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Wood biomass ash as a raw material in concrete industry

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Subject review

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Wood biomass ash as a raw material in concrete industry

The trend of wood biomass use as a renewable energy source has contributed to an increase in the quantity of wood biomass ash (WBA) that is regarded as waste. Currently, 70 % of WBA is landfilled, 20 % is used in agriculture, and 10 % is used for other purposes. The aim of this paper is to carry out an extensive analysis of the current situation regarding WBA production in Croatia and other European countries. An overview of the types and properties of WBA in relation to the type of wood biomass is given, and parameters relevant for WBA use in concrete industry are presented.

Key words:

wood biomass ash, bottom ash, fly ash, chemical composition, supplementary cementitious material, mineral admixture

Pregledni rad

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Pepeo drvne biomase kao sirovina u betonskoj industriji

Trend korištenja drvne biomase kao obnovljivog izvora energije utjecao je na povećanje količina proizvedenog pepela drvene biomase (PDB) kao otpada. Zasad se 70 % PDB-a odlaže, 20 % se koristi u poljoprivredi, dok se 10 % koristi za razne primjene. Cilj je ovog rada provesti opsežnu analizu sadašnjeg stanja proizvodnje PDB-a u Hrvatskoj i u Europi. Prikazane su vrste i svojstva PDB-a u odnosu na vrstu drvne biomase te parametri relevantni za korištenje PDB-a u betonskoj industriji.

Ključne riječi:

pepeo drvene biomase, pepeo s dna peći, leteći pepeo, kemijski sastav, zamjenski cementni materijal, mineralni dodatak

Übersichtsarbeit

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Asche aus Holzbiomasse als Rohstoff in der Betonindustrie

Der Trend, Holzbiomasse als erneuerbare Energiequelle zu nutzen, hat zu einem Anstieg der Menge an Asche in Holzbiomasse (PDB) geführt, die als Abfall anfällt. Bisher wurden 70 % der PDB entsorgt, 20 % werden in der Landwirtschaft und 10 % für verschiedene Anwendungen verwendet. Ziel dieser Arbeit ist es, eine umfassende Analyse des gegenwärtigen Produktionsstandes von PDB in Kroatien und in Europa durchzuführen. Die Typen und Eigenschaften der PDB werden in Bezug auf die Art der Holzbiomasse und die für die Verwendung der PDB in der Betonindustrie relevanten Parameter angegeben.

Schlüsselwörter:

Asche aus Holzbiomasse, Asche vom Boden des Ofens, Flugasche, chemische Zusammensetzung, zusätzliches Zementmaterial, mineralischer Zusatzstoff

1. Introduction

Solid and gaseous biomass fuelled power plants are the biggest source of renewable energy in the EU and are expected to make a key contribution to the 20 % EU renewable energy target by 2020. Promotion of advantages and opportunities of renewable energy resources (RES) in Croatia and in the European Union (EU) has led to a significant increase in the number of biomass power plants, wood biomass plants in particular. Globally, biomass today contributes with 8–15 % to the gross final energy consumption for heating and cooling, electricity production and transport [1–9], whereas in the EU this contribution amounts to 16 % [10]. Also, an increase in biomass production of almost 37 % is predicted by 2020 in the National Renewable Energy Action Plans (NREAPs) of EU member states [11], while by 2050, the energy produced from biomass is expected to contribute with 33 - 50 % to the total primary energy production worldwide [3, 9, 12, 13].
The global increase in biomass quantity is estimated at 112 – 220 billion tonnes per year [11-16]. However, the annual global production of biomass with the potential of utilisation for energy production is estimated at approximately 3 billion tonnes for forest biomass [2], 1.1 - 3.1 billion tonnes for agricultural biomass and residues [2, 17, 18], and approximately 1.1 billion tonnes for municipal waste [12]. Even though in 2020 a large share of solid biomass will be supplied by EU countries, an additional increase in biomass import from third countries is to be expected.
Wood waste is considered to be a carbon neutral fuel, since wood absorbs the same amount of carbon dioxide while growing as released by combustion, and is preferred to other biomasses due to reduced residue production [19]. Even though thermal incineration reduces the mass and volume of waste [20], the growing trend of using biomass as a renewable energy source (RES) also results in a higher generation of wood biomass ash (WBA). Typically, combustion of 1 tonne of forest biomass and wood waste generates 5 MWh of energy as well as 20 – 50 kg of bottom ash and fly ash [21]. Currently, 70 % of wood biomass ash (WBA) is landfilled, 20 % tends to be used as a soil supplement in agriculture and the remaining 10 % is used for miscellaneous applications [19, 22, 23]. However, disposal of wood ash in landfills should be properly engineered due to possible air contamination with fine particles by wind, which can cause respiratory health problems to residents near the disposal site [24]. Contamination of ground water resources also presents a major problem due to leaching of heavy metals from the ash or seepage of rain water in the case of landfilling. An increase in the cost of landfilling in the form of waste tax or disposal fee, as well as difficulties in acquiring new landfill sites, and stricter EU landfill directives, may be expected [25]. It is therefore necessary to find ways and methods for WBA application that are environmentally sound and economically justified. The aim of this paper is to carry out an extensive analysis of the current situation regarding WBA production in Croatia and, more broadly, in Europe, as part of the research project *TAREC² Transformation of Wood Biomass Ash into Resilient Construction Composites* funded by Croatian Science Foundation.

