Harvest residues ash as a pozzolanic additive for engineering applications: a review and the catalogue

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**ABSTRACT**

Biomass ashes originating from wood and harvest residues combustion may be considered as one of the prospective environmentally friendly candidates for supplementary cementitious materials (SCM) production. In the region of Vojvodina province, biomass waste is becoming increasingly important as “green” fuel, thus allowing the reduction of the environmental impact of waste disposal, lowering the expensive fossil fuels application and its subsequent greenhouse gases emission. In the light of the above, the present paper surveys the experimental studies of harvest residues ash (HRA) as a pozzolanic additive for engineering applications. Thus far conducted research on the HRA possible application in cementitious systems, worldwide and in the studied region, has been summarized and the benefits of such approaches outlined. Finally, locally available types of wheat straw, soya straw, sunflower husk, silo waste, oil rapeseed - based ashes were collected, characterized both physically and chemically, evaluated and presented through catalogue. The reactivity results, depending on the amorphous silica content and the achieved level of fineness, are very promising in terms of the potential reuse of these ashes in cementing systems.

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**Keywords**

biomass ash, SCM, green fuel, catalogue, cement-based composites

1 **Introduction: biomass as res**

Using biomass to provide energy services is one of the most versatile options for increasing the share of renewable energy in the global energy system. Biomass for energy production may be obtained from a diverse range of sources, the most important of which are energy crops, agricultural and forestry residues, wastes, and existing forestry. There is a wide dispute about the most important factors affecting the contribution biomass might make to primary energy supply. These include the availability of arable land (agricultural land may be expanded at the expense of forested areas; or lost due to soil degradation or urbanization etc.), the productivity of the biomass grown on the land (climate change) and competition for alternate uses of the land (waste landfilling).

On the other hand, some scenarios assume that increases in food demand will primarily be met through increases in crop yields, which should be particularly required in developing countries. Forecasting models indicate that developing countries will account for most of the rapid urban population increase by 2050, hence the percentage of global energy used in cities is expected to increase considerably. Although cities continue to use fossil fuels as the main source of energy, biomass acts for a growing renewable energy source (RES) with high growth potential, due to its wide availability as a by-product of many industrial and agricultural processes.

As previously mentioned, the global economy is primarily based on fossil fuels to produce electricity, heat, fuels and energy, whereas they account for 81% of the total primary energy supply; nuclear energy produce 5% and RES 14% (of which the contribution of biomass is about 70%) [1]. The use of RES in the EU has grown from 13.2% in 2010 to 18.0% in 2018 [2]. Biomass is today used primarily for: 1) feed, 2) food and 3) energy, fuels and chemical feedstock production and, based on its availability and ever increasing demands, could act as an alternative to fossil resources by its conversion into food, feed, and bioenergy. Despite the large consumption of biomass as an energy source, enormous quantities remain in landfills as unused waste/raw materials.

Biomass-based materials are characterized by lower emissions of greenhouse gases than those from non-renewable sources, such as oil and coal. Combustion of biomass results in pollutant emissions, but not as much as in case of fossil fuels. Therefore, an increase in biomass...
renewable energy consumption reduces CO₂ emissions and cuts the demand for fossil fuels and their associated greenhouse gases (GHG) emission.

The potential of Serbia in RES is estimated at 6 million tons per year, whereas biomass accounts for 64%, i.e. 3.3 million tons annually. In the structure of planned primary energy production in Serbia for 2014, RES participated with 1.819 million tons per year, which accounted for about 17% of domestic primary energy production. In this, the highest share had solid biomass - 58%. Greatest potential of biomass in Serbia lies in the agricultural residue and wood biomass, a total of about 2.7 million tons (1.7 million tons in the remains of agricultural production and about 1 million tons in wood biomass) [3]. The utilization possibility of biomass as a fuel can be evaluated through its low thermal power - Table 1. Apart from these two sources of biomass, further major source is the residue of livestock production. Another group of biomass sources includes energy plants (e.g. miscanthus, fast-growing poplar and the like), and plants that serve as raw material for biodiesel and bioethanol (rapeseed, sunflower, corn, etc.).

