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Assessment of Wood-Based Fly Ash as Alternative Cement Replacement

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Abstract: The abandonment of coal energy plants in the near future will result in a substantially reduced availability of the coal fly ash broadly used as an efficient supplementary material. In line with the growth of alternative and renewable energy resources, the amount of biomass-based ash rises substantially. Nevertheless, a diverse chemical composition prevents a broader utilization of biomass-based fly ash compared to coal ash on an industrial scale. On this account, the present work is aimed at investigating the basic physical and mechanical properties of concrete mortars modified by a high volume of biomass fly ash (BFA) from wood combustion. Delivered results confirm a significant potential of BFA in the building industry. Experimental analysis of concrete mortars with BFA reveals preservation or even improvement of compressive and bending strength up to 30 wt.% cement replacement. On the contrary, higher dosages induce a gradual decrease in mechanical performance. The performed Life Cycle Assessment analysis reveals the perspective of BFA incorporation taking into account environmental issues considering the ratio between preservation of mechanical performance per normalized endpoint environmental score that allows a direct comparison with other alternatives.

Keywords: cement replacement; biomass fly ash; mechanical performance; cement mortar design; environmental score; life cycle assessment

1. Introduction

Portland cement was used for many decades as a primary binding material, which provides excellent mechanical performance compared to several other materials. The worldwide production of cement binder amounts to almost 5 Gt and due to high calcination temperature requires significant energy inputs. Moreover, the cement industry is responsible for almost 10% of the worldwide carbon diode emission associated with anthropogenic activity [1].

Therefore, this field has attracted the attention of several researchers in order to access an adequate solution to reduce the consumption of Portland cement by the utilization of supplementary cementitious materials (SCMs) [2–6].

The research aimed at the investigation of various industrial by-products has revealed many having latent hydraulic properties or so-called pozzolans. Among the others, the most used and preferred are materials such as blast furnace slag, metakaolin, silica fume, fly ash, and many others [7–12]. The application of the above-mentioned materials is not only associated with a decreased environmental burden, but also enhances concrete properties in terms of the long-term durability, strength development at a later age, rheology optimization, and autogenous shrinkage moderation. Utilization of SCMs was found beneficial by Abbas et al. [5] for control of the alkali–silica reaction by incorporation of sugarcane

bagasse ash and reactive aggerates, which lowered the CaO/SiO_2 ratio thanks to alkali absorption and dilution processes.

In these terms, coal fly ash was found as a very suitable material for cement replacement thanks to its availability and satisfactory pozzolanic activity as described in hundreds of research works all over the world [5,6,9–13].

However, the changing paradigm towards the circular economy and support of green and renewable energy sources has the potential to significantly change the current concrete industry due to its dependence on selected industries that will undergo a significant transformation in the upcoming years [14,15]. Namely, the prevailing application of coal fly ash in the cement industry will face problems in the future related to the availability of this material as a result of a transformation of the energy sector according to the plans on restrictions of coal power plant operation [16,17].

In this sense, awaited changes can be viewed as driving for a sufficient and abundant alternative. Concurrently, the combustion of biomass attracts more and more attention, and the use of biomass incineration ash could help to overcome of the described issues [18,19]. Besides the environmental benefits described in several works aimed at the utilization of biomass fly ash (BFA) as an aggregate replacement or partial cement replacement, substantial improvements in the sense of material performance can be found [20,21]. Namely, rice husk ash and sugar cane bagasse ash were used for the modification of concrete mixtures to improve the thermal performance of such mixtures as a result of increased porosity [22,23]. On the other hand, a significant reduction in the compressive strength was found, which poses a distinct disadvantage of BFA application as described by various authors [19,24]. Notwithstanding, some pioneer works have concluded improved mechanical strength when the interaction between the cement and applied supplementary cementitious materials is well predicted and tailored [22]. This fact lays predominantly in the expansive nature of the BFA hydration products. This feature was noted by Van Tittelboom and De Belie [25] as a desired material ability to control the risk of autogenous shrinkage associated with cementitious binders. The utilization of expansive additives with latent hydraulic properties can substantially improve the self-healing capability of concrete mixtures. Considering the present challenges, the number of studies aimed at the utilization of BFA rising; however, the obtained knowledge could not be generalized yet due to diverse chemical and phase composition [26,27]. As found, one of the main barriers consists also in the high content of organic and inorganic compounds that may result in an adverse effect on functional properties [28,29]. Among others, the wood-derived fly ash has been found as a promising candidate due to relatively stable composition and limited content of undesired compounds [30,31]. The performed research aimed at investigating pozzolanic and hydraulic activity refers to favorable CaO, Al_2O_3, and SiO_2 content. However, due to the lowered reactivity compared to Portland cement, mixtures with BFA usually require increased water dosage in order to maintain the desirable rheology of a fresh mixture [32]. On the other hand, lowered reactivity of BFA leads to decreased heat evolution and limited cracking occurrence [33]. The mechanical strength of mixtures with BFA depends on the percentage of used BFA. As reported in the literature, up to 20 wt.% replacement can preserve the mechanical performance; however, due to substantial diversity in BFA composition, divergent results can be obtained [19,30].