The main objectives of this paper are to identify quantities of WBA produced and to determine main factors that influence WBA properties with regard to its use in concrete industry.
A survey involving 13 wood biomass power plants in Croatia was conducted in the scope of this paper. The survey provided data regarding combustion technologies, origin of biomass used as fuel, quantities of WBA, and waste management policies. The data collected in the survey will serve for long-term prediction of WBA quantities and, accordingly, for defining requirements enabling its sustainable management.

2. Wood biomass and power plants

The characteristics of WBA may differ to some extent, which primarily depends on tree species, combustion technology, and location where the ash is collected [19]. Wood biomass composition varies significantly depending on the type of biomass used, whereas its quality depends on the geographical location, variety in composition (tree species), climatic conditions in which the tree grows, and the harvesting technology used. Key quality criteria in describing wood chips (Figure 1) are [26, 27]: moisture/water content, homogeneity and size of wood chips, content of small particles, form of wood chips, their origin, ash content, impurities, and chemical composition. The quality of raw material entering as input into energy supply affects the output, i.e. the quality of wood is a very important factor that influences the wood biomass ash properties [28].

Figure 1. Example of wood chips

By the end of March 2016, a total of 4079 biomass power plants were identified in the scope of the Basis BioEnergy project [29] in the 28 EU member countries. By country, the highest number of power plants is located in France, Austria, Finland, Germany, and Sweden (Figure 2).

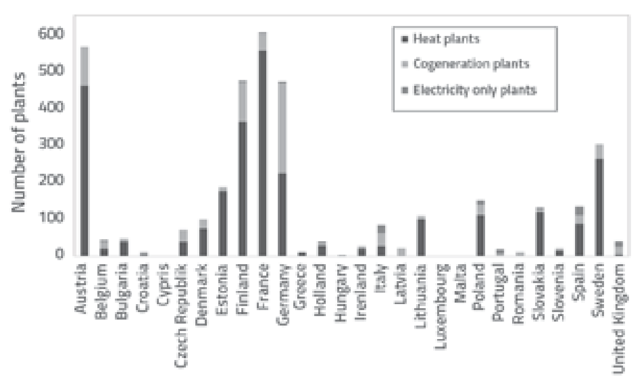

Figure 2. Number of biomass plants consuming wood chips in EU member states [29]

Three main types of combustors that use wood biomass as fuel are [30, 31]: grate combustors, fluidised bed combustors, and pulverised fuel combustors. Grate combustors are most commonly used in small and medium-sized biomass plants. Modern developments in the combustion system technology include a constantly moving, water-cooled grate combustion system, which consequently means that a wet throwaway process is being used for ash disposal from the fuel bed [28].
Fluidised bed combustors are divided into bubbling fluidised beds – BFB and circulating fluidised beds – CFB. Fluidised bed combustors are often used in medium-sized and large plants. With this type of combustors (BFB and CFB), biomass burns in a mixture of gas and a layer of sand, while the air needed for combustion is fed from below. A particularity of fluidised bed combustors (BFB and CFB) is that the bottom ash consists of two fractions - coarse and fine. The fine bottom ash that passes through the sieves of the combustor contains a significant amount of quartz sand, while the coarse bottom ash fraction, which stays on the sieve, often contains a large amount of impurities, such as stones, which can be found in the biomass itself [32].Pulverised fuel combustors are used in large power plants and for district heating purposes, as well as in systems where biomass is co-combusted with coal. It has to be said here that modern grate combustors are usually more cost-effective than fluidised bed combustors and are thus used more often.

3. Wood biomass ash

Wood biomass ash (WBA) is generated during energy production based on wood biomass. Ashes produced during wood biomass combustion can be divided into bottom ash (ash from the bottom of the incinerator) and fly ash (further divided into a coarse fraction (cyclone fly ash) and fine fraction (filter fly ash), Figure 3.

