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Environmental Efficiency Aspects of Basalt Fibers Reinforcement in Concrete Mixtures

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Abstract: Modern building materials must fulfill not only functional performance criteria but also reduce the environmental impact accompanied by their production. Within the past decades, fiber-reinforced materials have been found to be promising and durable materials that can be utilized in various fields. Among a wide range of reinforcement types, basalt fibers have been introduced as an alternative to broadly used steel fibers. As informed by the available literature, benefits linked with less energy-intensive production indicate a very good potential application of this material in terms of functional properties and, at the same time, a reduction in environmental burden. However, only a very limited amount of information is available on the actual impact of using basalt fibers in terms of environmental impact. In order to fill this gap, the present study describes, using Life Cycle Assessment, the environmental impacts associated with the production of basalt fibers. In order provide a more reliable and coherent overview, an analysis combining functional and environmental indicators was performed. The presented results reveal that the use of basalt reinforcement provides a significantly lower environmental intensity per strength unit, especially in the case of compressive and flexural strength.

Keywords: basalt fiber; environmental impact; life cycle assessment; eco-efficiency; carbon dioxide; complex assessment

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1. Introduction

Concrete, viewed as an abundant, versatile building material with good mechanical performance at a reasonable cost, is extensively used and produced in huge amounts [1]. Moreover, recent advances in the building industry and urbanism accompanied by increased demands on overall functional parameters, including increased durability, shrinkage resistance, and aggressive environmental resistance, have further increased its major role in the development of urban areas [2,3].

Considering the brittleness of plain concrete as a major functional disadvantage, the utilization of various fibers has been studied in detail in order to improve mechanical performance and extend service life [4,5]. Fiber-reinforced concrete (FRC) provides substantially improved shrinkage and expansion resistance, enhanced toughness, and mechanical performance improvement. In this regard, the following categories of fibers can be found in the literature: (1) metallic fibers—mostly steel fibers or stainless-steel fibers due to its availability, good compatibility with cementitious matrix, favorable mechanical properties, and reasonable price; (2) polymer fibers—synthetic fibers composed of polypropylene, nylon, polyvinyl alcohol, polyolefin, acrylic, aramid, and carbon; (3) natural fibers—mainly originating from plants; (4) glass fibers—silica and basalt based matrix and carbon fibers [6–9]. The performance of particular fiber types was studied in detail in several research papers that took into account acid attack, high-temperature loading, freeze-thaw resistance, chlorine resistance, durability in seawater environmental and coastal areas, etc. [9,10].

Taking into account the aforementioned issues, the basalt fibers were considered an interesting alternative to concrete reinforcement due to their good chemical and temperature stability, beneficial mechanical performance, no emission of toxic compounds, reasonable price, and limited environmental impact [11–13]. Specifically, the basalt fibers provide a better tensile strength in comparison with glass fibers, higher failure strain than carbon fibers, they have a lower weight than steel fibers, and there is only about a 50% strength reduction at 700 °C, the temperature at which most fibers decompose or become significantly deteriorated [14]. Jabbar et al. [15] concluded that the application of basalt fibers is also accompanied by the raised diagonal crack-load to a greater extent than steel fibers. Compared to PVA fibers, basalt fibers exhibit lower chemical and frictional bonding; however, this material performance could be improved by special additives.

In line with the awareness of sustainability in the construction industry, the effect of used materials on the natural environment, including all negative externalities, represents a substantial issue in building materials design. In this regard, the investigations of Akbar et al. [16] and Stoiber et al. [17] concluded that apart from mechanical performance benefits, cost-efficiency and relatively simple production and low weight are substantial factors that should be considered when selecting the type of reinforcing fibers (for example, carbon reinforcement suffers from a high cost and large environmental impact) [18]. Therefore, all input materials need to be carefully selected in order to mitigate the adverse effects associated with production, compliance with modern standards, and to balance mechanical, environmental, and economic performances [11].

The understanding of the environmental footprint of used materials becomes a very important issue contributing to the sustainable development principles adopted within modern building materials design [19]. In this regard, a robust environmental assessment such as Life Cycle Assessment (LCA) is utilized in order to determine the impact of material processing and serves as a tool for the identification of suitable components [20]. The robustness and widely standardized methodology of LCA predetermined its use for benchmarking various materials, including building material components. Taking into account the environmental footprint of building materials, the utilization of basalt fibers as a concrete reinforcement is widely presumed to be a prospective solution [21]. Notwithstanding, the overall impact needs to be discussed in a broader perspective to follow the sustainability principles similarly to the previously described environmental impacts of glass and carbon fiber-reinforced [13]. Unlike carbon or steel fibers, reliable datasets describing the environmental load associated with basalt fiber application are lacking in the available literature, and only a few pioneer works can be identified. Therefore, an understanding of the environmental impact associated with basalt fiber reinforcement needs to be provided in order to allow advanced comparison and responsible selection of individual concrete mixture constituents [22–24].

In order contribute to the understanding of basalt fiber production in terms of environmental impact, the present study describe the environmental externalities caused by basalt fiber manufacturing. The primary motivation of this study lies in a comprehensive description of basalt fiber production in terms of the Life Cycle Analysis. In order to highlight the contribution of this work in terms of environmental impacts, the calculated LCA results are combined together with mechanical parameters to form united parameters describing combined environmental/functional performance in comparison with common steel fiber reinforcement.

