binder. A: BA0SF; B: BA40SF; C: BA60SF; D: BA80SF; E: BA100SF. The life cycle assessments (LCAs) (production stage) were evaluated via the six methodological options of the ReCiPe2016 single-score method.
In the lowering of fossil resource scarcity, the avoidance of the need to transport BA and SF to the local concrete batching plant and the ferrosilicon plant, respectively, to the local concrete batching plant, and the avoidance of the need to transport BA, SF, and BFS to the disposal site and to put them in the coal-fired power plant and the ferrosilicon plant, resulted in environmental damage caused by the BA-based concrete mixtures with SF as an additional binder. The environmental impacts of replacing sand with coal bottom ash (BA) in concretes with silica fume (SF) and blast furnace slag (BFS) as additional binders were evaluated via the six methodological options of the ReCiPe2016 single-score method.

Table 4. p-Values of the differences in single-score evaluation between conventional concrete (BA0SF-BFS) and concretes with silica fume (SF) as an additional binder (BA40SF, BA60SF, BA80SF, and BA100SF) for the life cycle assessment (LCA) (production stage). The LCA results were evaluated via the six ReCiPe2016 single-score methodological options.

| Conventional Concrete | BA40SF | BA60SF | BA80SF | BA100SF |
|-----------------------|--------|--------|--------|---------|
| BA0SF                 | 0.1462 | 0.0738 | 0.0887 | 0.0547  |

1 Ordinal font represents a negative difference between the compared concretes; italic font means judgment was suspended regarding the difference between the compared concretes. 2 BA0SF, BA40SF, BA60SF, BA80SF, and BA100SF: 0, 40, 60, 80, and 100 wt% of sand replaced with bottom ash (BA), respectively.

Table 5. p-Values of the differences in single-score evaluation between conventional concrete (BA0SF-BFS) and concretes with silica fume (SF) and blast furnace slag (BFS) as additional binders (BA25SF-BFS, BA50SF-BFS, BA75SF-BFS, and BA100SF) for the life cycle assessment (LCA) (production stage). The LCA results were evaluated via the six ReCiPe2016 single-score methodological options.

| Conventional Concrete | BA25SF-BFS | BA50SF-BFS | BA75SF-BFS | BA100SF-BFS |
|-----------------------|------------|------------|------------|-------------|
| BA0SF                 | 0.1443     | 0.1148     | 0.0961     | 0.0779      |

1 Ordinal font represents a negative difference between the compared concretes; italic font means that judgment was suspended regarding the difference between the compared concretes. 2 BA0SF-BFS, BA25SF-BFS, BA50SF-BFS, BA75SF-BFS, and BA100SF-BFS: 0, 25, 50, 75, and 100 wt% of sand replaced with bottom ash (BA), respectively.

3.1. BA-Based Concrete Mixtures with SF as an Additional Binder

According to the ReCiPe2016 midpoint H method, the BA-based concrete mixtures with SF as an additional binder exhibited similar tendencies in the impacts of GWP, terrestrial ecotoxicity, water consumption, and fossil resource scarcity (Figure 3). However, when the sand in the concrete was sequentially replaced with BA, GWP, terrestrial ecotoxicity, and water consumption impacts were only slightly lowered, whereas the fossil resource scarcity impact was lowered to a much greater extent.

In the lowering of GWP, terrestrial ecotoxicity, and water consumption, the decrease in the quantity of sand and the increase in the benefit related to the avoidance of the need to dispose of the BA and SF byproducts prevailed over the increase in the traffic load due to the transportation of BA and SF from the coal-fired power plant and the ferrosilicon plant, respectively, to the local concrete batching plant. In the lowering of fossil resource scarcity, the avoidance of the need to transport BA and SF to the disposal site and their disposal to land is one factor which contributes to this decrease.

According to the six methodological options of the ReCiPe2016 single-score method, the environmental damage caused by the BA-based concrete mixtures with SF as an additional...
binder decreased in the following order: BA0_{SF} > BA40_{SF} > BA60_{SF} > BA80_{SF} > BA100_{SF} (Figure 4). The same order of decrease was observed for all six methodological options.