Figure 3. Samples of wood biomass ash: a) Bottom ash, b) Coarse fly ash, c) Fine filter fly ash

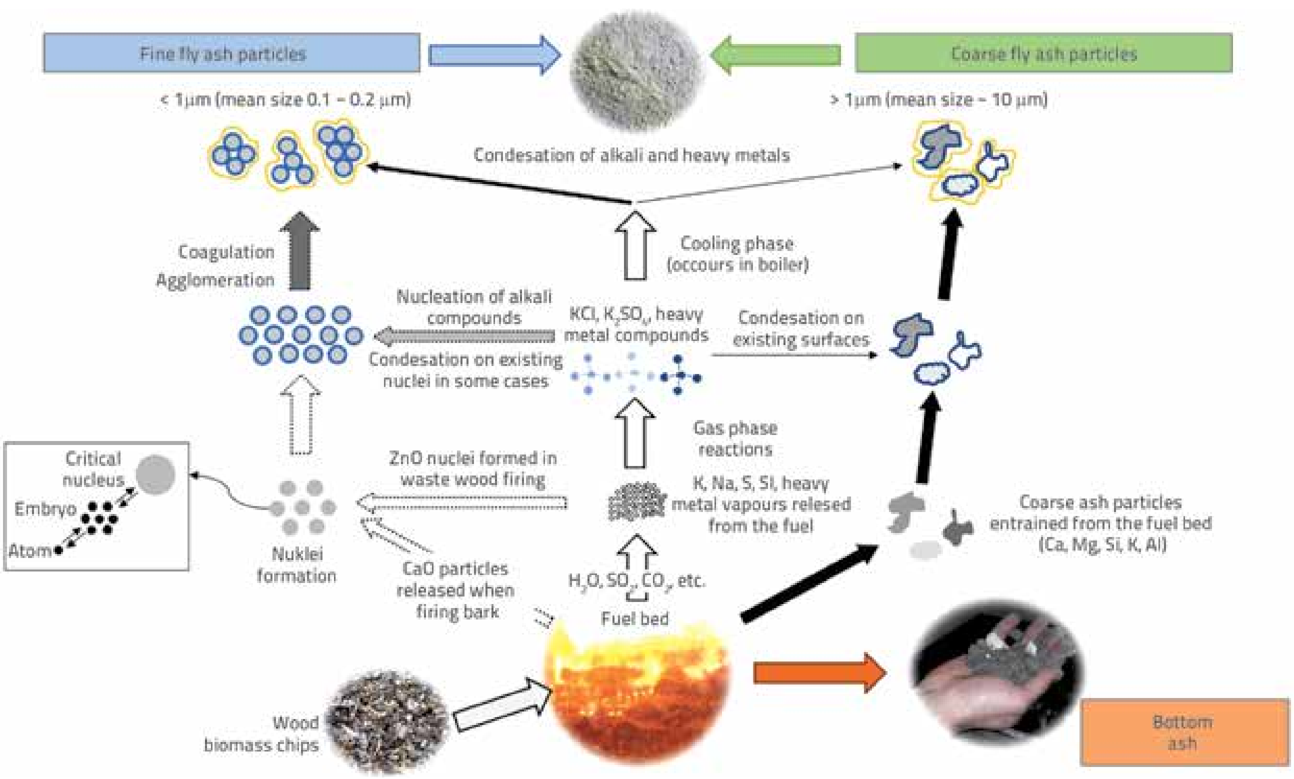

Figure 4. Schematic view of ash formation during biomass combustion on grate combustor, adjusted from [34, 35]

In biomass plants with an efficient fluidised bed combustion, the ash is predominantly fine fly ash with only a low share of coarse bottom ash that remains in combustion chamber. On the other hand, when grate combustors are used, wood ash is generally coarser and more prone to sedimentation in combustion chamber in form of bottom ash [24]. According to [33], in combustion plants using grate combustion chambers, bottom ash usually accounts for 60 – 90 % of the total ash weight, coarse fly ash takes up 2 – 30 %, and fine fly ash comprises only 2 – 15 % of the total ash weight.

Coarse fly ash (the size of several μm) is produced as a result of the entrainment of ash particles from fuel bed, while the formation of finer fractions (the so-called aerosols) with a diameter of less than 1 μm is a significantly more complex process involving nucleation and condensation processes [34], Figure 4. Due to differences in formation of the two fly ash fractions (coarse and fine – aerosols), and considering the differences in their chemical composition and behaviour, these two fly ash fractions should always be treated separately (Figure 5) [34].

Figure 5. Example of bottom and fly ash collection from Slavonija DI d.o.o. cogeneration plant, Slavonski Brod, Croatia

In biomass fuel, the ash content depends on the type of biomass and method of its collection, temperature of thermal treatment, and the type and hydrodynamics of the boiler [20, 36]. Higher temperature of thermal treatment usually results in a smaller quantity of ashes. The greatest influence on the quantity of ash generated by incineration of wood biomass (assuming that complete combustion takes place) is the type of biomass, combustion technology, and the location from which the ash is collected [19]. Many researchers have published data on the ash content in different types of biomass, and these data differ by several mass percentages, i.e. from 0.2 to 15.0 % [5, 25, 37-41]. This often implies a significant discrepancy in the amount of ash produced.

3.1. Chemical composition and morphology of WBA

Wood biomass ash (WBA) contains numerous organic and inorganic compounds and exhibits a heterogeneous composition that can vary quite significantly [42]. SEM-SE micrographs (Figure 6) show the size and morphological diversity of the coarse and fine fractions of fly WBA and bottom ash, whose particles can be spherical in shape, fused spherical, completely irregular, and porous [43].