2. Materials and Methods

In order to investigate the environmental impact related to basalt fiber production, relevant information describing the production processes and reference material properties were obtained from a medium-scale commercial company located in the EU. As described in previous studies, the fabrication of basalt fibers consists of several steps, starting with melting solidified lava stone, which occurs at 1500 °C, and is continued via extrusion into fibers, drying, and cutting into the desired length. Desalt rock melting requires a significant amount of energy, notwithstanding, no demands on additives supplied during the manufacturing process reduced the overall costs of production in comparison to glass fibers. As a result of raw material origin, the chemical composition of basalt fibers may vary. The chemical composition by the meaning of the content of the major oxide is shown in Table 1. It should be noted that slightly different weight fractions were identified by other researchers, particularly regarding the diversity in MgO and Fe_2O_3 content. This phenomenon may result in variations in functional properties—namely, the SiO_2 and Al_2O_3 content correlates with a tensile strength of fibers. In order to clearly specify the characterized basalt fiber properties, the main characteristics are shown in Table 2. Generally, the acidity modulus and viscosity modulus need to be at optimal values for the efficient production of continuous filaments.

Table 1. Chemical composition of basalt.

Oxide	Content (%)
SiO_2	54.3
Al_2O_3	13.3
Fe_2O_3	13.6
MgO	6.2
TiO_2	0.5
CaO	9.9
K_2O	0.9
Na_2O	1.3

Table 2. Material characteristics of basalt fibers.

Fiber Length	Diameter	Density	Young Modulus	Tensile Strength
45 mm	0.7 mm	2150 kg/m^3	42 GPa	10,000 MPa

2.1. Basalt Fiber Production Process

The production of continuous basalt filaments (see Figure 1) begins with quarrying basalt from sites and, consequently, crushed into the desired fraction (4–20 mm) by diesel-fueled mobile crushing machinery. This process consists of two subsequent crushing operations. First, the basalt rock is moved into the jaw crusher by a vibrating feeder to maintain primary crushing. Such preprocessed rock is fed to a cone crusher for secondary crushing. Basalt aggregates possessing the desired size are washed and transported by lorries to storage. Particles that do not meet the size requirement need to be crushed in the cone crusher again.

The production process continues by melting in a melting furnace at a temperature of around 1500 °C. As opposed to glass fiber production, basalt filament manufacturing does not require any additional admixtures or secondary materials; therefore, only the crushed basalt rock is supplied by a loader. Basalt melting takes place at a temperature about of 1500 °C; however, unlike glass, dark basalt absorbs a substantially higher amount of infrared energy, which results in non-uniform distribution of temperature in the molten mixture [25]. In this regard, the melting period needs to be extended to reach the homogenous melting of basalt rock. For this purpose, in the past, the melting process was modified compared to glass melting in order to reduce unnecessary inhomogeneity occurrence and to increase the efficiency of the melting stage. According to Meng et al. [26], the use of multiple electrodes immersed in molten basalt may decrease the melting period.

After the completion of basalt melting, the continuous filaments, possessing a diameter range from 9 to 18 microns, are formed by passing through platinum flange holes. Formed filaments are drawn from molten basalt and consequently lubricated. Afterward, the filaments are winded into reels and stored. Formed basalt fibers are transported to concrete plants and are used as reinforcement.

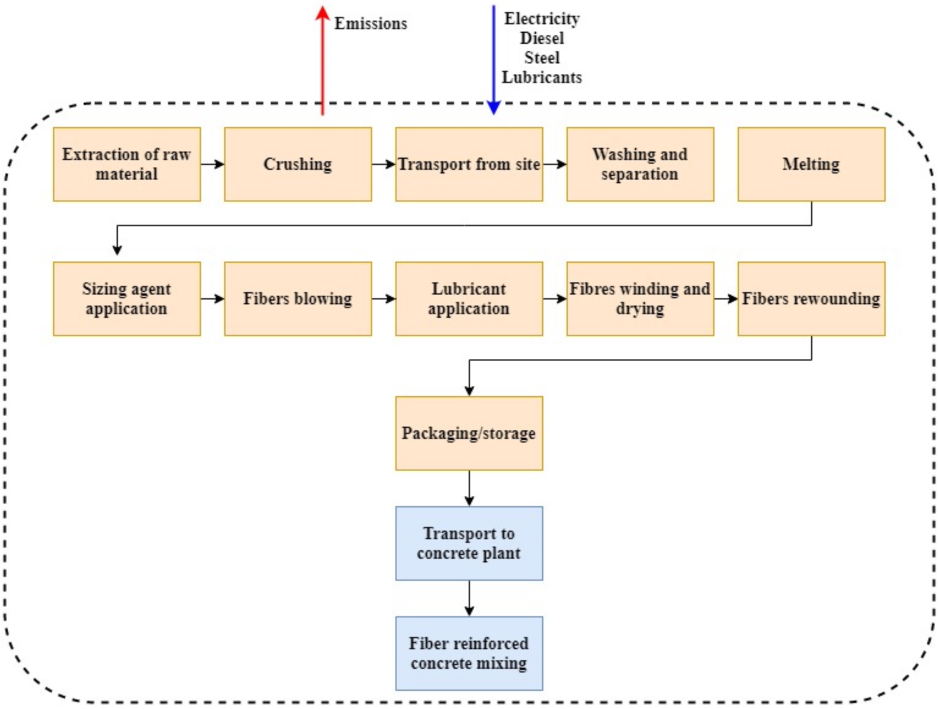

Figure 1. Schema of basalt fiber production.