Considering the environmental impact of Portland cement replacement, utilization of waste or by-products provides prospective results thanks to only minor production inputs and omitted calcination of limestone, which poses a major source of carbon dioxide emissions. Therefore, the utilization of SCMs represents a viable solution from this point of view. Avoiding high-temperature treatment processing provides an indisputable advantage due to saved fuel and thus related pollution associated with combustion [34]. Benefits of BFA utilization do not lie in mitigated carbon dioxide emissions only, the limited content of hazardous elements compared to fly ash from coal combustion also substantially decreases related adverse effect on human health and the natural environment [35].

The comprehensive study of Dandautiya and Singh [36] identified substantial environmental savings by performing life cycle assessment (LCA) of fly ash used as SCM. Namely, a reduction of 38%

in carbon dioxide production was attained when 15 wt.% replaced by FA and copper tailings. Similarly, the study of Pavlík et al. [37] aimed at the utilization of sewage sludge disclosed a decrease of about 30% in primary energy consumption. On the other hand, the study of Panesar et al. [38] determined that transportation distances matter for reaching the environmental and economic viability of cement replacement. Namely, the threshold distance of about 800 km was found as the corresponding break-even distance up to 40 wt.% cement replacement. Based on the above-described findings, the enumeration of savings related to cement replacement still requires further research to highlight potential benefits. Since the LCA analysis was introduced, it has found a broad utilization in the sense of determination of possible environmental gains thanks to Portland cement or natural aggregate replacement [39]. Especially the results obtained from cement replacement point to substantial mitigation of the environmental burden. To be more specific, Tosti et al. [40] provided LCA of BFA modified cement composites; however, the particular importance was paid only on lowered content of trace elements. Medina et al. [41] consider the application of bottom fly ash from biomass combustion as an effective cement replacement towards more eco-friendly composites; however, the environmental impact is not discussed in the manuscript. In this sense, the work of Sakir et al. [42] deals only with potential carbon dioxide savings. Findings reported by Teixeira et al. [30] deal with LCA of BFA replacement of cement; notwithstanding, presented results are not linked together with functional parameters, and only midpoint indicators are listed.

However, the real contribution of such initiatives does not result in a notable decrease in negative externalities. This fact can be assigned to a limited acceptance of "greener" building materials [43]. The relatively poor adoption of modified binders represents a barrier towards a more sustainable construction industry [44]. However, the change of this paradigm needs to be completed not only by the technical parameters but combined with other scientific disciplines involved in the sustainability principles [45]. In a nutshell, new materials design and development must go hand in hand with corresponding leadership, convincing communication, and complex assessment of eco-friendly materials to overcome major barriers in the conservative building industry.

The main goal of this paper consists in the investigation of the suitability of biomass fly ash originated from wood materials for modification of cementitious materials in order to provide sustainable replacement of Portland cement. The mechanical strength, as well as material microstructure, is studied to access the potential of BFA utilization in the building industry by the meaning of the primary material parameters. Since the environmental load associated with the cement production poses a substantial concern, the Life Cycle Assessment analysis is employed to access potential benefits related to environmental issues. The obtained results are presented in form of midpoint and endpoint indicators and completed by newly introduced eco-functional parameters that allow balanced assessment of functional and environmental impacts.

2. Materials and Methods

2.1. Studied Materials

BFA was used for the preparation of high-volume mixtures to reduce the cement dosage. Figure 1 shows the particle size distribution of Portland cement together with BFA determined by the laser diffraction. As one can see, BFA had a similar fineness of particles compared to Portland cement. Namely, the average diameter was around 48 mm, which is only slightly coarser than Portland cement. The chemical composition of BFA revealed by the help of X-ray fluorescence (XRF) refers to the dominant share of SiO_2, K_2O, and CaO, which predetermines the applicability of BFA in cementitious materials (see Table 1). In Table 2, authors show the mineralogical composition of BFA and the amount of amorphous portion determined by X-ray diffraction (XRD). The reactivity of BFA is supposed to depend on the amorphous content. In general, the chemical and mineralogical composition is similar to FA obtained by various researchers who conclude the importance of an amorphous portion for successful incorporation into materials matrix and promotion of hydration at later ages [11]. In this

