Chapter

Utilization of Wood Biomass Ash in Concrete Industry

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Abstract

The use of energy from wood biomass plants results in the production of large quantities of wood biomass ash (WBA). Most of the WBA is disposed of and some are used as a soil supplement in agriculture. In the concrete industry, there is a high potential for substitution of certain components with suitable alternative materials. Depending on its physical and chemical properties, WBA can be used in concrete production as a partial replacement for cement or as a substitute for fine aggregates. The suitability of locally available WBA should be evaluated in terms of microtexture, chemical, and mineralogical composition. This paper presents the types of WBA produced by different combustion technology, the influence of WBA as a cement replacement on the properties of cement composites in the fresh and hardened state, an overview of the environmental impact of WBA cement composites, and the market opportunities and readiness for reuse of WBA as a new potential supplementary cementitious material.

Keywords: wood biomass ash, supplementary cementitious material, compressive strength, cement composites, concrete industry

1. Introduction

The policy of promoting and increasing the use of wood biomass as a renewable energy source affects the increase in the amount of wood biomass ash (WBA) produced [1]. Comprehensive statistics on the annual production of WBA in the European Union are not available. However, Austria, Denmark, Germany, Italy, the Netherlands, and Sweden account for about 2.9 million t/y of biomass ash [2], while a survey conducted in Croatia revealed that about 25,414 t/y of produced WBA is landfilled [3]. Existing data estimated that Europe will generate up to 15.5×10^7 tons of WBA in 2020 [4], highlighting the urgency of strategic foresight in waste management. Currently, WBA is underutilized in the EU and mostly disposed of in landfills [5–8], resulting in additional costs and risks to the environment. The cost of biomass ash disposal ranges from 100 to 500 EUR/ton [9, 10]. About, 1.7 million EUR per year are paid for the disposal of WBA in Austria [11]. In the future, an increase in the cost of landfilling in the form of waste taxes or disposal fees, as well as difficulties in acquiring new landfills and stricter EU landfill directives, may be expected. Unsystematic management of WBA can lead to environmental pollution and potential risks to human health: WBA can be easily transported through the air and consequently cause health problems related to the respiratory system of the population living in the vicinity of the landfill [12], while uncontrolled landfilling of WBA can lead to groundwater pollution through leaching of heavy metals from WBA or infiltration of rainwater [13]. European policies promote and stimulate green innovations in the reuse of waste as secondary raw materials to boost the market and new green business opportunities [14]. It is, therefore, necessary to find ways and methods for the application of WBA that are environmentally sound and economically justified. Previous studies [15–19] have shown that the resulting WBA can be reused in certain industries due to their properties and chemical composition, especially in the concrete industry. However, existing regulations and standards currently preclude the use of WBA in the concrete industry [20, 21].

The objectives of this chapter are: (1) to determine what types of combustion technologies are currently in use and what types of WBA are produced by each combustion technology, the properties of these WBAs, and the factors that most influence WBA properties, as well as the physical and chemical properties that could influence the use of WBA in cement composites; (2) to assess the influence of WBA as a cement replacement on the properties of cement composites in the fresh and hardened states; (3) to provide a brief overview of the environmental impact of the use of WBA in the mortar and concrete mixes; and finally (4) to identify the market opportunities and readiness for reuse of a new potential supplementary cementitious material (SCM).

2. Wood biomass ash characterization

There are several factors that affect the quality and quantity of WBA obtained by using wood biomass in power plants. Based on [22], these factors can be divided into three main groups as shown in **Table 1**. According to **Table 1** and a detailed review of the literature, it is necessary to highlight (1) the type of biomass used for power generation, (2) the plant technology used, (3) the combustion temperature, (4) the location of WBA collection, and (5) the conditions of WBA storage. In the following, the influence of these parameters on the characterization of WBA is discussed in detail.

One of the factors that could have an influence on the properties of WBA is the area of biomass cultivation and the condition and type of soil [24], but this influence is not very large. From the tertiary group of influences, it appears that ash from wood

Group of influence	Formation process	Influence	Time of formation	References
Primary	Natural	Biomass—type Biomass cultivation area soil condition and type combustion technology	Before and during plant growing, and cutting	[13, 15, 22–29]
Secondary	Anthropogenic (technogenic)	Temperature of combustion location of WBA collecting	During combustion	[13, 15, 22, 23, 25–30]
Tertiary	Natural	Disposal and transportation	During disposal and transportation of WBA	[22, 26]

Table 1.
Groups of influence contributing to the chemical composition of WBA (adapted from Vassilev et al. [22]).