2.2. *Life Cycle Analysis*

The LCA consist of four main steps, i.e., goal and scope definition, life cycle inventory description, life cycle impact assessment characterization, and the interpretation of the result. In order to cover information relevant to LCA assessment of basalt fiber production and use, this concept was extended by the characterization of combined environmental/functional assessments. Within this analysis, the guidelines provided in EN 14040 and EN 14044 were followed in order to meet the LCA requirements for reproducibility of analysis, transparency, and comparability. The LCA analysis was carried out with the help of SimaPro LCA software v 9.0 equipped with the Ecoinvent database v3.5 [27].

2.2.1. Goal and Scope Definition

The principal goal of this paper consists of defining the environmental footprint of basalt fiber production considering the cradle-to-gate boundary conditions. The functional unit for this study was defined as 1 metric ton of basalt fibers with the material parameters shown in Table 2. In order to access the overall effect of using basalt fiber reinforcement, including the environmental and functional efficiency, the mechanical performance results obtained from Jabbar et al. [15] were employed. This approach allows the characterization of effects related to basalt fiber use in terms of mechanical strength and environmental externalities. The mechanical properties are summarized in Table 3.

Table 3. Mechanical performance of basalt/steel fiber reinforced concrete, adopted from [15].

	Compressive Strength (MPa)	Tensile Strength (MPa)	Flexural Strength (MPa)
SFRC 0.5	112.53	14.72	43.76
SFRC 1.5	137.18	19.81	52.75
BFRC 0.5	148.81	12.68	47.39
BFRC 1.5	145.39	8.34	41.24

With the variety of applications of such produced fibers, the cradle-to-gate cycle is used. The environmental footprint also needs to be linked with basic material performance in order to access functional/environmental effectivity.

2.2.2. Life Cycle Inventory

The life cycle inventory (see Table 4) contains all inputs considered within the evaluation per functional unit (1 ton of basalt fibers). In this regard, the datasets related to steel fiber production, concrete production, transportation of raw materials, etc., are available in several databases, including the Ecoinvent database. However, basalt fiber production is not accessed within these databases (only the basalt quarrying process is available and characterized); thus, new processes have to be created. In order to cover all material and energy inputs and consider the volume of outputs, the primary data describing basalt fiber production were obtained from the basalt fiber producer. Data for intended materials production, transportation, and processing are provided by the Ecoinvent database v.3.5 with the help of SimaPro LCA software 9.0. Since basalt fiber production depends on the availability of material resources, regional factors need to be taken into account. According to available literature, vast resources of basalt are located in Iceland and Russia [28]. However, the scarcity of relevant data sources from Russia diminishes the relevance of this locality; therefore, Iceland is considered a production region. Accordingly, the energy mix of Iceland is considered. To provide a more comprehensive and reliable comparison, transportation to Central Europe is included within the calculation

Table 4. Material and energy inputs associated with basalt fiber production per functional unit.

Input	Quantity/FU
Water	748.0 kg
Basalt rock	1400.0 kg
Lubricating oil	2.1 kg
Silicone	4.0 kg
Electricity	1.2 MWh
Natural gas	12.5 GJ
Diesel	12.4 L

Data describing the environmental load accompanied with steel fiber and concrete production were adopted from Yin et al. [29] and Jabbar et al. [15].

2.2.3. Transportation Distances

As mentioned above, the local scarcity of basalt quarries distorts the LCA comparison if adequate transportation to concrete plants is neglected. In order to overcome this issue, the concrete production plant in the Czech Republic was considered. This assumption requires the calculation of sea ship transport and consequent truck transport from the Iceland basalt fiber production factory for basalt fibers. On the other hand, the steel fiber reinforcement scenario requires only about 75 km transport by trucks.

2.2.4. System Boundaries and Limitations

The performed research takes into account the direct consequences of consumed inputs (raw materials, energy, transportation, and processes), and on the other hand resulting outputs in the form of final products and externalities. In the scope of the analysis, the cradle-to-gate boundaries are used.

2.2.5. Life Cycle Impact Assessment

The impact assessment method IMPACT 2002+ methodology was used based on its complexity and broad acceptance by the scientific audience [30]. IMPACT 2002+ provides a robust platform that includes 15 midpoint indicators for the characterization of various environmental footprints at midpoint levels as follows: Aquatic acidification (AC); Aquatic Ecotoxicity (AE); Aquatic eutrophication (AEU); Carcinogens (CA); Global Warming (GW); Ionizing Radiation (IA); Land Occupation (LO); Mineral Extraction (ME); Non-carcinogens (NCA); Non-renewable Energy (NRE); Ozone Layer Depletion (OLD); Photochemical Oxidation (PO); Respiratory Effects (RE); Terrestrial Acidification/Nitrification (TAN); and Terrestrial Ecotoxicity (TE). The characterization at endpoint levels was performed by Human health, Ecosystem Quality, Climate Change, and Resources Consumption categories. The calculated results were aggregated to a normalized single score and used for consequent characterization of the material performance.