Pitman [44] reports that chemical composition of wood, and consequently that of WBA, depends not only on the type of wood stock, but also on the tree parts being incinerated, and so concludes that the branches and roots (waste left from forest management) are generally richer in elements than stem wood itself, and that the bark and foliage have 5 – 10 times greater concentrations than stem wood, especially when Ca, Mn, Al, and S are concerned. It is also known that the concentrations of Ca, Mg, and Fe in foliage increase with foliage age, whereas concentrations of N, P, and K decrease [44]. This affects the difference in chemical composition of WBA depending on the season in which the tree was cut in, i.e. when the biomass was collected. This is one of the reasons for such large deviations from mean oxide content values in chemical composition of WBA (Figure 7).

The quantity of CaO and other carbonates depends not only on the type of wood stock, but also on the conditions of WBA storage and transport, since hydration and carbonation of CaO can spontaneously occur in wet conditions [43]. If WBA with up to 50 % of CaO comes into contact with moisture or water, a chemical reaction will occur and $Ca(OH)_2$ will be produced, which will later in contact with CO_2 from the air result in the formation of $CaCO_3$, and that will bring about changes in the chemical and

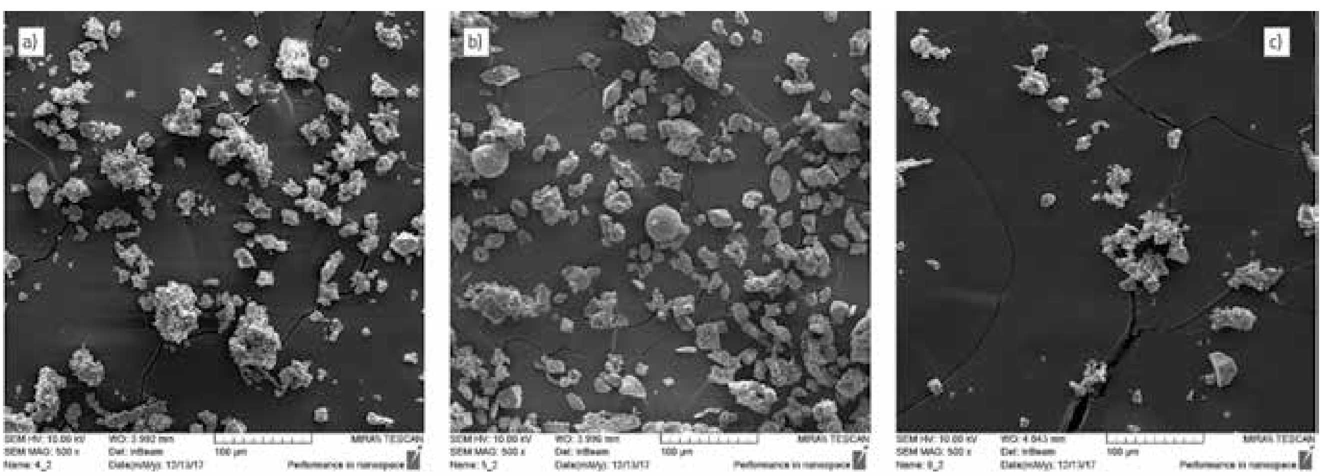

Figure 6. SEM micrographs showing size and morphological diversity of: (a) bottom ash; (b) coarse fly ash; (c) fine fly ash

physical properties of WBA and result in ageing, i.e. hardening of WBA [32]. Simultaneously, an increase in the mass of WBA dry matter will occur during its storage.

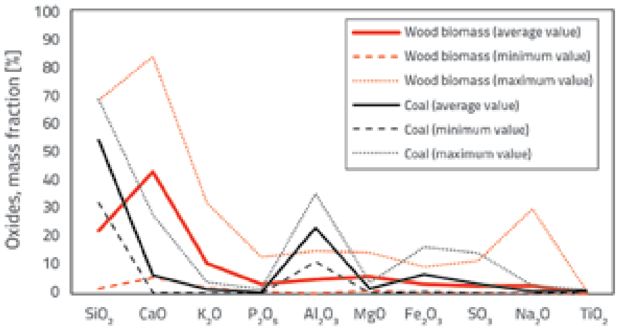

Figure 7. Minimum, maximum and average oxide values in chemical composition of various types of WBA (source of data: [2, 20, 45])

This phenomenon can be interpreted as strong indication that the dry mass increase is caused by reaction in which CaO and H_2O create $Ca(OH)_2$. Additionally, WBA also contains various components that contain $(OH)_2$ groups (such as illite, kaolinite etc.) or crystallization water (for example calcium silicate hydrate, gismondite, gypsum, ettringite etc.), which are formed by hydration and hydroxylation of less stable components [42], and so they also contribute to mass increase due to WBA contact with moisture or water. With CFB combustors a significant mass increase of dry matter does not occur, which is explained by the ash being „diluted" by a larger quantity of SiO_2 from the quartz sand being used in the CFB furnace.