study, the amorphous content consists of almost 53 wt.%, which can be accepted as satisfactory for the cement replacement [46]. The Chapelle test was used for determination of pozzolanic activity of raw BFA. The measurement was based on the quantification of $Ca(OH)_2$ fixed by 1 g of BFA when mixed with 2 g of CaO and 250 mL of distilled water. The solution was heated up to 80 °C (kept for for 24 h) with continuous stirring. Then, the samples were filtered with the Bünner funnel and obtained filtrate was titrated against HCl with bromophenol blue indicator in order to provide OH^- concentration. Consequently, Ca^{2+} content was given by help of titration with EDTA solution and Murexide indicator.
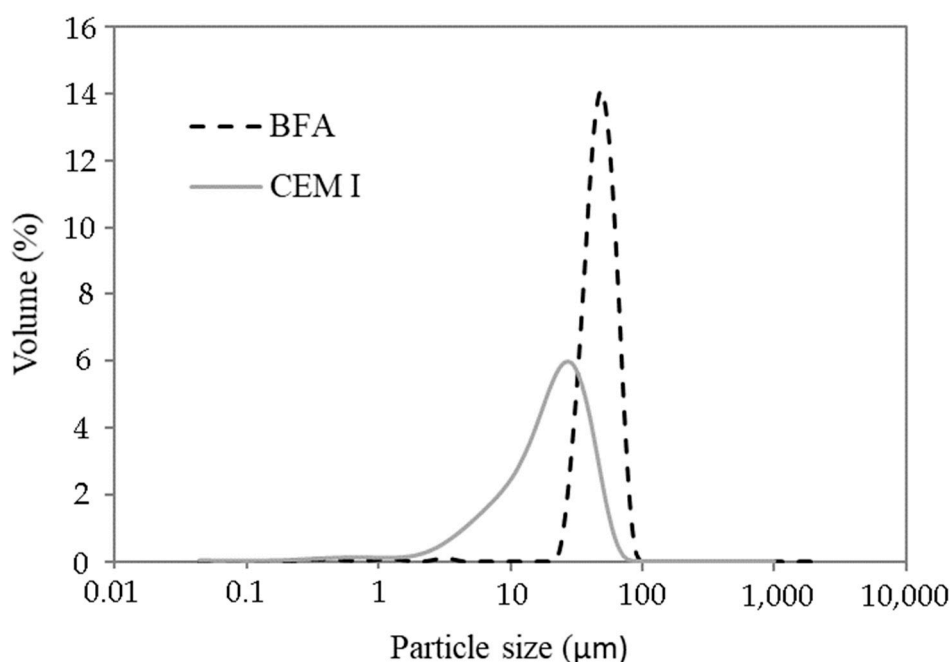

Figure 1. Particle size distribution curves of BFA and CEM I.

Table 1. Oxide composition of BFA.

Oxide	SiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	CaO	MgO	Na$_2$O	K$_2$O	Cl$^-$	SO$_3^-$	P$_2$O$_5$	LOI
wt.%	30.05	9.24	3.76	40.42	2.68	0.52	3.18	0.32	6.43	1.67	0.47

Table 2. Mineralogical composition of BFA.

Phase	wt.%
Amorphous	52.9
Quartz (SiO$_2$)	11.2
Calcite (CaCO$_3$)	6.5
Lime (CaO)	6.1
Portlandit (Ca(OH)$_2$)	11.9
Anortite (CaAl$_2$Si$_2$O$_8$)	2.5
Muskovite (KAl$_2$(AlSi$_3$O$_{10}$) (OH)$_2$)	3.9

The pozzolanic activity results by the meaning of the Chapelle test revealed about 546 mg CaO/g, which substantially exceeds the minimum required value (=330 mg CaO/g).

Within this study, Portland cement CEM I 42.5 R was used for the reference cement paste further modified by BFA produced within the combustion of waste wood at a biomass power plant. On this account, cement was replaced up to 70 wt.% in 10 wt.% steps to reveal the effect of BFA on material properties in a hardened state. The water/binder ratio (w/b) was adjusted according to the fresh mixture workability determined by the flow table test. Due to the characteristics of BFA particles, w/b ratio was increased from the initial 0.5 (reference mixture) to 0.67 (BFA70), since preliminary tests with used

BFA have revealed a limited superplasticizer effectivity with higher cement replacement ratios (above 50 wt.%). The detailed information describing the composition of the mixture is given in Table 3.

Table 3. Mixtures composition.

Mixture	Cement (kg/m^3)	BFA (kg/m^3)	Aggregate (kg/m^3)	w/b
REF	407.8	0.0	1223.3	0.50
BFA10	354.6	39.4	1182.0	0.50
BFA20	310.8	77.7	1165.3	0.50
BFA30	261.3	112.0	1119.7	0.56
BFA40	219.5	146.3	1097.4	0.56
BFA50	175.9	175.9	1055.5	0.61
BFA60	137.1	205.6	1028.2	0.61
BFA70	98.7	230.2	986.7	0.67

Studied mixtures were prepared within three independent mixing cycles (sets) for each mixture according to standardized procedures described in national standard ČSN EN 206. The BFA obtained comes from high-volume production; thus, the composition of BFA may be considered as very stable over time. The casted samples were cured for 28 days in a highly humid environment at 21 °C and consequently dried in a heating oven at 80 °C to remove redundant moisture. Such treated samples were subjected to an experimental analysis performed under laboratory conditions, i.e., 21 °C and 35%RH.

2.2. Experimental Methods

2.2.1. Materials Characterization

Particle size distribution was determined by the help of Analysette 22 MicroTec plus (FRITSCH, Germany) working on the laser diffraction principle with a measuring range of up to 2 mm. Large particles were detected by an infrared laser having a large distance to the measuring cell. A green laser was utilized for the detection of fine particles. The repeatability of the device according to ISO 13320 is at d50 ≤ 1%.

The chemical and mineralogical composition of ceramic powder was determined by XRF and XRD analysis. X-ray diffractograms were measured with a diffractometer PANalytical X'PertPRO (PANalytical, Almelo, The Netherlands) with Bragg–Brentano configuration (CoK α radiation source, a voltage of 40 kV at 30 mA) and fast linear detector X'Celerator. Measured diffractograms were analyzed by the computer code HighScorePlus 3.0.5 (PANalytical, Almelo, The Netherlands), compared with the database data from JCPDS PDF2, Sets 1–54 (International Centre for Diffraction Data, Newton Square, PA, USA). The amount of the particular crystalline phases was determined by the Rietveld method using the code DiffracPlus Topas 4.2. The chemical composition was determined by XRF spectroscopy (Thermo ARL 9400 XP). The reproducibility of the measurement was 0.0001%, and the standard measurement error 0.02%.