2.2.6. Environmental/Functional Assessment

In order to access the combined assessment of environmental and functional parameters, the eco-efficiency indicators introduced by Damineli et al. [31], also used in several follow-up studies [32,33], were adopted. The overall environmental/functional efficiency E_x describing the environmental costs (represented by the normalized environmental single score) per functional unit of functional performance (in this study, compressive strength, Rc; flexural strength, Rf; and tensile strength, Rt, were used). It is defined as follows:

$$E_x = \frac{E}{R_x} \quad (1)$$

where E (mPt) is the normalized environmental single score, and R_x the functional performance parameter.

Similarly, the CO_2 intensity index provides an overview of the amount of emitted amount CO_2 per unit of the functional performance. The carbon dioxide efficiency index C can be defined as follows:

$$C_x = \frac{C}{R_x} \quad (2)$$

where C (CO_2) is the cumulative CO_2 emissions, and R_x the functional performance parameter.

3. Results and Discussion

The LCA results shown in Table 5 show the associated environmental externalities accompanied by continuous basalt fiber production. It should be also noted that favorable Iceland electricity mix composed mainly from geothermal sources further improved the calculated environmental effects. In this regard, CO_2 production associated with 1 ton BF manufacturing accounts for about 398 kg CO_2 eq. On the other hand, electricity represents a rather minor part of consumed energy, since the used furnace is fueled by natural gas combustion. Planned restrictions aimed at the mitigation of fossil fuels combustion may, in this sense, further reduce carbon dioxide emissions. However, the specifics of Iceland cannot be transferred to other European countries conclusively. Figure 2 depicts the contribution of particular processes and consumed materials within basalt fiber manufacturing. As observed, the most intense impact corresponds to natural gas combustion in the melting furnace, especially for the Global Warming, Carcinogens, and Non-renewable energy consumption midpoint impact categories. The substantial impact is also accompanied by the employment of heavy machinery powered by diesel, required within raw basalt quarrying, loading, and crushing. As is evident, the silicon and other lubricant consumptions represent a notable material input particularly reflected in the Ozone Layer Depletion and Land Occupation categories. The use of lubricating oil causes adverse effects on the Respiratory Organics midpoint indicator. Similar findings provided by Dong et al. [13] pointed to substantial environmental impact of applied epoxy resin and lubricating agents. The obtained values are in agreement with the presumptions of various authors, who attributed reduced environmental impact to BF production, in comparison to steel or glass fibers [22,34]. As observed in the work of Akbar et al. [16], almost all currently used types of fiber reinforcement are linked to a similar impact on aquatic organisms by acidification. On the other hand, substantial differences in Ozone Layer Depletion, as well as Global Warming potential, can be noted regardless of the used methodology [35]. Substantial attention should be paid to the associated local environmental impacts and not only to the energy mix composition but also with respect to local transportation distances and used transport, which may distort environmental impact substantially [36]. The values of environmental impact may slightly differ according to used raw material and the used production technology [37].

Table 5. LCA midpoint indicators.

Category	Unit	Value
Carcinogens (AC)	kg C_2H_3Cl eq	1.52×10
Non-Carcinogens (NC)	kg C_2H_3Cl eq	1.21×10
Respiratory Inorganics (RI)	kg $PM_{2.5}$ eq	3.20×10^{-1}
Ionizing Radiation (IR)	Bq C^{-14} eq	2.30×10^{3}
Ozone Layer Depletion (OLD)	kg CFC^{-11} eq	3.51×10^{-5}
Respiratory Organics (RO)	kg C_2H_4 eq	1.75×10^{-1}
Aquatic Ecotoxicity (AE)	kg TEG water	2.56×10^{5}
Terrestrial Ecotoxicity (TE)	kg TEG soil	5.74×10^{4}
Terrestrial Acid/Nutri (TAN)	kg SO_2 eq	6.56×10^{0}
Land Occupation (LO)	m^2org.arable	8.05×10^{0}
Aquatic Acidification (AA)	kg SO_2 eq	1.34×10^{0}
Aquatic Eutrophication (AEU)	kg PO_4 P-lim	4.03×10^{-2}
Global Warming (GW)	kg CO_2 eq	3.98×10^{2}
Non-Renewable Energy (NRE)	MJ primary	6.63×10^{3}
Mineral Extraction (ME)	MJ surplus	6.55×10^{0}