Certain researchers consider that WBA is hydrophilic and that its particles tend to swell during water absorption into the pores, which occurs simultaneously with chemical reactions during WBA oxide hydration [44]. Due to wetting (swelling), there is a 12.5 % increase in volume in relation to the original WBA volume. It is assumed that the minerals most responsible for the swelling are calcite, portlandite and calcium silicate [44].

WBA pH value decreases during storage, although no significant difference in WBA pH levels has been recorded between dry and wet storage, regardless of the amount of water. A decrease in the pH value is recorded during the first 4 weeks, after which period it becomes constant at about pH = 12 - 13 [32].

Vassilev et al. [46] point out that there are certain types of WBA that cause serious concern about the potential air, water, soil and plant pollution. Significant differences can be detected, especially in the heavy metal content, when one compares bottom ash, coarse fly ash (from cyclones) or fine fly ash (from electrostatic precipitators). The greatest oscillations occur in volatile heavy metals such as Zn, Pb and Cd, whose content rises as particle size decreases. The data shown in Table 1 indicate that WBA could contain alarming amounts of Ag, As, Ba, Cd, Cl, Cr, Cu, Hg, Mn, Mo, Ni, Pb, S, Sb, Se, Sn, Th, Tl, U, V and Zn.

Since biomass fly ash particles are lighter (their bulk density is 101 – 830 kg/m^3) and smaller (mean particle size is usually less than 10 – 100 μm) than the fly ash produced by coal combustion, there is an increased risk to the health and safety of people during transport and handling of wood biomass fly ash due to potential inhalation of small particles of fly WBA, which can enter and be retained deep in pulmonary alveoli [6, 39]. Exposure to sulphates and fine particles with an aerodynamic diameter smaller than 2,5 μm has been proven to correlate with cardiopulmonary and lung cancer mortality [6]. High content of Cd in some types of WBA also presents a health hazard, since Cd accumulates in the kidneys and affects bone density [6]. In case of WBA landfilling, groundwater and surface water pollution also presents a serious problem due to leaching of heavy metals from WBA [25].

Utilising WBA involves logistical challenges for owners and managers of wood biomass plants, as well as for companies that collect WBA from biomass plants. Proper storage undoubtedly implies preventing environmental pollution at storage sites, as well as storage that will not significantly change WBA properties before it is used as a secondary raw material. Methods of WBA storage, disposal and/or utilisation primarily depend on its chemical and physical properties, and so identification, quantification and subsequent characterisation of WBA can be regarded as the first and foremost step in identifying proper WBA management and utilisation [34, 46].

3.2. Estimated amounts and current application of WBA in world

Although amounts of produced WBA are significantly lower in comparison to amounts from coal-fired power plants, finding potential ways of utilising produced WBA is still of great importance. Based on published data [25], it is generally thought that, by incinerating their complete wood biomass potential, the leading wood biomass consuming countries could produce the amounts shown in Figure 8.

Table 1. Heavy metal content in bottom and fly ash [44]

Element	As	Cd	Co	Cr	Cu	Hg	Mn	Ni	Pb	V	Zn
Bottom ash	0.2 - 3	0.4 - 0,7	0 - 7	>60	15 - 300	<0.4	2500 - 5500	40-250	15 - 60	10 - 120	15 - 1000
Fly ash	1 - 60	6 - 40	3 - 200	40 - 250	~200	0 - 1	6000 - 9000	20 - 100	40 - 1000	20 - 30	40 - 700

Future trends of using biomass to produce energy suggest that the amount of WBA will have doubled by the year 2020, while an annual increase in production to 15.5 $\times 10^6$ tonnes of biomass ash is possible in EU member countries [33]. It should also be noted that the current practice of WBA disposal in Europe causes material losses, and that it represents an additional environmental issue [43, 47-49].

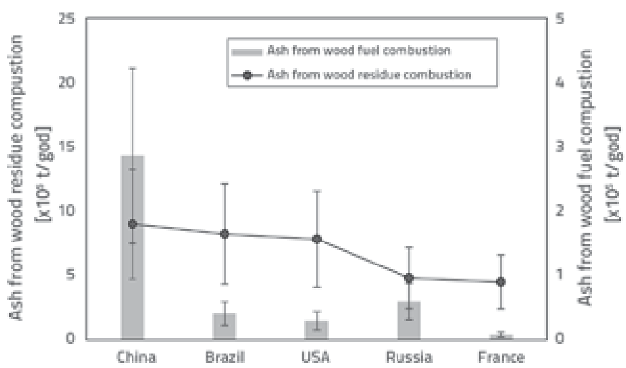

Figure 8. Estimated amounts of WBA based on complete wood biomass potential in selected countries [25]