It is estimated that the total potential of biomass from agriculture in Serbia is about 12.5 million tons per year. In 2019, the share of crop production in the total value of agricultural production equaled 66.0%, and that of livestock production equaled 34.0% [6]. When compared to 2018 the net index of physical volume of agricultural production decreased by 1.2%. There are many small individual landowners in Serbia, who deal with production of cereals or industrial plants, like sunflower or soya. A lot of crop farming production, almost 75% is achieved in small or medium size private ownership, while only about 25% of crop farming production belongs to agricultural companies of relatively larger size [7]. It is estimated that about half of harvest residues at large agricultural farms can be used for energy purposes, while only about 20% harvest residues, generated on relatively small private farms, can be used for energy purposes. Total quantities of harvested crops in Serbia for the period 2015-2019 are listed in Table 2.

Table 1 - The energy potential of biomass production [4], [5]

| Agricultural biomass | Low thermal power (MJ/kg) | Woody biomass | Low thermal power (MJ/kg) | Other fuels | Low thermal power (MJ/kg) |
|----------------------|---------------------------|---------------|--------------------------|------------|--------------------------|
| Wheat straw          | 14,4                      | Beech bark    | 18,0                     | Brown coal | 22,5                     |
| Barley straw         | 14,2                      | wood          | 18,8                     | Charcoal   | 28,8                     |
| Oat straw            | 14,5                      | Oak bark      | 19,7                     | Light fuel oil | 42,1        |
| Rye straw            | 14                        | wood          | 18,4                     | Light fuel oil | 41,8        |
| Corn                 | 13,5                      | Spruce bark   | 21,2                     | Petrol     | 42,0                     |
| Sunflower stem       | 14,5                      | wood          | 19,7                     |            |                          |
| Sunflower shell      | 17,55                     | Fir bark      | 21,0                     |            |                          |
| Soya straw           | 15,7                      | wood          | 19,5                     |            |                          |
| Rapeseed straw       | 17,4                      | Pine bark     | 20,6                     |            |                          |
| Stalks of tobacco    | 13,85                     | wood          | 21,2                     |            |                          |

Table 2 - Harvested crops in Serbia for the period 2015-2019 [6]

| Crop            | Harvested quantity (in tons) per year |
|-----------------|--------------------------------------|
|                 | 2015. | 2016. | 2017. | 2018. | 2019. |
| Wheat           | 6528203 | 6884538 | 2275623 | 2941601 | 2534643 |
| Maize           | 5454841 | 7376737 | 4018370 | 6964770 | 7344542 |
| Soya            | 454431 | 576446 | 461272 | 645607 | 700502 |
| Sunflower       | 437084 | 621127 | 540590 | 733706 | 729079 |
| Rapeseed        | 334022 | 394042 | 487400 | 135422 | 84311 |
| Tobacco         | 8776   | 7811  | 7773  | 7797 | 7992 |
| Sugar beet      | 2183194 | 2683859 | 2513495 | 2325303 | 2305316 |
| **Total**       | 1299931 | 1418922 | 9865263 | 13753578 | 13706385 |
The use of biomass ashes as building materials in engineering practice in Serbia has been scarcely investigated so far. Previous studies, conducted mostly on cement mortars blended with HRA [8,9,10,11], have documented that mortars, blended with wheat straw ash and soya straw ash, show a promising performance in strength, depending on the level of fineness and chemical composition of these ashes. However, very few studies have dealt with the reactivity and pozzolanic properties of other other available biomass ashes in Serbia.

The present study is to give a brief review on the usage of different HRA, both globally and in Serbia, based on the type of the ash. In addition, locally available waste materials, originating from agriculture in Serbia, are explored and systematically presented through catalogue for possible SCM application for the first time.