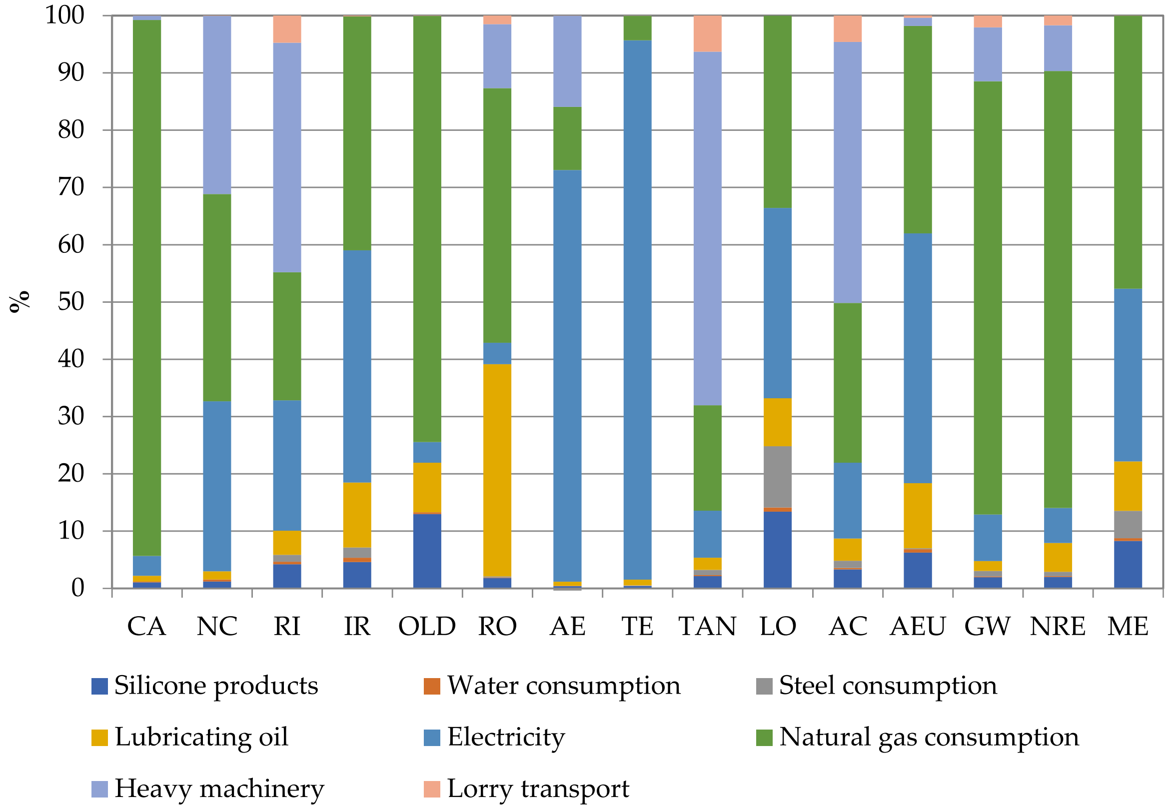

Figure 2. Midpoint impacts of basalt fiber production.

The normalized endpoint level impacts represented by human health, ecosystem quality, climate change, and resources are shown in Figure 3. Looking at the results at the endpoint level, the most intense consequences consist of natural gas combustion across all categories except Ecosystem Quality. This endpoint category suffers mostly from electricity consumption. Significantly lower environmental load is related to the use natural fibers, which in recent years attracted eminent attention due to lower requirements on material processing. This issue was studied by Zhou et al. [38], who concluded substantial environmental savings by the replacement of glass fibers by kenaf fibers. However, the differences in the functional properties of basalt fibers such as long-term stability, durability, and high-temperature resistance render it impossible to provide an unambiguous comparison of various fibers and at the same time refer to the need to use a multi-criteria assessment that could cover more than just environmental factors [16,39]. In this regard, Chen et al. [18] questioned the benefits of natural fibers due to large amounts of epoxy resin, which nullified the advantages of natural fiber compared to carbon fibers.

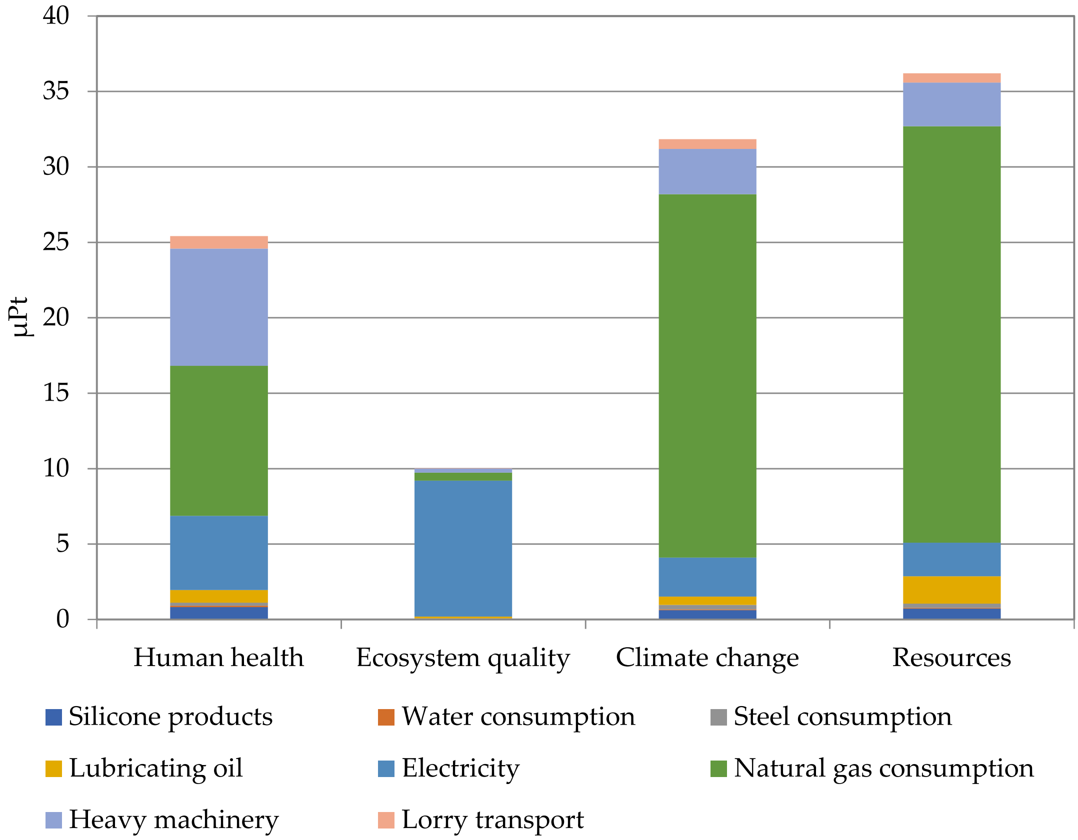

Figure 3. Endpoint impacts of basalt fiber production.