Since WBA is rich in nutrients, it is regularly used for fertilisation and soil improvement in Austria, Sweden, Finland, Denmark, and Germany [32]. Although WBA is used in agriculture, there are several problems to consider [50]. Fly WBA is rich in K, but most of N is released in the gas phase. Additionally, P is present in its insoluble form, which means it may take several decades for it to become available to plants. Fly WBA is often rich in heavy metals, and their concentration is therefore often higher than permitted limits [32]. On the other hand, the only advantage of using bottom WBA is the smaller content in heavy metals, while its disadvantage is a considerable nutrient loss (due to the cut-off of both fly ash fractions, only 40 – 60 % of K, P and Mg can be utilised sustainably) [33]. Furthermore, the ashes produced in fluidised bed combustors (BFB and CFB) usually contain less nutrients and heavy metals due to a high content of SiO_2 in the sand mixed with WBA [33].

It should be emphasized that environmentally friendly utilisation of WBA is feasible only with WBA produced from chemically untreated wood (WBA from contaminated wood biomass such as waste wood cannot be used for fertilisation and soil improvement) [34]. Sustainable WBA utilisation in agriculture means that the natural cycle should be closed, i.e. WBA should be integrated into the natural cycle of minerals (nutrients). Biedermann and Obernberger [34] have shown that, during the process of energy production from chemically untreated wood biomass, the natural mineral cycle is disturbed by the sedimentation of heavy metals in forest ecosystems. Due to high levels of heavy metals that would disrupt the natural mineral cycle, it is not possible to recycle the total amount of WBA produced in the process of combustion of bark, wood chip and sawdust [34]. The most important heavy metals (in terms of environmental impact) in biomass fuel are Zn and Cd, and they are most frequently contained in fly ash, while nutrients (K, Mg and P) as well as Ca are primarily found in bottom ash. When considering the heavy metal content and weight distribution in individual ash fractions, it is evident that volatile heavy metals are primarily concentrated in the fine fly ash fraction (Figure 9).

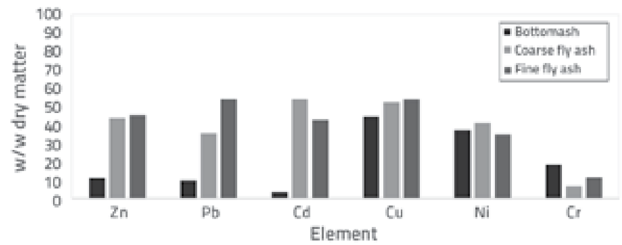

Figure 9. Average distribution of selected highly volatile (Zn, Pb, Cd) and least volatile (Cu, Ni, Cr) heavy metals between individual WBA fractions obtained from grate combustor furnaces [33]

3.3. Application of WBA in construction industry

In a recent communication [51], the European Commission (EC) has established that the construction sector plays an important role in the delivery of the Europe 2020 Strategy on smart, sustainable and inclusive growth [52]. There is a pressing need for innovation in sustainable construction, particularly in cement-based materials so as to ensure EU's long-term objective of 80 - 95 % reduction of greenhouse gas emissions and to contribute to the preservation of natural resources. Therefore, the utilization of wood biomass ash in construction is an environmentally motivated choice for cutting down disposal costs but also for conserving natural resources and reducing greenhouse gas emissions.

Research presented in [53] reveals that the wood biomass ashes (WBA) have low silica, low alumina and high calcium oxide content, compared to the coal and co-fired fly ashes (FA and CA) which have high silica, medium alumina and low calcium oxide content. Vassilev et al. [46] show that minerals in WBA can be divided into: active (lime, periclase, anhydrite, basanite, calcium silicates, Ca-Mg silicates and aluminosilicates, Ca-enriched glass etc.), semi-active (portlandite, brucite, gypsum, carbonates, clay and mica minerals, feldspars, iron oxides, Ca-containing glass, etc.), pozzolanic (glass) and inert or inactive (quartz, mullite, some carbon minerals). The aforelisted WBA mineral classification is based on their properties from the mineralogical viewpoint, whereby active and semi-active WBA minerals represent reactive substances when in contact with water [46].

Hardening and binder effects result from the formation of new and relatively stable silicates, aluminosilicates, sulphates, carbonates, hydrates and oxyhydroxides, which contain water molecules and/or a hydroxyl group. These newly-formed crystals and amorphous products bind pozzolanic and inert minerals relatively rapidly in such a multicomponent system. On the other hand, pozzolanic reactions of WBA are mostly diffusion-governed processes and begin to occur in the later part of the hardening process [46]. The complex processes briefly explained here actually play a leading role in the production and use of building materials.