### Table 3 - Main indicators of forestry in Serbia, 2015-2019 [6]

| Year | Total forest exploitation | Regular artificial forestation, ha |
|------|---------------------------|----------------------------------|
|      | Felled wood stock, gross volume, thousand m³ | Total | Conifers | Broadleaved |
| 2015 | 2928 | 1736 | 668 | 1068 |
| 2016 | 3134 | 1280 | 585 | 695 |
| 2017 | 3192 | 1984 | 654 | 1330 |
| 2018 | 3220 | 1547 | 694 | 853 |
| 2019 | 3313 | 3077 | 604 | 2473 |

2 Literature review on the application of different biomass ashes

The properties of biomass ashes, generated by biomass combustion, vary widely and heavily depend on: 1) biomass type; 2) combustion technology and temperature; 3) the location where the ashes are collected (fly ash, bottom furnace ash); 4) further treatment of the ashes (grinding processing). These contributing factors influence two major elements of potential biomass ashes application as SCMs: amorphous silica content and the level of fineness.

Below is a brief overview of the different types of biomass ashes used in the experimental research worldwide and the results obtained therein.

2.1 Rice husk ash

Rice husk ash (RHA) is a combustion by-product of grain husks of rice, as waste agricultural material. India is the world's second rice producer, immediately after China, with nearly 104 million tons of rice produced annually. Annually, nearly 3.7 million tons of rice husks are produced. The rice husk contains about 50% cellulose, 25-30% lignin and 15-20% amorphous silica gel. Several studies have been carried out to evaluate the feasibility of RHA. These studies have shown that:

- RHA can be used as low cost building material, improving the durability of the cementitious system and producing high strength concrete [12];
- After combustion (the optimum combustion temperature for obtaining highly reactive RHA is 600°C), the ash is primarily composed of reactive silica and is characterized with high level of fineness [13];
- By using RHA, as replacement of part of the cement, consistency of fresh concrete is reduced due to the large specific surface area of the ash, hence a higher amount of water is required for concrete to maintain the same consistency. As a result of the reduced amount of cement and pozzolanic activity, the setting time is prolonged;
- Due to the flier effect (fine particles of RHA), a very dense structure is formed, with reduced permeability, decreased drying shrinkage and improved mechanical properties. Studies in which up to 20% of cement was replaced with RHA showed up to 85% lower permeability to penetration of chlorides. Also, RHA application, as a substitute for a part of cement in concrete, the frost resistance and the alkali-silicate reaction is shown to be
significantly increased \[14\]. Therefore, the usage of this type of ash contributes to the improved physical, mechanical and durability properties of cement composites.

2.2 Sugarcane bagasse ash

Sugarcane bagasse ash (SCBA) is an industrial byproduct produced in the sugar mills after the extraction of sugar from the sugarcane, whereas fibrous material (bagasse) is obtained. India, along with Brazil, is the largest sugarcane producer in the world. Approximately 380 million tons of sugarcane is produced annually in India, disposing a large amount of waste or ash, thereby. Optimum combustion temperature for obtaining highly reactive ash is estimated at 600-800°C \[15\]. Conducted studies revealed a favourable chemical composition of the ash in terms of its pozzolanic activity, primarily due to the high content of amorphous silica (≈78%) \[16\]. The authors summarized following observations regarding the properties and use of SCBA as SCM:

- The bulk density of SCBA is lesser than OPC; the volume occupied for a supposed mass will be higher, hence ash particles fill the small pores of concrete making it less permeable \[17\];
- Due to high level of fineness the concrete containing SCBA require higher amount of super-plasticizing as compared to the control mix to achieve the same workability \[18\];
- OPC replacement of 10% by weight of SCBA allows obtaining concrete with excellent mechanical performance and durability properties \[19\];
- The use of SCBA is efficient in the production of self-compacting concrete \[20\].

2.3 Palm oil fuel ash

Palm oil fuel ash (POFA) is a waste material resulting from the combustion of palm fibres and leaves for the generation of electricity. Currently, in Malaysia, oil palm plantations spread over three million hectares of land, whereby more than 15 million tons of palm oil is produced annually, generating 2.6 million tons of ash, thereby. Uncontrolled disposal of this type of ash occupies valuable land, but also leads to pollution of the environment and disruption of human health. The summarized knowledge on the applications of the ash in engineering practice includes:

- The appropriate fineness could be achieved by using a grinding mill;
- Due to a relatively high content of silica (55-65%), it can be extremely reactive, depending on the adjusted level of fineness \[21\];
- Along with ordinary pozzolanic materials, POFA reduces the consistency, lowers the heat of the hydration and prolongs the setting time of the concrete;
- Most of the researchers obtained the compressive strength of concrete containing 10–30% POFA higher than that of control concrete \[22\]. The early age increase is attributed to the filler effect of the fine ash particles, while at the later stages; the subsequent formation of C-S-H products improves the interfacial bonding between the pastes and the aggregates and thus increases the strength.