The analysis of the BA-based concrete mixtures with SF as an additional binder (Table 4) showed that the difference between BA0_{SF} and BA40_{SF} was found negative to a statistically significant degree ($p = 0.1462$). However, judgment was suspended for the differences between BA0_{SF} and BA60_{SF}, BA0_{SF} and BA80_{SF}, and BA0_{SF} and BA100_{SF} (0.0547 ≤ $p$ ≤ 0.0887).

Therefore, according to the rankings (Figure 4) and the p-value analyses (Table 4) of the LCA results, the concretes with the lowest environmental impacts were found to be BA100_{SF}, BA80_{SF}, and BA60_{SF}, while BA40_{SF} and BA0_{SF} were revealed as the concretes with the highest environmental impacts.

3.2. BA-Based Concrete Mixtures with SF and BFS as Additional Binders

According to ReCiPe2016 midpoint H method, the BA-based concrete mixtures with SF and BFS as additional binders exhibited similar tendencies in terms of the impacts of GWP, terrestrial ecotoxicity, water consumption, and fossil resource scarcity (Figure 5) to those of the BA-based concrete mixtures with SF as an additional binder (Figure 3). In particular, as in the case of concrete mixtures, the results indicate that when the sand in the concrete was sequentially replaced with BA, the GWP, terrestrial ecotoxicity, and water consumption impacts were only slightly decreased, whereas the fossil resource scarcity impact was decreased to a much greater extent.

Regarding the decreases in the GWP, terrestrial ecotoxicity, and water consumption, the decrease in the quantity of sand and the increase in the benefit related to the avoidance of the need to dispose of the BA and SF byproducts and to produce steel (which is supposed to be produced from the BFS before being used as a byproduct) were more predominant than the increase in the traffic load due to the transportation of BA, SF, and BFS from the coal-fired power plant, ferrosilicon plant, and steel mill, respectively, to the local concrete batching plant. Regarding the decreases in fossil resource scarcity, the avoidance of the need to transport BA, SF, and BFS to the disposal site was the factor contributing to this decrease.

In addition, for the BA-based concrete mixtures with SF and BFS as additional binders (Figure 5), a reduction in the GWP, terrestrial ecotoxicity, water consumption, and fossil resource scarcity impacts of 0.8–8.5% from that of the BA-based concrete mixtures with SF as an additional binder (Figure 3) was obtained. These results indicated the influence of the quantity of byproducts that were used as additional binders, namely, the BA-based concrete with two byproducts (SF and BFS) as additional binders brought more environmental benefits than the BA-based concrete with one byproduct (SF) as an additional binder.

According to the six methodological options of the ReCiPe2016 single-score method, the environmental damage caused by the BA-based concrete mixtures with SF and BFS as additional binders decreased in the following order: BA0_{SF-BFS} > BA25_{SF-BFS} > BA50_{SF-BFS} > BA75_{SF-BFS} > BA100_{SF-BFS} (Figure 6). The same order of decrease was observed for all six methodological options.

The analysis of the BA-based concrete mixtures with SF and BFS as additional binders (Table 5) showed that the differences between BA0_{SF-BFS} and BA25_{SF-BFS} and between BA0_{SF-BFS} and BA50_{SF-BFS} were negative to a statistically significant degree ($p = 0.1443$ and $p = 0.1148$). However, judgment was suspended for the differences between BA0_{SF-BFS} and BA75_{SF-BFS} and between BA0_{SF-BFS} and BA100_{SF-BFS} ($p = 0.0961$ and $p = 0.0779$).

Therefore, according to the rankings (Figure 6) and p-value analyses (Table 5) of the LCA results, the concretes with the lowest environmental impacts were found to be BA100_{SF-BFS} and BA75_{SF-BFS}, while BA50_{SF-BFS}, BA25_{SF-BFS}, and BA0_{SF-BFS} were revealed as the concretes with the highest environmental impacts.