Since chemical composition of WBA (both bottom and fly ash) differs from that of coal ash [54, 55] and does not satisfy the existing regulation for use of fly ash in cement (EN 450-1) [56], further research is needed to determine the potential and adequacy of WBA as a cement replacement and/or mineral admixture in mineral composite products. It should however be noted here that biomass ash can be and is used in the construction industry for other purposes as well [46]: for silica xerogel blocks used as thermal insulation, geopolymer synthesis, self-levelling mortars, road subbase, pavement structures, lightweight (expanded) aggregates, lightweight bricks, blocks, drywall, concrete blocks, autoclaved aerated concrete, bricks, binders for low-strength materials, asphalt as well as bitumen-based products. The use of WBA in concrete products has to be harmonised with Regulation (EU) No. 305/2011 [57]. Given the requirements of the existing regulations, WBA can be used in construction products based on the System 4 of assessment and verification of constancy of performance. The declaration on the constancy of performance of construction products is provided by the manufacturer. The manufacturer shall carry out: determination of the product-type on the basis of type testing, type calculation, tabulated values or descriptive documentation of the product and factory production control [57]. Construction products covered by System 4 are for example precast concrete drainage elements and concrete paving blocks.

4. Wood biomass ash in Croatia

In order to use WBA as new material in concrete industry, it is necessary to make its detail characterization. As seen before, there are several factors that influence WBA properties and WBA amount. Therefore, a survey was made under project *TAREC² Transformation of Wood Biomass Ash into Resilient Construction Composites* to identify the combustion technologies, origin of biomass, quantities of WBA, and waste management policies. The survey questionnaire was filled in by 13 respondents who represented biomass plants with a total installed power of 35.435 MW_e and 99.31 MW_t or 72.8 % of the total installed power in wood biomass plants in the Republic of Croatia in 2017. Given the type and installed power, this survey encompassed the following biomass plants: medium biomass boilers with electric output of 1 MW_e to 9.9 MW_e and small to medium biomass boilers with thermal output of 0.85 MW_t to 16 MW_t. Out of these plants, 11 wood biomass plants are cogeneration plants (producing both electrical and thermal energy), while two are district heating plants.

All respondents stated that they use clean wood chips. However, 85 % of the respondents also use other types of wood biomass such as wood chips with impurities (earth and stone), forest residues from harvesting wood – green chips (wood chips from fresh roundwood and residues, including brushwood and peaks), chips from the whole wood (e.g. wood chips containing bark, brushwood, needles/leaves) and waste from wood industry (including bark). None of the respondents uses residues from agriculture, herbaceous plants (grass and weed) and wood pellets or briquettes. All respondents use biomass from the state-owned company *Hrvatske šume* Ltd. Additionally, 61.5 % use biomass from wood processing industry and/or private forests, and 38.5 % use all three sources of wood biomass. Mostly used species of wood are beech and oak, followed by hornbeam and, to a lesser extent, poplar and mixed wood, spruce, willow, and fir. None of the respondents use treated wood biomass or co-combustion with fossil fuels.

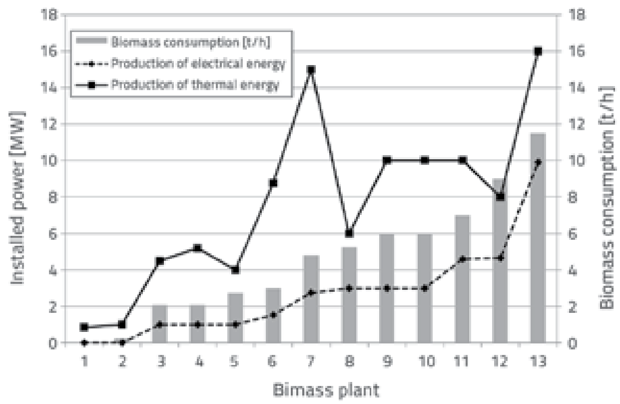

Figure 10. Biomass consumption per hour vs installed power

Biomass consumption per hour, shown in Figure 10, is dependent on the installed capacity of the plant. The survey results show that for medium sized plants biomass consumption ranges from 2 to 11.5 t per hour, while 5 tonnes per hour can be considered as an average consumption. Production is stopped one to three times a year for maintenance, resulting in 7580 operating hours or approximately 316 days per year as an average for these 13 plants. It was also found that 85 % of the biomass plants check the biomass moisture levels through their quality control system. On an average, moisture content of biomass ranges from 20 to 60 %.

Grate combustor technology is used by 69.2 % of biomass plants, 23.1 % use pulverised fuel combustors and 7.7 % use combustion in bubbling fluidised bed (with silicate sand). The combustion temperature ranges from 500 to 1000 °C with an average temperature of 800 °C. Based on the conducted survey, 77 % of the respondents think that the quality of the ash is constant during the year while the combustion temperature varies, as expected, depending on the humidity and quality of biomass received.