The flow table test of cement mortars was determined based on standard EN 12350-5. The workability of the fresh mixture was verified using the flow table test, and the measured spread diameter was approx. 160 mm in both perpendicular directions. This test was carried out to investigate the effect of applied BFA on the rheologic properties and a need for additional water dosage.

The matrix density of studied concrete mortars with BFA admixture was done by employing the helium pycnometer Pycnomatic ATC (Thermo Scientific, Waltham, MA, USA). The accuracy of the gas volume measurement using this device is ±0.01% from the measured value, whereas the accuracy of used analytical balances is ±0.0001 g. The bulk density results were delivered by a common gravimetrical method by using a digital caliper for the volume determination and laboratory weights. The measurement of bulk density uncertainty was 5.3%. On the basis of the knowledge of the matrix and bulk density, the total open porosity was calculated.

The mercury intrusion porosimetry (MIP) experiment was employed to access information on the pore size distribution and total pore volume. For this purpose, Pascal 140 was used as a low-pressure station for mercury filling and measurement up to atmospheric pressure. In order to depict the amount and diameter of smaller pores, Pascal 440 was used (both devices Thermo Scientific). This device allows reaching pressure of up to 400 MPa, which corresponds to pores with a diameter of about 3 nm. Within the evaluation of the measured data, the circular cross-section of capillaries was assumed, whereas the mercury contact angle was assumed to be 130°. The contact surface tension of mercury was 480 mN/m, and its density was 13,541 g/cm^3. The measurements were realized at 22 °C. The sample mass was approx. 1.0 g.

Compressive strength and flexural strength as the main mechanical parameters were determined by the employment of the device VEB WPM Leipzig, having a stiff loading frame with a capacity of 3000 kN. The strength was determined for 28-days cured samples. Both tests were done on the basis of Standard EN 1015-11 after 28 days of water curing. The bending strength was measured in a three-point arrangement on prismatic samples with dimensions of 40 × 40 × 160 mm. This test was performed on three samples, while the rest of the broken prisms were used for the compressive strength testing. The uncertainty of measurement for compressive strength was 2.4%, and 2.1% for bending strength.

2.2.2. Environmental Analysis

Goal and Scope of the Study

The goal of the performed environmental analysis was to evaluate the effect of cement replacement by high levels of BFA on the environmental impacts. The simplified environmental analysis was performed to access the benefits associated with partial replacement of Portland cement by BFA during the production stage. The functional unit of 1 metric ton of final blended mortar modified by 0, 10, 20, 30, 40, 50, 60, and 70 wt.% of BFA was analyzed. In the scope of this study, the Impact 2002+ methodology (version 3.15, Simapro 8.5) includes 15 impact categories that provide a robust platform for the determination of environmental load at both midpoint and endpoint level [47].

The employed methodology is based on the ISO 14040 standard, which consists of four consequent steps as a definition of goal and scope of the study, inventory analysis, impact assessment, and interpretation.

Boundary Conditions

Three alternative uses of BFA are considered, namely, the utilization of BFA as cement replacement con concrete mixture design. The analysis covers regional factors of the Czech Republic, but with slight modifications, it can be applied to other central European countries. The Czech Republic, compared to substantially larger countries such as Poland, France, or Germany, can use shorter transportation distances, which are often viewed as a substantial barrier the environmental and economic viability [48]. Based on the location of current biomass energy plants and area of the Czech Republic, transport distances up to 70 km by using lorries with a loading capacity of 20 t are assumed.

Taking into account the national energy mix, a high share of electricity is supplied from coal and natural gas energy plants (57%), 39% from nuclear plants, and about 4% from renewable energy plants.

Life Cycle Inventory

The life cycle inventory (LCI) includes all inputs and outputs for the cement replacement scenario by the meaning of the material collection, storage, and transportation to the concrete plant. Thanks to the ready-to-use properties of BFA, the material does not require any energy-demanding treatment. All relevant data sources are listed in Table 4 as implemented in the software Simapro LCA 8.5. The data for raw material production, processing, transport emission, and energy production was given by the Ecoinvent database v.3.5. The consumption of auxiliary materials, such as water for dust control or

steel for machinery maintenance and lubricants, was taken into account. Since BFA is landfilled due to a lack of utilization options, no environmental costs are associated with the material processing due to its ready-to-use properties.

Table 4. Sources of LCI datasets.