In order to assess the differences in environmental impact thoroughly, the mix composition from the work of Jabbar et al. [15] is adopted, and the final environmental impact of mixtures with 0.5 and 1.5% of fiber reinforcement is considered. As observed from the presented results plotted in Figure 4 at the midpoint level and Figure 5 at the endpoint level, better environmental performance can be assigned to the application of basalt fibers over steel reinforcement. Namely, the mix with 1.5% steel fiber exhibited significantly increased environmental load compared to the other options. Surprisingly, the mixture reinforced by 0.5% steel fiber content did not exhibit such diverse results compared to basalt fibers. Moreover, in several midpoint categories such as Ozone Layer Depletion, Aquatic Ecotoxicity, Land Occupation, and Terrestrial Ecotoxicity, more favorable impacts can be assigned to steel fiber reinforcement. The reason for this peculiarity is linked with different material properties, particularly material density. While the volume of the used fiber reinforcement is equal for both materials, the weight differs significantly. In other words, the 0.5 volumetric percentage of basalt fibers corresponds to 10.75 kg, while in the case of basalt fibers, the same volume of steel fibers weighs almost 40 kg. This disparity is even more pronounced for the mixture with 1.5%, where about 32.25 kg of basalt fibers needs to be dosed or 117.75 kg for steel alternatives. Therefore, the embodied emissions are substantially lower for basalt fibers compared to steel fibers. It should be noted that the sensitivity analysis performed by Dong et al. [13], dealing with the glass and carbon fiber reinforced polymer bar production, reveals that the amount of used cement is the most important factor with a major effect on the final environmental score. Thus, regardless of the importance of transportation, material handling used energy mix, etc., and the production stage contributes more than 90% to the entire life cycle of environmental impact.

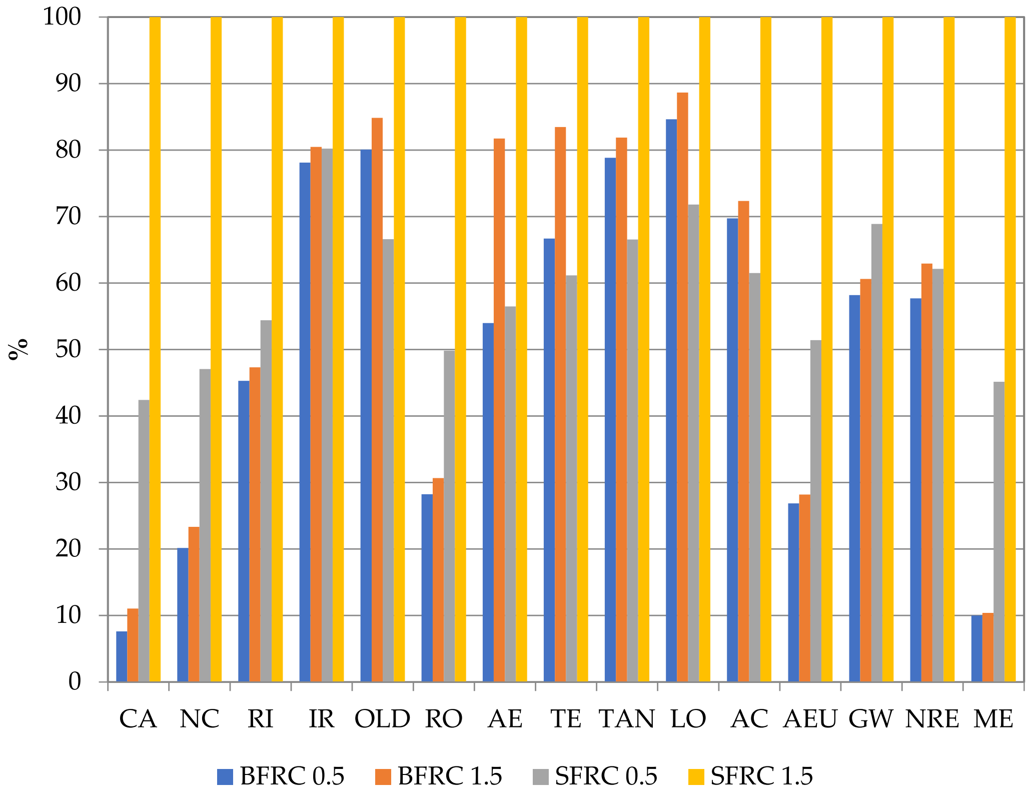

Figure 4. Midpoint comparison of concrete reinforced by basalt and steel fibers.