The total amount of WBA produced by combustion in the surveyed biomass plants amounts to 15,190 tons per year. Bottom furnace ash makes 65 % of the total ash produced, finer fly ash fraction (from electrostatic or bag filters) 22 %, and

Table 2. Estimate of current and future annual WBA production in Croatia

Estimated annual consumption of wood biomass	3,1 % wt% of WBA content (based on the survey results)
819.820 t/year According to the installed power of 56.709 MW_e in October 2018	25.414 t/year
1.240.709 t/year According to the total power of plants with whom Croatian Energy Market Operator (HROTE) concluded contracts for 85.823 MW_e electrical energy purchase by February 2016 - calculation based on the survey results	38.461 t/year
1.530.000 t/year According to Total wood biomass potential in Croatia	47.430 t/year

coarser fly ash fraction (from cyclone separator) makes 13 % of the total amount of WBA. If average operational hours are considered (7,580 hours) together with the calculated average consumption of 5 tonnes per hour, 37,900 tonnes per year of wood biomass is consumed in one biomass plant. For 13 wood biomass plants in Croatia, this makes 492,700 tons of biomass, which is approximately 1/3 of the estimated wood biomass market potential in Croatia. Thus, 3.1 % of WBA is generated during combustion of 1 ton of wood biomass.

This WBA is in the most cases (69 %) stored in closed containers and, while it is not in contact with precipitation, it is in contact with air moisture. 15 % is cooled and collected by water in the wet ash handling systems and stored in containers. 8 % of the plants store WBA in sealed containers that prevent its contact with precipitation or moisture from the air, while 8 % stipulate that WBA is stored in "big bags". Further management of WBA is entrusted to authorized waste management companies in only 39 % of cases. Others landfill the ash in their own landfills (23 %) or WBA is collected by the companies that use the ash in agriculture (38 %).

The WBA quality control is conducted but without a uniform system, and it mainly depends on the judgement of biomass plant operators. Overall, chemical analysis is conducted once a year, while the heavy metal content is tested more often, up to four times a year. Regardless of the current WBA management practices, the survey showed that there is an overall interest to declare the WBA as being a by-product that is fit for use in concrete industry. The biomass plant owners are even prepared to invest some funds to enable WBA use in concrete industry.

Extrapolation can be performed based on the above survey to calculate the total estimated consumption of the wood biomass in the Republic of Croatia (Table 2). The estimation is based on the installed capacity of all 29 biomass plants that are currently in operation (data from October 2018), and it amounts to a total of 819,820 t of biomass per year, which is approximately 54 % of the estimated potential of wood biomass market in Croatia. Furthermore, based on the average generation of 3.1 % of ash as established in the survey, it is estimated that the total amount of WBA in the existing biomass plants in Croatia is 25,414 tons annually; out of which bottom ash accounts for 65 % (16,519 t), fine fraction fly ash from electrostatic or bag filter 22 % (5,591 t), and coarse fraction fly ash from cyclone separator 13 % (3,304 t). The survey results were also used to estimate the capacity to 85.823 MWe based on plants that are currently under construction, and according to electricity purchase contracts signed with the Croatian Energy Market Operator Ltd. Also WBA production can be estimated according to the potential of the wood biomass market in Croatia [58, 59], which is 47,430 t annually.

5. Conclusion

It can be concluded based on the state of the art review given in this paper that, in addition to agricultural applications, other possible uses of WBA should also be explored, especially in the light of the pressing need for innovations in sustainable construction, particularly in cement-based materials, the aim being to ensure compliance with the EU's long-term objective of 80 - 95 % reduction of greenhouse gas emissions, but also to contribute to the preservation of natural resources and use of renewable materials.

Survey results obtained in the scope of the project *TAREC² Transformation of Wood Biomass Ash into Resilient Construction Composites* have provided significant data for further WBA management in concrete industry. According to survey results, approximately 25,414 t/year of WBA are produced today in Croatia. The bottom furnace ash accounts for 65 %, finer fraction of fly ash 22 %, and coarser fly ash 13 % of the total WBA produced. The WBA management is entrusted to the authorized waste management companies in 39 % of cases only. Others deposit the ash in their own landfills (23 %), or WBA is being collected by the companies that use the ash in agriculture (38 %). The trend of increase in the number of new power plants further underscores the problem of WBA management in Croatia. Optimistic feedback given by the surveyed power plants, as well as the current knowledge on WBA use in concrete industry, form a solid foundation for WBA management. The results will be used to ensure better understanding and explanation of further WBA characterization, which will be conducted on the locally available WBA from the aspect of micro-texture, chemical and mineralogical composition, and pozzolanic activity, in order to identify its best fitting application in concrete. Also, the data can be used for the long term prediction of WBA production, and for developing WBA management strategies in the framework of sustainability.

The possibility of using WBA in Croatia as a raw material in concrete is currently investigated in the framework of the TAREC[2] project, the aim being to determine the potential and adequacy of WBA use as cement replacement and/or as mineral admixture in cement composites. This includes characterization of available WBA, and definition of its compatibility with cement and other supplementary cementitious materials, in order to identify, for each by-product, the best fitting and acceptable application in concrete industry.

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