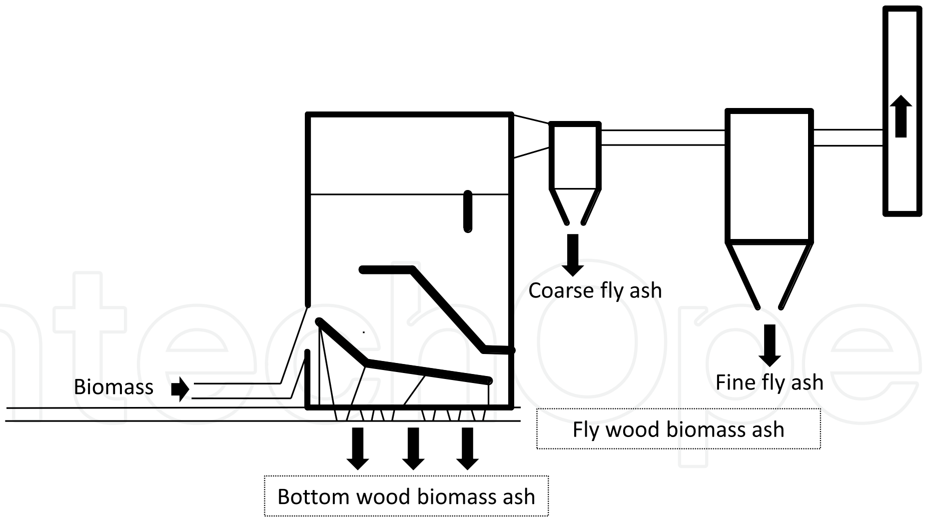

Figure 1.
WBA classification based on WBA collection in power plants (adapted from Obernberger et al. [35] and Eijk et al. [36]).

biomass undergoes certain chemical processes during its collection and disposal. The plant technology, i.e., the technology of wood biomass combustion in the power plants, as one of the factors affecting the physical and chemical properties of the produced WBA, is divided into grate combustors, fluidized bed combustors, and pulverized fuel combustors [10]. Three different types of WBA can be generated in a power plant [26, 31–34]: bottom ash (1) collected at the bottom of the chamber (bottom WBA); fly ash, which may be a relatively coarse fraction, (2) collected from cyclones or boilers; and a relatively fine fraction of fly ash, and (3) collected from electrostatic precipitators and bag filters (**Figure 1**). In some power plants bottom ash and fly ash are collected in one container as mixed WBA.

In grate combustion technology, 60–90% of the WBA from the bottom of the furnace is formed on the grate, while in fluidized bed combustion, fly WBA is the dominant ash formed [37–39]. The particles from the bottom of the furnace are larger than the fly WBA [7, 40]. This can be observed from **Figure 2**, which shows the particle size distribution of WBAs [41] and cement, and the grading curve of the bottom WBAs and aggregate (particle size 0–4 and 4–8 mm) per the combustion technology. The authors [41] proposed a cumulative grading curve for all particle sizes of the bottom WBAs as they were sieved through a 1 mm sieve to eliminate impurities and larger fractions. Grate combustion has a higher influence on the particle size distribution of the fly bottom WBAs where a generally large diversity of granulometric curve of bottom WBA compared to aggregate can be seen in **Figure 2**. Grate-fired systems are designed to cope with a degree of the sintering and partial fusion of the ash on the grate. Poor fuel distribution, relatively poor air distribution, and local high temperature on the grate can lead to the formation of relatively large ash agglomerates that reduce combustion efficiency [42]. This occurrence could lead to larger particles of the WBA sample [43]. It can also be inferred from **Figure 2** that the particles of bottom WBA from fluidized bed combustion technology and pulverized fuel combustors are smaller than those of bottom WBA from grate combustion power plants.

The WBA produced at the bottom of the combustion chamber is often mixed with mineral impurities such as sand, stones, and soil contained in the biomass, as well as sintered ash particles. In addition to the coarse and fine fraction of the fly WBA inside the plant, smoke dust of the finest fraction is also emitted together with