Material/Process	Value (per FU)	Source
Gravel	according to mixture composition	Gravel crushed [49]
Steel	0.03 kg	Stainless steel [49]
Lubricants	0.05 L	Silicon, liquid [49]
Transportation	70 km	Lorry transport, 22t [49]
Storage	3.1 kWh	Electricity mix, at consumer [49]
Shovel loading	9.4 MJ	Diesel, burned in agricultural machinery [50]
Conveyor belts	5.4 kWh	Electricity mix, at consumer [49]
Cement	according to mixture composition	Cement production [49]
Water	according to mixture composition	Tap water [49]
Handling	3.3 kWh	Electricity, Material handling [50]
Demolding	1.2 kWh	Electricity, Samples preparation [50,51]
Casting	6.4 kWh	Electricity, Samples casting [50,51]

Avoided Production

The avoided production represents an important benefit arising from the utilization of various waste products. However, the avoided landfilling cannot be included within the positive externalities according to the European Standards; thus, only a prevented use of virgin resources should be accounted for as real beneficial outputs [52]. The replacement of Portland cement brings substantial environmental savings due to its demanding production; therefore, utilization of ready-to-use waste material represents a favorable solution in terms of ecology. The replacement rate determination is a widely underestimated and neglected factor despite its particular importance. The Portland cement replacement in construction practice is inevitably connected with the worsened customer perception due to various factors related to limited knowledge, concerns about the service life, deterioration processes, etc. Additionlly, several social and economic factors were questioned in order to describe the common barriers to sustainable development in the construction industry [51]. In order to determine the replacement level of Portland cement, the performance of modified mortars and the market demand were used for the calculation of market perception coefficient M. The value of M is based on the ratio between deterioration/improvement of functional properties (F_p) and customer perception (C_p) given by economical competitiveness of the material, available knowledge base, and social perception as follows:

$$M = F_p \cdot C_p \tag{1}$$

While the definition of F_p does not pose a substantial issue, in this case, defined as the mechanical performance index (compressive strength and bending strength compared to reference mixture in ratio 2:1), C_p may vary substantially across the locations and time. Applied C_p was derived from information collected from the concrete plant in the Czech Republic having the experience with alteration of binders. The used coefficients are given in Table 5. The lowered C_p values for mixtures with lower BFA content can be assigned to minor environmental benefits and substantial awareness of material deterioration, but on the other hand, mixtures with high BFA content can be viewed as advanced sustainable material applicable for specific purposes.

Table 5. Market perception coefficient.

Mixture	F_p	C_p	M
REF	1.00	1.00	1.00
BFA10	1.22	0.78	0.95
BFA20	1.10	0.83	0.92
BFA30	0.87	0.90	0.78
BFA40	0.78	0.93	0.73
BFA50	0.66	0.95	0.62
BFA60	0.60	0.97	0.58
BFA70	0.33	1.30	0.43

Life Cycle Impact Assessment

The impact categories used within the study were as follows: Aquatic acidification (AAC), 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 inorganics (RI), Respiratory organics (RO), Terrestrial acidification/nitrification (TAN), and Terrestrial ecotoxicity (TE). For the comparison of different scenarios, the environmental midpoint impact categories were used for the determination of the endpoint impact categories, which included human health, ecosystem quality, climate change, and resources [47,53].

Combined Environmental/Functional Assessment

To increase the readability and provide a complex overview of achieved results, a combined index of the functional and environmental aspects and the ratio between the functional performance and global warming contribution are accessed based on the suggestions of [54,55]. For this purpose, the complex environmental efficiency *CEE* given by the weighted endpoint single score per functional unit represented by the compressive strength is introduced. The definition of the combined indicator is:

$$CEE = \frac{SC}{R_c} \tag{2}$$

where *SC* (mPt) is the weighted single score delivered by Simapro 8.5 (methodology Impact 2002+), and R_c (MPa) is the compressive strength. The ratio between the functional properties represented by the global warming efficiency *GWE* is given as:

$$GWE = \frac{GWP}{R_c} \tag{3}$$

where *GWP* (kg CO_2 eq) is the climate change potential given by Simapro 8.5 (methodology Impact 2002+).

## 3. Results and Discussion

3.1. Functional Properties

Basic physical properties accessed in Table 6 show a substantial influence of BFA dosages on material structure formation. The distinct drop in bulk density, as well as increase in the total open porosity, on the other hand, can be assigned to higher batch water dosages as a result of reduced workability of mixtures with BFA. The matrix density of studies' mortars was slightly decreased due to the lower density of BFA (2088 kg/m^3) compared to Portland cement (3159 kg/m^3). As a result, in total open porosity varied from an initial 33.1% for reference mixture to 42% for BFA70.

Table 6. Basic physical properties of studied mixtures.

Mixture	Bulk Density (kg/m³)	Matrix Density (kg/m³)	Porosity (%)
REF	1835	2663	33.1
BFA10	1773	2671	32.6
BFA20	1748	2639	33.8
BFA30	1702	2647	35.7
BFA40	1668	2635	36.7
BFA50	1622	2650	38.8
BFA60	1580	2663	40.7
BFA70	1536	2649	42.0