4. Discussion

The aim of this study was to conduct LCAs of BA-based concretes (in which sand had been substituted with BA in different proportions) with comparable compressive strength values to
conventional concrete. In these BA-based concretes, comparable compressive strength was achieved by including the additional byproducts (SF and BFS) and thereby increasing the total binder content. Two types of concrete—BA-based concrete mixtures with SF as an additional binder and BA-based concrete mixtures with SF and BFS as additional binders—were evaluated. The LCA values of the concretes were determined using (i) the ReCiPe2016 midpoint H method and (ii) six methodological options of the ReCiPe2016 single-score method.

The ReCiPe2016 midpoint H method results of the BA-based concrete mixtures with SF as an additional binder and the BA-based concrete mixtures with SF and BFS as additional binders demonstrated decreasing environmental impacts related to GWP, terrestrial ecotoxicity, water consumption, and fossil resource scarcity in the BA-based concretes compared with conventional concretes (Figures 3 and 5). Such results were obtained due to the application of consequential LCA modeling for the byproducts, which allowed the expansion of the studied system boundaries to include consequences of using byproducts from other industries in the concrete industry [22]. In this study, the avoidance of the need to transport BA, SF, and BFS to the disposal site and to put them in a landfill (Figures 3 and 5) as well as the avoided need to produce virgin steel (Figure 5) were considered bonuses and their contributions were subtracted from the total impact of concrete production.

Similar results were reported by Turk et al. [11], who studied byproduct-based concretes, in which sand had been partially replaced by foundry sand or steel slag and which contained FA as a mineral admixture, and conducted consequential LCA modeling for the byproducts. As a result, GWP, acidification potential, eutrophication potential, and the photochemical ozone creation potential for the byproduct-based concretes decreased compared with conventional concretes [11].

The analysis of the six methodological options of the ReCiPe2016 single-score method of the BA-based concrete mixtures recommended a high percentage—more than 40 wt % and more than 75 wt %—of sand replacement with BA for BA-based concrete with SF as an additional binder and BA-based concrete mixtures with SF and BFS as additional binders, respectively. These results are in contrast with the results presented by Pushkar [8], who recommended replacing sand with BA at up to 50 wt %. This is because Pushkar [8] considered BA as “waste” from coal-based electricity production with zero damage in concrete production. Therefore, in contrast to the consequential LCA modeling performed in the present study, bonuses were accounted for related to the avoidance of transportation of BA to the disposal site and the avoidance of landfilling [8].

In addition to the different byproduct modeling approaches (consequential or waste), other studies reported additional factors that may contribute to the sensitivity of the LCAs of byproduct-based concretes, such as the transportation distance for the delivery of byproducts to the concrete batch plant (short or long [11]) and the byproduct-based concrete design approach (with fixed slump ranges or fixed W/C ratios [8]). Regarding the transportation distances, Turk et al. [11] reported that short distances (up to 100 km) bring environmental benefits, whereas long distances (more than 100 km) bring environmental damage. Regarding the byproduct-based concrete design approach, Pushkar [8] reported that fixed slump ranges bring environmental benefits, whereas fixed W/C ratios bring environmental damage.

5. Conclusions

The use of BA instead of sand is an active research issue. Thus, we studied the environmental impacts of such replacement for two BA-based concrete mixtures: concrete with SF as an additional binder and concrete with SF and BFS as additional binders. The following conclusions were drawn:

1. According to the ReCiPe2016 midpoint H method, the increasing substitution of sand with BA in the concrete with SF as an additional binder and in the concrete with SF and BFS as additional binders led to lowered values of global warming potential, terrestrial ecotoxicity, water consumption, and especially, fossil resource scarcity. The BA-based concrete with more byproducts (SF and BFS) as additional binders brought more environmental benefits than the BA-based concrete with fewer byproducts (SF) as additional binders.
2. According to the six methodological options of the ReCiPe2016 single-score method, for the BA-based concretes with SF as an additional binder and SF and BFS as additional binders, the concretes with 40–100 and 75–100 wt % of sand replacement, respectively, seemed to cause the least environmental damage.

However, the environmental benefit of BA-based concrete with additional byproducts is still an open research issue. In the future, additional mixtures of such concretes should be considered to further clarify the environmental effects of additional byproducts that provide higher binder contents in BA-based concretes.

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