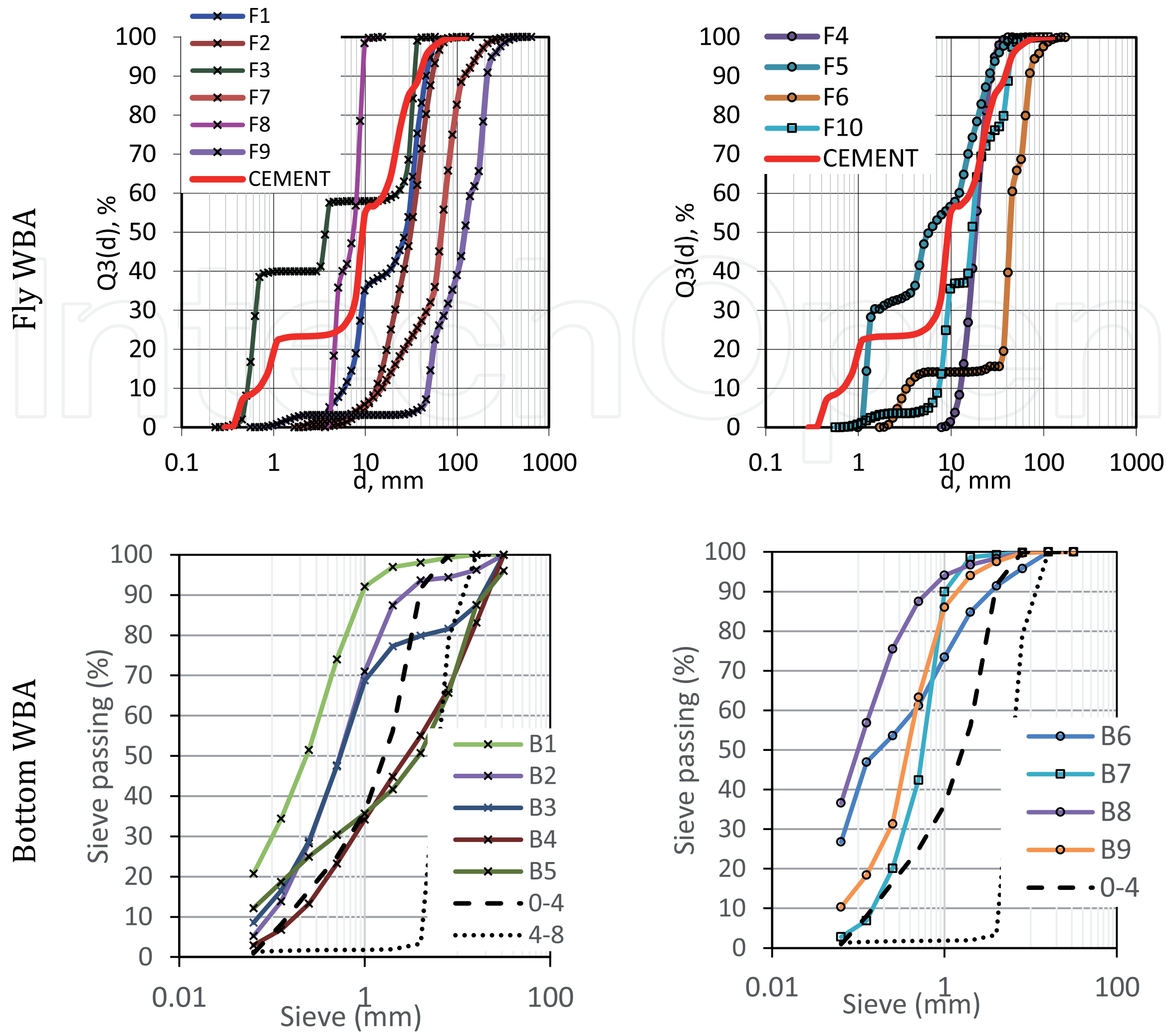

Figure 2.
Particle size distribution of fly WBA (F) (published in Carević et al. [41]) and bottom WBA (B) compared to the different combustion technologies used (x: grate combustion; ○: pulverized fuel combustors; and □: fluidized bed combustors).

the flue gases [35]. In fluidized bed combustion, the lower WBA consists of sand particles, mainly quartz, added during combustion, inorganic components (soil or small stones), and unburned biomass fraction [32, 38]. Modern solutions of the combustion system on the grate may include a continuously moving and water-cooled grate, which consequently means that wet ash removal is performed from the bottom of the furnace [44]. In view of the above, it is very important to know what type of technology is used and at what location in the power plant the WBA is collected to further characterize the WBA. The choice of plant technology has a significant impact on the chemical composition of the WBA: fluidized-bed technology uses additives such as quartz sand as bed material, which can have a positive impact on the chemical composition of the WBA and contributes to a high SiO2 content compared to other combustion technologies [10, 45, 46]. The morphology of WBA (**Figure 3**) mostly showed non-uniform structure, inhomogeneous particle surface, and particles with different shapes, which could lead to higher water absorption and have a corresponding negative effect on the workability of the cement composites [28, 47–48].