Results obtained from the MIP experiment accessed in Figure 2 reveal changes in pore size distribution in modified blended cement mortars. Apparently, incorporation of BFA affected the pore volume in all studied ranges, which complies with the increase in the total open porosity. A significant shift in the pore volume was obtained in microporous ranges from 0.001 to 0.01 μm and from 0.01 to 0.1 μm. The threshold parameter can be considered incorporation of 30 wt.% of BFA and higher, which induced substantial changes in the material microstructure. Mixtures having a higher content than 30 wt.% of BFA exhibited a gradual increase in pore volume. Here, the maximal pore volume for BFA70 reached almost a level almost three times higher compared to the reference mixture. On the other hand, only minor changes were observed in the macroporous range. Revealed changes can be assigned to changes in the workability of the fresh mixture and increased w/b ratio.
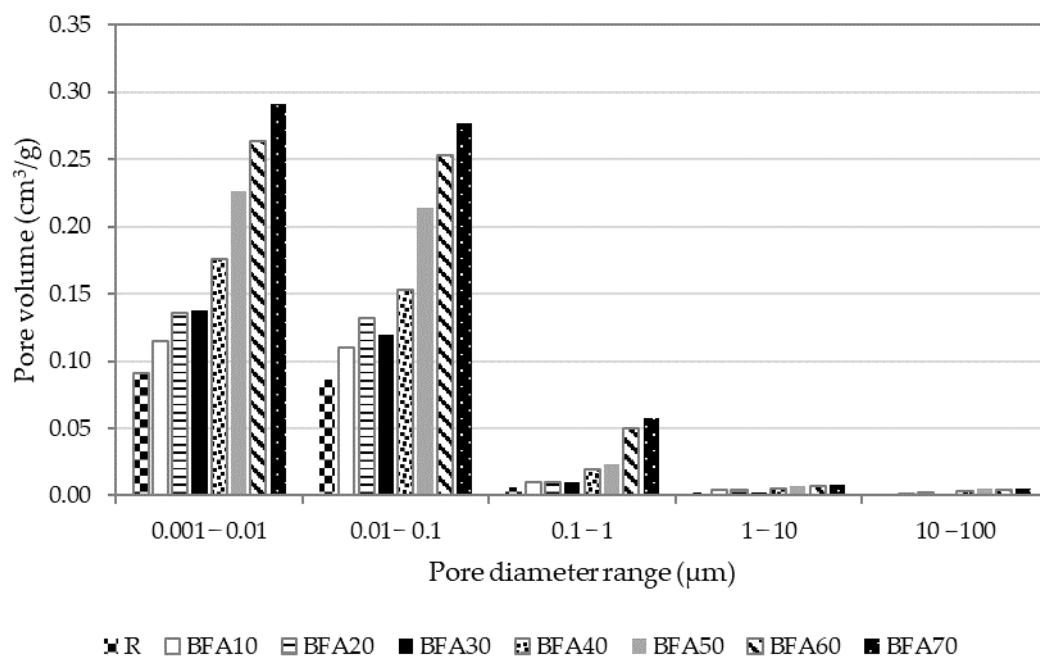
Figure 2. Pore size distribution of studied mixtures.

Looking at Figure 3 where the mechanical performance of the studied mixture is given, a considerable both compressive and bending strength reduction can be distinguished for mixtures having a higher content of BFA. On the other hand, a slight improvement in both mechanical parameters was achieved when 10 wt.% and 20 wt.% of BFA was applied. Specifically, the compressive strength was shifted to about 16% in the case of BFA10 and 6% for BFA20. The obtained increase in bending strength was even more distinct: 33% for BF10 and 19% for BFA20. However, incorporation of dosages exceeding 20 wt.% induced a gradual decrease in mechanical performance. A satisfactory mechanical resistance was gained up to 40 wt.% of cement replacement when compressive strength resulted in 40.5 MPa. BFA50, BFA60, and particularly BFA70 induced substantial reduction of studied mechanical

parameters. Lowered results of mechanical strength comply with the changes in material porosity, as described above. In other words, mixtures containing from 40 to 70 wt.% of BFA dosage showed a substantial strength loss as a result of a shift in material porosity. In the light of these findings, 30 wt.% can be accepted as a threshold parameter for mixture design. Provided compressive/bending strength ratio R_t/R_c shows a more significant decline of compressive strength compared to bending strength. Contrary to the results of de Matos et al. [13], who studied the effect of high volume dosages of FA, incorporation of BFA improved the strength only when applied up to 20 wt.%. In comparison to the traditional SCMs such as furnace slag of CFA, BFA used in this study does not provide sufficient preservation of mechanical performance due to limited reactivity and lower content of the amorphous phase that caused a worsening of the mechanical strength. Notwithstanding, the perspectives of biomass-based ash as an alternative SCM to CFA were noted by Memon et al. [56], who described the correlation between the burning temperature and pozzolanic activity. The follow-up work of Amin et al. [57] achieved similarly promising results with cement replacement up to 30%. Apart from the mentioned issues, a substantial effect on functional properties is accompanied by the diameter of the particles [36]. To be more specific, more favorable results of the compressive strength correlate with higher amorphous portion and particle size. Therefore, particular importance needs to also be paid to the source of the biomass and type and combustion temperature that may influence the obtained results considerably [58].
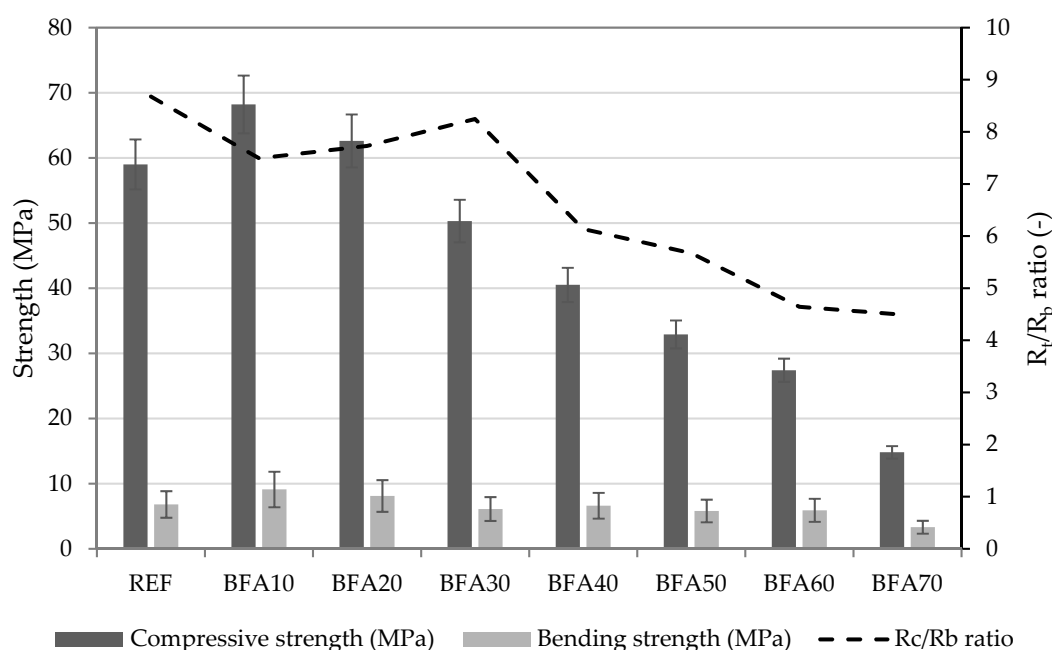