2.4 Corn cob ash

Over 500 million tons of corn is produced annually in the world. The United States is the largest producer of corn with 43%, followed by Africa with 7%. There is a significant opportunity to burn the waste parts of corn plant (cobs and stover) after harvest, and use the ash as a potential cement replacement. A review of the literature shows mixed results regarding the inclusion of corn cob ash (CCA) in concrete:

- CCA contains more than 65% reactive silica \[23\];
- Many researchers reported a significant reduction in the compressive strength as a result of replacing OPC with CCA \[24, 25\];
- Concrete incorporating CCA exhibits lower water absorption and shows better resistance to sulphate attack compared to the reference concrete \[26\];
- Authors outline mixed results regarding the influence of CCA on the fresh properties of concrete, as well. Some reported the reduced concrete slump with the addition of CCA, while others found that CCA increases the concrete slump;

The mixed results can be connected with a variety of factors, such as: the use of different watering regimens (irrigated vs. non-irrigated corn), type of fertilizer, and the species of corn, in addition to aforementioned indicators.

2.5 Wheat straw ash

Wheat is one of the primary sources of food. The current utilization of wheat straw is associated with energy source, pulp and paper, nano-materials, bioethanol, fertilizer, additive for mud houses. Considerable amounts of wheat straw ash (WSA), which has been investigated to a small extent as a potential pozzolanic material, are generated in the process of straw combustion. According to the literature results on the reactivity and possible WSA application in cementitious systems, following observations were noted:

- The chemical composition of WSA (obtained in Serbia) is characterized by high alkali content (20%) and significant amorphous silica content (52%) \[27\];
- Mechanical processing, such as grinding in lab ball mill, could significantly reduce the particle size, increase the level of fineness and amplify the amorphousness of WSA \[28\];
- WSA fulfills criteria for pozzolanic materials, including: activity index, setting time and soundness of powder fly ash materials, given in EN 450-1 \[29\];
- Optimum cement replacement level, determined by \[29\], was estimated at 15%, whereas the mortar containing 15% WSA has shown comparable strength to that of control mortar at 7 days, and even higher strength at ages of 28 and 91 days, respectively. Similar trend was registered by Dehane et al. \[30\]. At the age of 28 days, the strength of the mortar with 12.5% WSA exceeded the strength of the reference mortar, and this difference, due to the pozzolanic reaction, increased over time. This mortar was characterized by a smaller water absorption compared to the absorption of the OPC mortar at the age of 28 days (due to the filler effect of small WSA particles);
- Optimum cement replacement level with WSA in cement mortars is determined to be 30%, without any adverse effect on its mechanical properties \[9\].
2.6 Other biomass ashes

Few researchers have provided the information on far less utilized biomass ashes, such as: oyster shells ash [31], groundnut shells ash [32], bamboo leaf ash [33], sunflower stalk ash [34], sunflower husk ash [35], miscanthus ash [36], barley ash [37], olive husk ash [35], coconut shell ash [38], rape straw ash [39] and eucalyptus biomass ash [40].

The major factor for the valorization of biomass ashes lies in the fact that they contain high amounts of reactive silica, which makes them suitable as cement substitutes. Silica content of different types of biomass ashes, used as cement substitutes worldwide, as well as recommended replacement level, by authors, is given in Table 4.

3 Harvest residues ash - potential in APV, Serbia

The first step in preparing catalogue of available biomass ashes is to summarize collected information. In the region, which is involved in the research (Bačka, Srem and Mačva), within the realization of the project IPA Interreg ECO Build, cooperation was established with eleven companies that use harvest residues as an energy source for obtaining heat energy. A brief overview of the available types and quantities of generated biomass ashes in AP Vojvodina is presented in Table 5. Samples of biomass ashes were taken and basic data on generated ashes were collected, including:
- types of used biomass,
- combustion technology,
- achieved combustion temperatures in boiler furnace,
- generated quantities of biomass ash per year,
- disposal of biomass ash, as generated by-product.