Figure 4 compares the chemical composition of 46 samples of different ash types collected from the power plants: fly, bottom ash, and mixed ash. WBA is expected to contain a higher proportion of CaO than pozzolanic oxide, the sum of SiO_2, Al_2O_3,

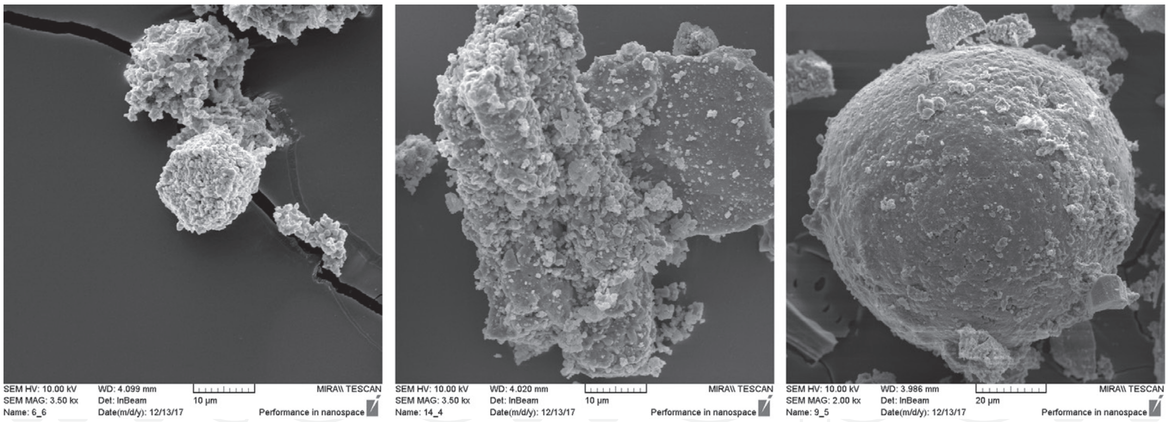

Figure 3.
Morphology of the WBA.

and Fe_2O_3 (median values for CaO were 48.61% compared to 13.49% for pozzolanic oxide for all WBA samples), indicating lower pozzolanic activity and pronounced hydraulic activity [23]. Higher alkali levels (K_2O and Na_2O) can also be observed,