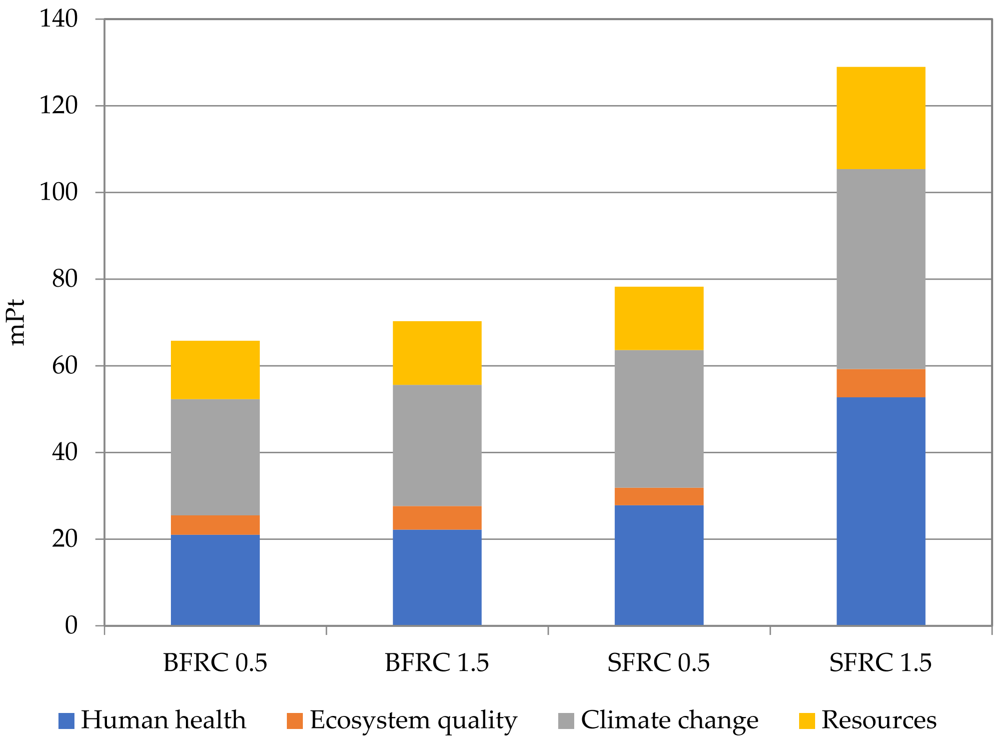

Figure 5. Endpoint comparison of concrete reinforced by basalt and steel fibers.

The results at the endpoint level correlate with the above-mentioned findings as depicted in Figure 4. As shown, all endpoint impact categories were influenced proportionally, while the single score index point to the lowest environmental load associated with BFRC 0.5, followed by BFRC 1.5 and SFRC 0.5. Mixture SFRC 1.5 revealed significantly worsened values, which were almost twice high as BFRC 0.5.

However, the separate evaluation of functional environmental performance does not provide a comprehensive overview of material performance in terms of sustainable measures. In this regard, a combined environmental/functional assessment takes place, and thereby more reliable and thorough insights can be found. With the help of the presented results of Jabbar et al. [15], the following indexes (see Figures 6 and 7) can be presented, and crucial findings can be formulated. As is evident, the eco-efficiency of all of the studied mixtures gradually increased in line with the shift in reinforcement dosage. Here, the "environmental costs" per MPa for flexural and compressive strength were lowest for BFRC 0.5, followed by BFRC 1.5. In other words, the utilization of basalt fibers represents a viable solution with sufficient functional performance and reduced environmental costs in comparison to a conventional solution. On the other hand, the noted drop in tensile strength observed for BFRC 1.5 diminished the environmental viability of this mixture. Similar trends were also observed for the CO_2 intensity index. The quite low CO_2 emissions are related to the functional parameters of concrete reinforced by basalt fibers, which is almost half in case of the compressive strength. The undesired drop in the tensile strength of basalt mixtures is due to the limited capability of basalt fibers to redistribute the stress; therefore, even more favorable environmental performance cannot balance the loss in tensile strength [24]. The energy/mechanical index accessed by Zhang et al. [38] refers to the favorable results of basalt fiber reinforcement over carbon fibers. In this regard, the application of basalt fibers as a concrete reinforcement can be viewed as favorable options contributing to extended material performance and concurrently contributing to sustainable goals. The comparison of reinforced façade panels studied by Laiblova et al. [11] reveals the environmental benefits associated with basalt reinforcement use; however, the authors did not provide the source of input data used for particular reinforcement assessment. In this sense, the provided results cannot be clearly compared with regard to possible differences in the production methods of basalt fibers [35].