Based on the gathered information, most of the harvest residues ashes produced are either disposed of in landfill or recycled on agricultural fields or forest, while the companies which combust biomass pay considerable price for the transportation and landfilling of these ashes.

### Table 4 - Silica content and recommended cement replacement level of various biomass ashes

| Ash Type                        | Silica Content (%) | Reference                      | Recommended Cement Replacement Level |
|---------------------------------|-------------------|--------------------------------|-------------------------------------|
| Rice husk ash (RHA)             | 80-95             | Siddika et al. [41]            | 30%                                 |
| Corn cob ash (CCA)              | 60-70             | Adesanya et al. [42]           | 10%                                 |
| Wheat straw ash (WSA)           | 50-70             | Šupić et al. [9]               | 30%                                 |
| Palm oil fuel ash (POFA)        | 55-80             | Thomas et al. [22]             | 20%                                 |
| Sugar cane straw ash (SCSA)     | 35                | Khalil. et al. [19]            | 20%                                 |
| Sunflower stalk ash (SSA)       | 25                | Aksog˘an O. et al. [43]        | 10%                                 |
| Bamboo leaf ash (BLA)           | 75-85             | Cociñaa E.V. et al. [44]       | 20%                                 |
| Groundnut shell ash (GSA)       | 40-50             | Alaneme K.K. et al. [45]       | 8%                                  |
| Oyster shell ash (OSA)          | 5                 | Gengying Li et al. [46]        | more research necessary            |
| Miscanthus ash (MA)             | 50-60             | Wigley F. et al. [47]          | more research necessary            |
| Barley husk ash (BHA)           | 70-80             | Khalil et al. [48]             | 20%                                 |
| Sunflower husk ash (SHA)        | 30-60             | Demirbas A. et al. [49]        | 15%                                 |
| Olive stone (pit) ash (OSA)     | 5                 | Font et al. [50]               | more research necessary            |
| Coconut shell ash (CSA)         | 65                | Opeyemi J. et al. [51]         | more research necessary            |
| Rape straw ash (RSA)            | 35                | Masiá T.A.A. et al. [52]       | more research necessary            |
| Eucalyptus biomass ash (EBA)    | 1-5               | Teixeira A.H.C. [53]           | more research necessary            |
Table 5 - Available quantities of biomass ashes in AP Vojvodina

| Company                        | Biomass type                          | Temperature of combustion | Types of biomass ashes                                      | Produced quantities of ash per year (tons) |
|--------------------------------|---------------------------------------|---------------------------|---------------------------------------------------------------|-------------------------------------------|
| Mitrosrem Sremska Mitrovica    | wheat straw soya straw 600-650°C      | 1. ash from boiler furnace | 2. ash from multiciklon 3. fly biomass ash                    | 15                                        |
| Soya Protein Bečej             | wheat straw soya straw 700-900°C      | 1. ash from boiler furnace | 2. ash from multiciklon 3. fly biomass ash                    | 1100                                      |
| The Veterinary Institute Subotica | agro pellets of wheat straw and soya straw 450-550°C | 1. ash from boiler furnace | 2. ash from multiciklon 3. fly biomass ash                    | 240                                       |
| Hipol Odžaci                   | agro pellets of soya straw 800-1000°C | 1. ash from boiler furnace | 2. ash from multiciklon 3. fly biomass ash                    | 700                                       |
| Victoria Starch Zrenjanin      | agro pellets of wheat straw and soya straw unknown | 1. ash from boiler furnace | 2. ash from multiciklon 3. fly biomass ash                    | 9                                         |
| Almex-IPOK Zrenjanin           | agro pellets of wheat straw and soya straw sunflower husk 700-900°C | 1. ash from boiler furnace | 2. ash from multiciklon 3. fly biomass ash                    | 1100                                      |
| KNOT-AUTOFLEX Bečej            | wheat straw soya straw unknown        | 1. ash from boiler furnace | 2. ash from multiciklon 3. fly biomass ash                    | 60                                        |
| Fishery Lovćenac               | soya straw unknown                    | 1. ash from boiler furnace | 2. ash from multiciklon 3. fly biomass ash                    | 9                                         |
| Victoria Oil Šid               | sunflower husk 700-1000°C             | 1. ash from boiler furnace | 2. ash from multiciklon 3. fly biomass ash                    | 720                                       |
| Sava Kovačević Vrbas           | cob corn 500°C                        | 1. ash from boiler furnace | 2. ash from multiciklon 3. fly biomass ash                    | 30                                        |
| PTK Panonija Mecker farm       | wheat straw soya straw 500°C          | 1. ash from boiler furnace | 2. ash from multiciklon 3. fly biomass ash                    | 60                                        |
| **Total**                      |                                       |                           |                                                               | ≈ 5.000 tons                              |
4 Properties and catalogue of harvest residues ashes in APV Vojvodina