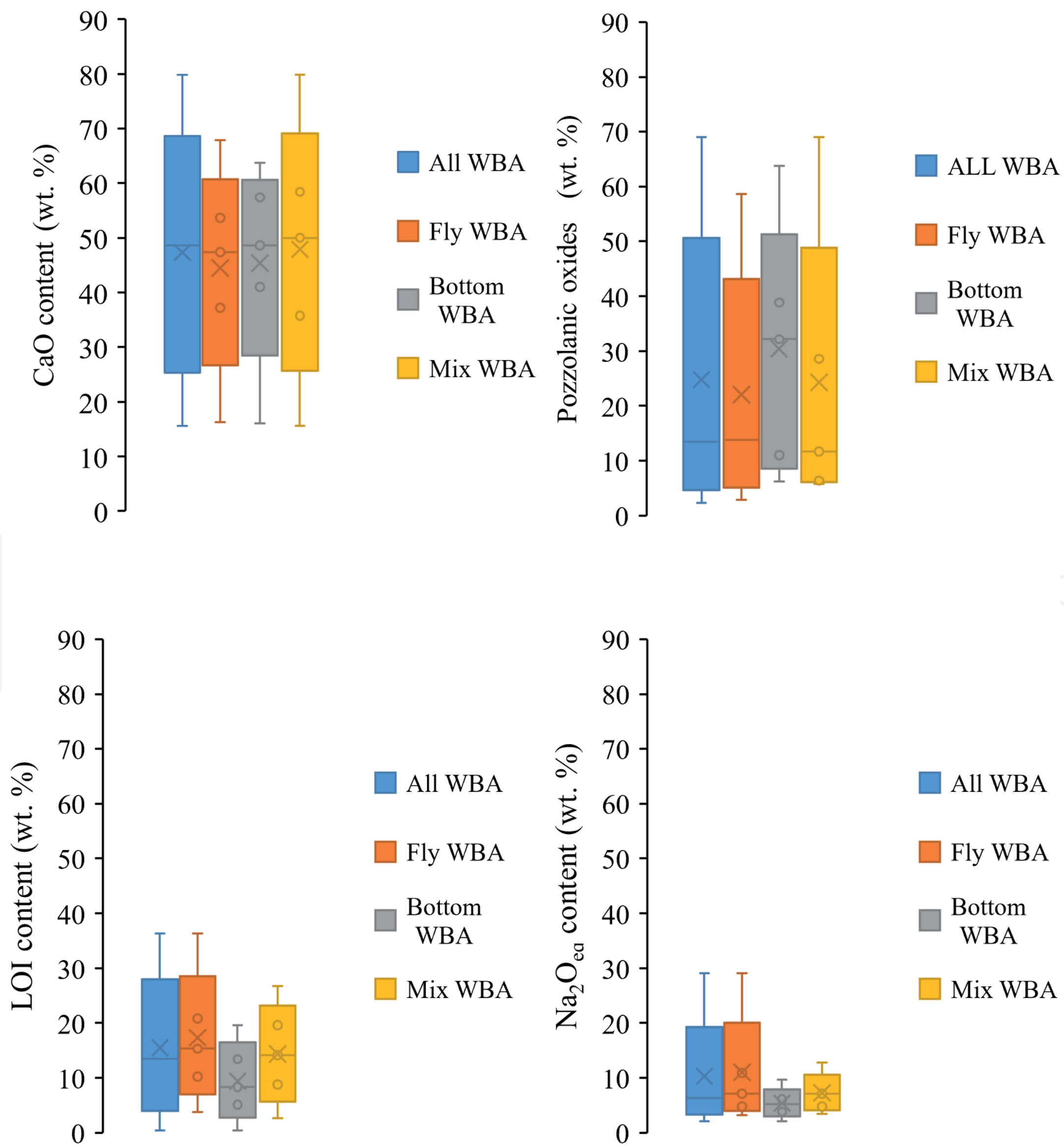

Figure 4.
Boxplots of chemical parameters from the WBA database (N = 46) by WBA type [41, 46].

which may be reflected in the mechanical and durability properties of cement composites with WBA [49]. This is particularly pronounced in the fly WBA samples. Alkali is an integral part of the characterization of untreated biomass and in woody biomass, alkalis are bound to the organic structure, so their higher content in WBA was expected. High alkali content can cause high porosity in the hardened cement matrix, resulting in lower strength and durability [15, 23, 25]. Since the CaO content is higher in all WBA specimens, free CaO is expected, a significant amount of which can cause volume instability (swelling) during the hydration process and the formation of cracks [33, 50, 51]. As shown in **Figure 4**, the fly WBA showed the highest median LOI value (15.3 wt.%) which is significantly higher than the maximum value allowed by EN 450-1 (Category C < 9 wt.%) [20]. Unburnt carbon and inorganic compounds can significantly affect the properties of concrete (workability, setting time, mechanical properties) [52].

3. Technical feasibility and valorization of WBA use as supplementary cementitious material

A review of the available literature leads to the conclusion that the application of WBA significantly depends on its properties, which depend primarily on the characteristics of the biomass used, i.e., the type of biomass, the plant technology, the combustion temperature and the location of ash collection and storage. For this reason, the chemical composition causes variation in the properties of the tested cement composites. The use of WBA in the cement composites leads to an increase in water demand, which may be related to the morphology of WBA (irregular particle shape and fineness), free CaO and alkali content, and LOI values [43, 53]. According to [23], increasing the content of WBA as a cement replacement resulted in decreased workability of cement pastes, while water treatment (washing of WBA) had a positive effect on the workability of cement mixtures due to physical modification: treatment by washing decreased the average ash particle size, porosity, and specific surface area of WBA. Increasing the proportion of WBA in mortar mixes prolonged the setting time, while cement pastes with a WBA content of 15% should be dimensionally stable despite the high content of CaO minerals in WBA (free CaO and MgO) [43]. The effect of WBA on the hydration of binders was studied by monitoring the heat release with isothermal calorimetry, where the induction period is prolonged by the addition of WBA regardless of the type and chemical properties of WBA [54]. Mixtures with WBA exhibit a slower increase in strength. However, with time the compressive strength increases so that after 28 days the compressive strength of the samples with 5 and 10% WBA is equal to or higher than that of the reference samples without ash (**Figure 5**). The effects of higher proportions of WBA on compressive strength have been shown to be unfavorable in studies. Therefore, it is not recommended to increase the proportion of WBA in structural concrete to more than 20% [16, 55, 56].

In addition to the mechanical properties of cement composites with different proportions of WBA, tests of durability properties are also important. Capillary absorption is defined as the transport of fluids due to surface tension that occurs in capillary pores. Capillary pores are the main pathway through which water and other aggressive substances penetrate cementitious composites and cause permanent problems. Therefore, capillary absorption testing is often used as one of the tests and quality assessments of cementitious composites to select a suitable concrete/mortar for the construction of structural elements exposed to liquids containing aggressive substances (usually