Figure 3. Mechanical parameters of studied mixtures.

Notwithstanding, the utilization of pozzolanic admixture is usually accompanied with delayed strength development, as reported by Vejmelková et al. [59]. The delayed strength evolution depends significantly on the cement replacement level; thus, further increase at later ages can be expected for mixtures with higher BFA content. On the contrary, the BFA is being viewed as less reactive compared to CFA furnace slag due to coarse particles. However, the production of BFA with sufficient fineness may result in substantial improvement of the concrete strength preservation.

3.2. Environmental Assessment

Performed environmental analysis accessed in Figure 4 reveals a substantial positive effect of cement replacement by BFA in almost all monitored midpoint categories. Similar results were also revealed for all endpoint categories (Table 7). Considering the plotted results, a gradual decrease in

both selected environmental indicators was achieved. As can be seen, the reference concrete mortar poses a substantial environmental load compared to mixtures with BFA. Only two impact categories (carcinogens and non-carcinogens) exhibited a slightly increased environmental burden for BFA10 that could be associated with the effect of transportation of BFA. The benefits of the BFA application over traditional coal-combustion fly ash (CFA) widely used in the concrete industry are based on the negligible content of the trace elements; thus, no leaching procedure is required. Similar findings can be found also for endpoint impact categories and refer to a significantly lowered environmental impact compared to CFA application [36] and can be viewed as a more favorable scenario over aggregates replacement [60,61]. Taking into account the preservation of functional performance of studied mixtures, BFA30 with satisfactory mechanical parameters provides about 60% environmental savings on average in monitored midpoint and endpoint impact categories. The most favorable results were achieved in the following categories: ionizing radiation, terrestrial ecotoxicity, aquatic ecotoxicity, and land occupation, where even a small cement replacement induced a substantial improvement in the sense of the mitigation of environmental externalities. Despite the negative effect of BFA when applied in higher dosages, the overall environmental benefit is similar as described in the work of de Matos et al. [13]. This disparity, assigned to considerably higher transportation distances in the Brazil region, comply with results described by Panesar et al. [41], who investigated the effect of transportation distances to the environmental viability of alternative scenarios.
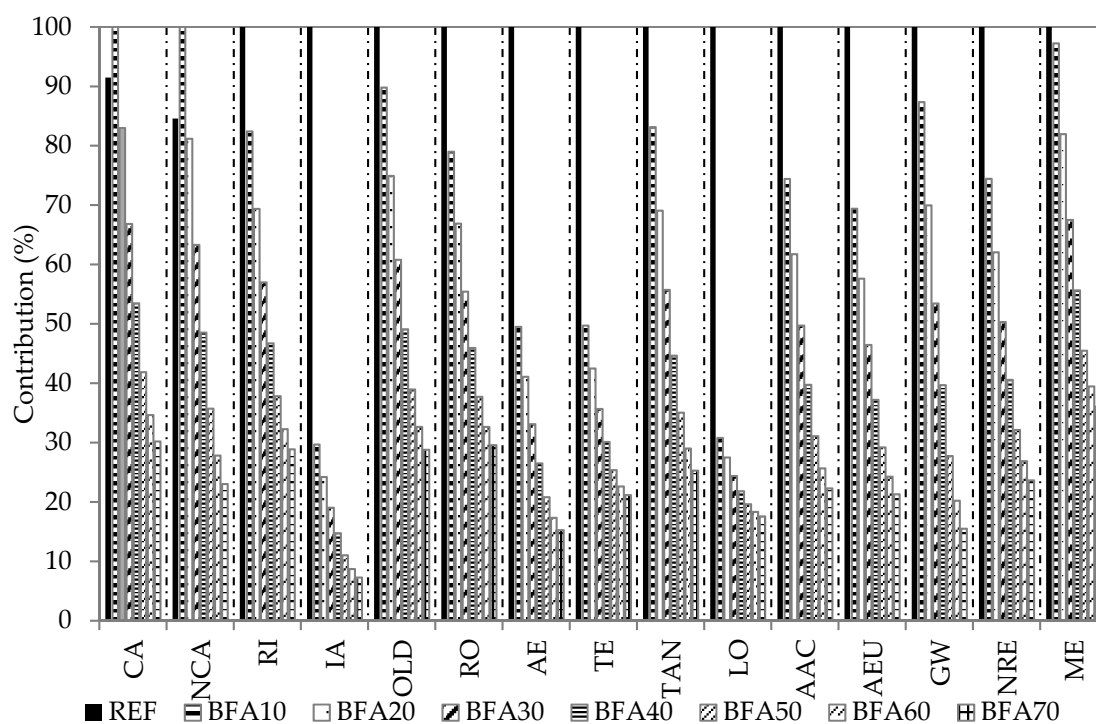