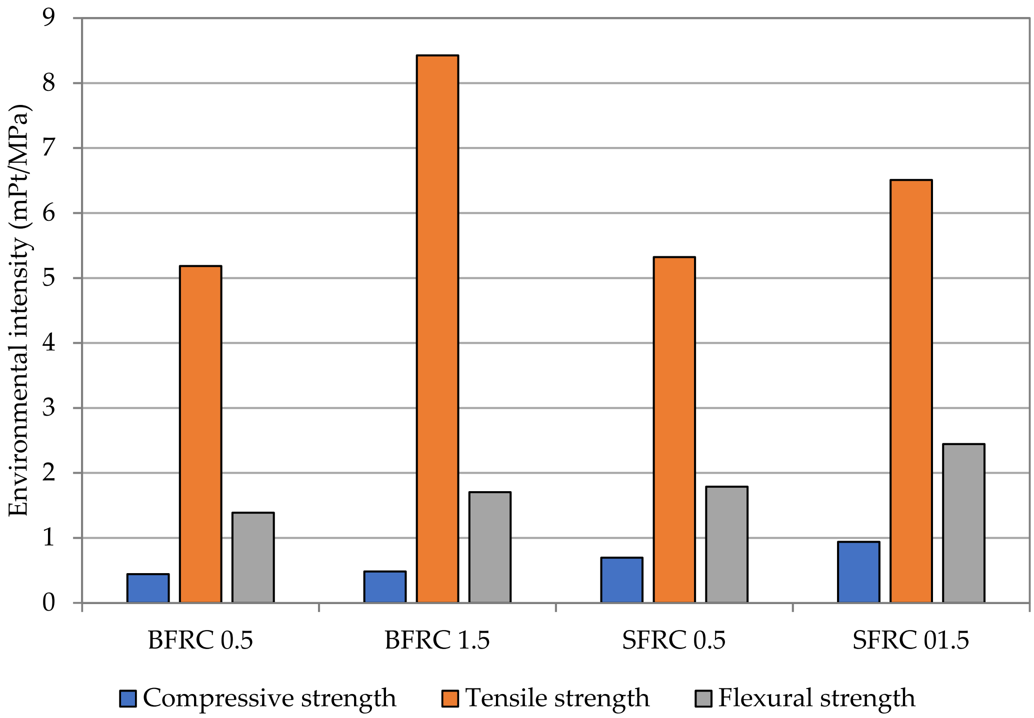

Figure 6. Eco-efficiency comparison of concrete reinforced by basalt and steel fibers.

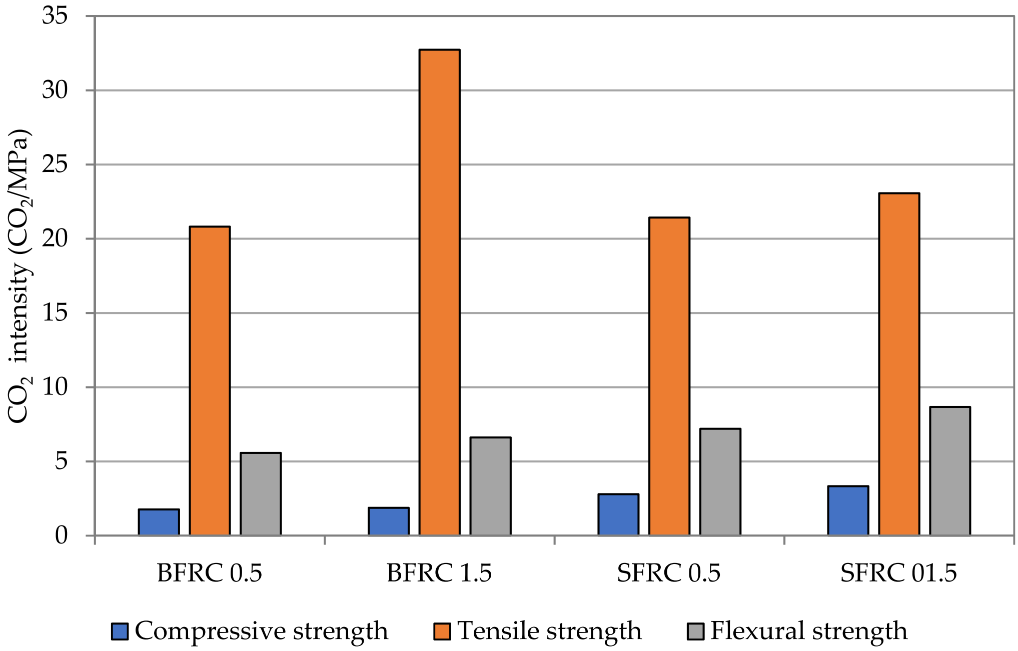

Figure 7. CO_2 intensity comparison of concrete reinforced by basalt and steel fibers.

4. Conclusions

Facing the new challenges in materials engineering based on the integration of environmental consequences of human activities, a detailed description of material alternatives needs to be provided. In order to correspond to the lacking data related to basalt fiber production, the performed study provides an environmental analysis of basalt fiber production with the help of LCA. As is evident from the results of the employed analysis, the basalt fibers can be deemed as environmentally lower damaging reinforcements compared to conventional steel fibers. The observed benefit lies, in particular, in the lower density of the basalt, which reduces the demands on material transport and handling. This effect was very distinct, particularly when compared to 1.5% of the reinforcement dosage.

If we consider the results published in this study in describing the environmental consequences of the use of basalt fibers and also the findings in the published studies, which describe the mechanical properties in detail, basalt fibers can be perceived as a sustainable variant, providing great potential for use in construction applications. In order to describe overall material performance in terms of sustainable measures, the combined environmental/functional indexes were employed. As observed from the provided results, a major environmental profit was raised from basalt fiber use due to reduced environmental costs and low weight compared to steel fibers with concurrent preservations of mechanical performance. The environmental intensity, as well as the overall material performance, should be considered according to the intended application and material requirements, since both environmental intensity and carbon dioxide intensity per one MPa may vary for compressive, flexural, or tensile strength.

Future research studies aimed at the modification and optimization of building materials should include, at least, simplified environmental analysis, since the mitigation of environmental impact represents a major challenge for modern society. The eco-efficiency of the modern building corresponds not only to low-energy demand maintenance, but the embodied energy and environmental impacts should also be taken into account.

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