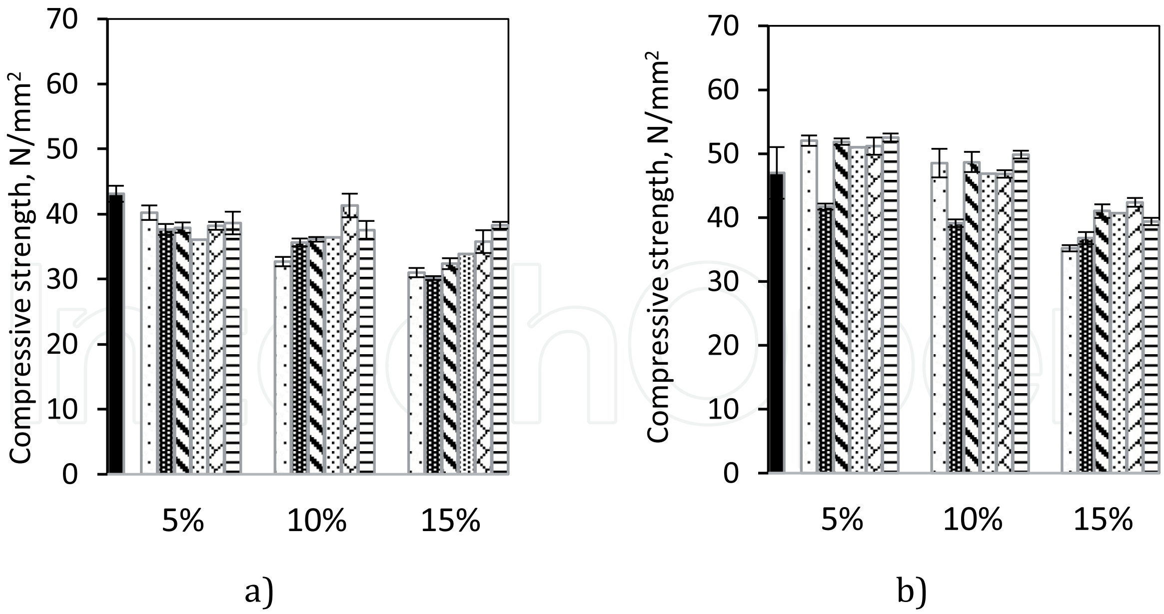

Figure 5.
Compressive strength: (a) after 7 days; and (b) after 28 days [43].

chloride or sulfate) during wetting/drying cycles. In studies [13, 43] that investigated the absorption of concrete with different proportions of WBA, an increase in absorption with WBA content was observed (an average increase in capillary absorption of up to 2.27% for mixes with 15% WBA content compared to the reference mix). The reason for the correlation between lower compressive strength and lower resistance to capillary absorption is the negative influence of the porous structure on these properties of the concrete [57]. The results of gas permeability showed the same trend as the capillary absorption coefficient: on average, the gas permeability of mortars with a WBA content of 5% decreased by 3.1%, while the cement replacement with 10 and 15% WBA increased by 12.41 and 24.31% compared to the reference mortar [58]. The researchers [59] suggested the addition of silica fume and they found that after 28 days, the gas permeability of mortar samples with 8% WBA and 7.5% silica fume decreased by

Property	Standard	Influence
Humidity	HRN EN 1097-5	Self-hardening
Visual examination	Visual examination	Durability properties: no resistance to freezing and thawing cycles (e.g., pieces of wood, etc.)
Grading	HRN EN 12620 or HRN EN 933-10	Defines the type of use (aggregate or mineral admixture)
LOI content	HRN EN 196-2	Setting time, water requirement, durability properties
SO_3 content	HRN EN 196-2	Durability properties, corrosion, volume instability
Na_2O_{eq} content	HRN EN 196-2	Alkali-aggregate reaction
MgO content	HRN EN 196-2	Volume instability (swelling, cracking)
Free CaO content	HRN EN 196-2	
Cl^- content	HRN EN 1744-1 or HRN EN 196-2	Corrosion

Table 2.
Recommended WBA properties that to be checked before use in concrete production [60].

6.6%. Chlorides are one of the main causes of corrosion and deterioration of reinforced concrete structures. Based on the results presented in [43, 58], a decrease in the chloride diffusion coefficient can be seen for all mixtures with fly WBA, except for the sample with one type of WBA, which is related to the WBA particle size.

To make WBA a valuable resource for the construction industry, technical requirements must be established. The purpose of these requirements is to enable concrete producers to ensure consistent quality and predictable behavior of the product without adverse effects on the durability and mechanical properties of the concrete [18]. Therefore, the overall effect of individual physical and chemical properties of the WBAs used on the mechanical properties and durability of cement composites was determined by evaluating the individual effects of the physical and chemical properties relative to the reference mix [58]. This study was carried out to provide concrete producers with a preliminary recommendation on the main WBA properties to be checked during reuse (**Table 2**).

4. Ecological feasibility of using WBA as supplementary cementitious material

In the construction sector, the use of industrial by-products as substitutes for natural raw materials is encouraged. When using alternative materials obtained as by-products from other industries, it is necessary to consider the environmental factor. One of the basic requirements for construction includes "hygiene, health, and environment" under the European regulation for construction products [61]. The assessment of the environmental impact of cement-based construction products is usually based on the determination of leaching, i.e. the potential release of ingredients such as trace elements (heavy metals) or organic compounds into the environment when the products come into direct contact with water or soil. The estimation of pollutant release can be done by standard short-term leaching tests and long-term tests [62, 63]. The Technical Committee of CEN TC 351 has developed laboratory tests to check the leaching of hazardous substances into nature using demineralized water as a leaching agent [63].