Figure 4. Comparison of midpoint indicators.

Table 7. Endpoint indicators.

Damage Category	REF (mPt)	BFA10 (mPt)	BFA20 (mPt)	BFA30 (mPt)	BFA40 (mPt)	BFA50 (mPt)	BFA60 (mPt)	BFA70 (mPt)
Total	85.20	70.22	57.52	45.45	35.43	26.75	21.30	17.90
Human health	22.12	19.14	16.06	13.13	10.70	8.60	7.28	6.48
Ecosystem quality	4.71	2.34	2.00	1.68	1.41	1.19	1.06	0.98
Climate change	41.00	35.81	28.68	21.90	16.27	11.38	8.29	6.35
Resources	17.37	12.93	10.78	8.74	7.05	5.59	4.67	4.11

In order to merge functional and environmental parameters for a clear comparison, the complex environmental efficiency and global warming efficiency are presented in Table 8. As one can see, *CEE* is gradually dropped up to 60 wt.% cement replacement as well as for *GWE* thanks to the lowered processing of BFA. On the other hand, 70 wt.% dosage of BFA induced a substantial increase due to the deterioration of functional performance and negatives prevail. Considering the potential carbon dioxide savings delivered by the cement replacement to meet the CO_2 goals, the application may be viewed as beneficial, since the cement industry represent a substantial contributor to global CO_2 emissions. Obtained results comply with the findings of Onn et al. [61], who investigated the effect of a high volume replacement of cement by furnace slag. On the other hand, a critical factor may be viewed as the replacement ratio due to its importance for the achievement of environmental benefits. Despite the described negative effect of additional transportation cost related to disruption of established material flows, the relatively poor acceptance of building materials from alternative constituents poses a more significant barrier for future "greening" of the construction industry, as a substantial threat for the environmental footprint of the concrete industry lies in the abatement of coal power plants, the eminent source of coal-fly ash extensively used SCM. The planned transformation of the energy sector in order to meet deep CO_2 emission reduction comes along with eminent support of renewable energy sources in upcoming decades and the diminished importance of fossil fuels energy plants [62]. Considering this fact, in the medium term, the supply of CFA will be substantially limited, so sufficient alternatives for CFA must be introduced on time, to establish and optimize the relevant material flows [63]. Facing this challenge, the sustainability barriers include not only technical and functional parameters, but also the societal perception of sustainability issues and related environmental footprint [64]. This effect has been noticed by several researchers [65–67], who described the barriers related to sustainable measures adoption. The sustainability transition is being viewed predominantly as a technical or techno-economical challenge that is based on optimization of materials flows in all life stages of used materials as well as improvement in the energy consumption for the building maintenance, the heating and cooling demands in particular.

Table 8. Combined functional/environmental parameters.

Mixture	*CEE* (mPt/MPa)	*GWE* (kg CO_2/MPa)
REF	1.25	5.95
BFA10	1.12	5.67
BFA20	0.97	4.81
BFA30	0.90	4.31
BFA40	0.87	3.98
BFA50	0.81	3.43
BFA60	0.78	3.00
BFA70	1.21	4.25

One of the main reasons, besides the functional parameters, that prevents the efficient sustainable transition in the building sector is the neglect of social factors [54]. In other words, to address the sustainable issues better, the social factors should be included and supported by relevant stakeholders (leadership, supply chains, project managers), since the technical part seems to be at least partially solved [45].

4. Conclusions

The performed work contemplates the utilization of biomass fly ash originated in the biomass power plant as a partial replacement of Portland cement for building elements. The performed analysis has revealed the potential of bio-based waste products, which can mitigate the negative environmental impact of the building industry. Obtained results proved the ability of BFA to replace the cement binder by up to 20 wt.% without any significant loss in mechanical performance. The 30 wt.% BFA dosage can be accepted as a threshold value for future studies. Alternatively, even higher dosages can be accepted

for low-performance applications. Prospective results can be expected for strength development at later ages due to pozzolanic properties and improved self-healing capability. The performed environmental analysis revealed approximately 25% potential savings including both primary energy consumption and carbon dioxide emissions when Portland cement is partially replaced and functional properties of the material in hardened state are maintained at a sufficient level. Based on minor BFA processing required for incorporation into cementitious mixtures, an overall environmental benefit can reach over 50%; however, the applicability of such modified material is limited due to loss of mechanical strength. Apart from the technical parameters, more intensive support from policymakers and other relevant stakeholders may help to overcome the current dysfunctional situation that is hindering the global benefits raised from the sustainable building sector.

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