The authors [25, 41, 64] found that the concentration of heavy metals such as Zn, Cd, Pb, and Hg is higher in fly WBA samples than in bottom samples. Therefore, the leaching/stabilization behavior of cementitious composites prepared with fly WBA

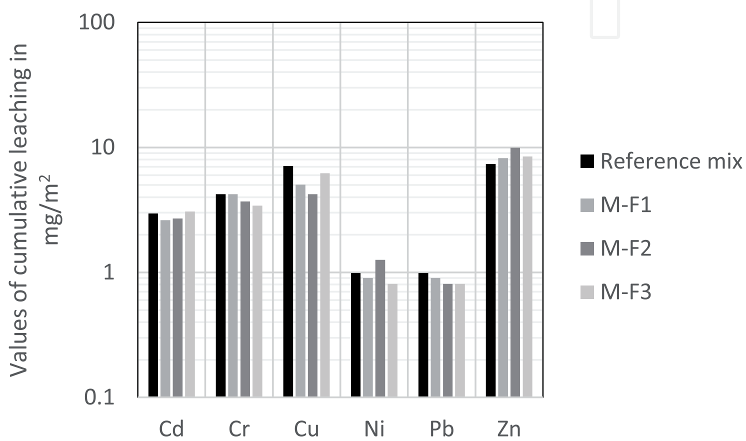

Figure 6.
Values of cumulative leaching in mg/m² for different metals (M-Fi-mortar mix with 15% of fly WBA) [65].

should be analyzed. According to the leaching results obtained by the author [65] for the observed heavy metals (Zn, Cd, CR, Cu, Ni, Pb) on monolithic specimens using 3 types of fly WBA (**Figure 6**), it was concluded that the leaching of heavy metals was acceptable, i.e., less than the limits according to the Dutch guidelines of the Soil Quality Ordinance [66] (limits for finished building materials according to the Soil Quality Ordinance for Cd: 3.8 mg/m^2; Cr: 120 mg/m^2; Cu: 98 mg/m^2; Ni: 81 mg/m^2; Pb: 400 mg/m^2; Zn: 800 mg/m^2). The same was confirmed by the authors [55, 67] when using ash from the combustion of pure wood biomass. This is explained by the ability of the cement matrix to physically and chemically bind contaminated elements (heavy metals) within the hydrate structure [68].

5. Market readiness of the WBA use as supplementary cementitious material

In order to explore the market readiness and capacity for using WBA as SCM in the concrete industry, a questionnaire was conducted among 11 concrete producers (SMEs) from Croatia with an approximate annual concrete production of at least 12,000 m3 to a maximum of 300,000 m3. The purpose of the questionnaire was to conduct a qualitative study of concrete and cement production and the views of SMEs on the reuse of WBA in their plants. According to the results of the survey, the most common strength classes in concrete production are C25/30 and C30/37 (each represented by 91%), followed by 64% of concrete use of strength classes C20/25, C35/45, and C40/50 (**Figure 7a**). The compressive strength of concrete is a common and important property in the design of concrete structures. In addition to compressive strength as a basic property of concrete,

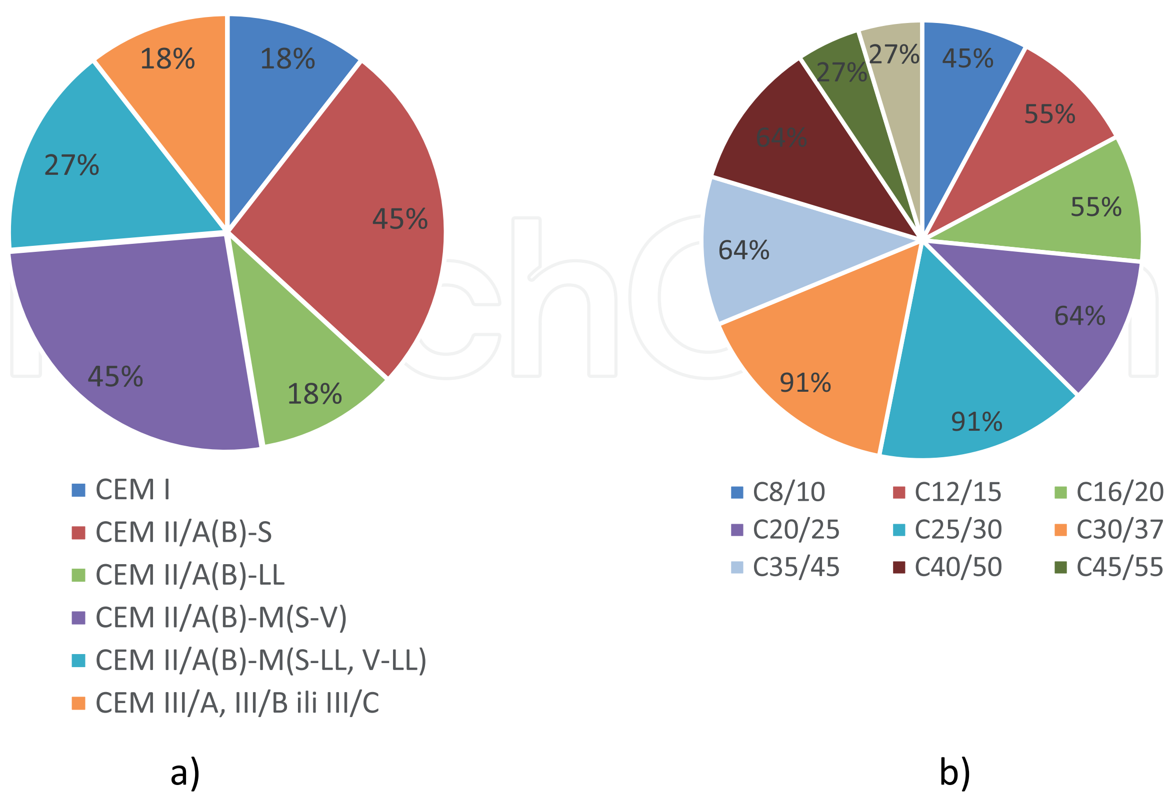

Figure 7.
(a) Concrete production share with respect to the compressive strength class; and (b) cement type share in the concrete production.

all respondents indicate water permeability. Other main properties most tested on hardened concrete are freeze-thaw resistance with or without de-icing salt (82%), wear resistance (82%), and chemical resistance (73%).

The average amount of cement used in concrete ranges from 295 to 340 kg per 1 m3 of concrete. 27% of the respondents use mineral admixtures in the production of concrete namely silica fume, coal fly ash, and metakaolin. The most common types of cement used in concrete production are shown in **Figure 7b** (multiple answers were possible): of the 15 types of cement on the market, blended cements are the most common: CEM II /A(B)-M(S-V) and CEM II /A(B)-S with 45% of use, CEM II /A(B)-M(S-LL, V-LL) with 27%, CEM II /A(B)-LL with 18% and CEM III /A(B, C), with 18%. Blended cements contain waste products as SCMs to replace clinker as the main source of CO_2 emissions in concrete production [69]. By using SCMs could result in CO^2 reduction of about 400 million tons per year [70]. These can be easily replicated as a possible circular solution for WBA management, which was recognized by concrete producers: 55% of respondents are familiar with the problem of WBA management and 91% of them are interested in using WBA in their plants. Concrete producers emphasized ensuring a consistent chemical and physical WBA quality to ensure the quality of the concrete produced.

Considering the current quantities of WBA in Croatia (25,414 tons per year [3]) and the data from the questionnaire analysis of cement and concrete production, all WBA can be used in cement and concrete production with regular quality control. For example, if 10% of cement is replaced by WBA, it is possible to reuse 1500 t of WBA per year in only one concrete plant with an average production of 50,000 m^3 concrete/year. This means that in the four concrete plants the whole amount of the finer WBA can be used, while the coarser fraction can be used as a substitute for the fine fraction of aggregates (sand).

6. Conclusions

According to all observed trends, waste ash from wood biomass combustion is expected to increase and the regulatory framework for waste management is becoming more stringent. In the design and planning phase of biomass power plants, it is important to determine the amounts of WBA generated and to find sustainable solutions for WBA management during the life cycle of the power plant. In the concrete industry, there is a high potential for substitution of certain components by adequate alternative materials, and in that context, the use of WBA has been examined. This paper presents comprehensive research of the properties of WBA necessary for its use as SCM in concrete. Based on the review of existing research and results of experimental testing shown in the paper, it can be expected that WBA reduces the workability of the cement composites, noting that cement replacement up to 10% has no significant effect on the consistency. This is probably due to the morphology of WBA, high alkali content, and LOI values. Increased setting time can also be expected, although results vary depending on the type of WBA used. For WBAs with a high CaO content, it is necessary to check the free CaO as it may affect the volume stability and durability properties of the cement composites. The comparison of the compressive strength of mortars and concretes shows a significant variability and influence of the different WBAs used on the compressive strength after 28 days with a tendency to decrease the compressive strength with a higher proportion of WBA.

The main logistical and long-term challenges that need to be considered when establishing an industrial symbiosis for sustainable WBA management are to ensure consistent WBA quality (proper storage and transportation of WBA from power suppliers to concrete producers); different types of WBA collection in power plants (e.g. mixing with water), which could affect WBA properties (self-hardening) and the need for additional pre-treatment of some WBA samples (e.g., grinding and/or screening) due to inefficient combustion of wood biomass or due to wood impurities, which could negatively affect durability properties.

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Conflict of interest

The authors declare no conflict of interest.

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