4.1 Materials and Methods

4.1.1 Materials

**Cement**

Ordinary Portland cement (OPC), originating from Lafarge cement factory in Beočin, Serbia, was used. The cement has a specific gravity of 3.1 g/cm³ and the Blaine fineness of 4.000 cm²/g.

**Biomass ashes**

For experimental investigation of chemical and physical properties and pozzolanic activity of biomass ashes, the following materials were collected and tested:

- Wheat straw ash (WSA), “Mitrosrem” Sremska Mitrovica,
- Mixed wheat and soya straw ash (WSSA-1), „Soya-protein” Bečej,
- Mixed wheat and soya straw ash (WSSA-2), „IPOK” Zrenjanin,
- Soya straw ash (SSA), „HIPOL” Odžaci,
- Silo waste ash (SWA), „Soya-protein” Bečej,
- Oil rapeseed ash (ORA), „Knot-Autoflex” Bečej,
- Mixed wheat straw and sunflower husk ash (WSSHA), „Soya-protein” Bečej,
- Sunflower husk ash (SHA), „Victoria Oil” Šid.

The ashes were roughly sieved (apart from SHA), through a 4mm sieve, in order to separate un-burnt straw and other large impurities. In order to obtain a material with satisfactory specific surface area, ashes were further ground in a laboratory ball mill for 6h.

4.1.2 Methods

The chemical composition of collected ashes was determined using energy dispersive X-ray fluorescence spectrometer (EDXRF 2000 Oxford instruments) according to EN 196-2, 2015 and ISO 29581-2, 2010. The representative samples (100 g) were pulverized in a laboratory vibratory mill prior to the testing. The loss on ignition (LOI) was determined as a weight difference between 20 °C and 950 °C.

Specific surface area of biomass ashes was determined according to Blaine air permeability method given in EN 196-6, 2011, which is widely used for the fineness determination of hydraulic cement. The test is based on the principle of resistance to air flow through a partially compacted sample of powder material.

Soundness of biomass ashes was determined in accordance with EN 196-3, 2010. The method is used for assessing whether this physical property of a SCM material is in conformity with the requirements given in EN 450-1.

The pozzolanic activity was studied on samples prepared according to the procedure given in SRPS B.C1.018, 2015. Mortars were prepared with biomass ash, slaked lime and standard sand, with the following mass proportions: \( m_{\text{sl}}:m_{\text{bash}}:m_{\text{qs}}=1:2:9 \) and water – binder ratio 0.6 (where: \( m_{\text{sl}} \) – mass of slaked lime; \( m_{\text{bash}} \) – mass of biomass ash; \( m_{\text{qs}} \) – mass of CEN standard sand). After compacting, the samples were hermetically sealed and cured for 24 h at 20 °C, then for 5 days at 55 °C. Subsequently, 24h period was allowed for samples cooling process to reach 20 °C, followed by compressive and flexural strength tests.

The activity index of biomass ashes was examined according to EN 450-1, 2014. Activity index is defined as a ratio (in percent) of the compressive strength of mortar prepared with 75% test cement plus 25% ash by mass, and the compressive strength of standard cement mortar, when tested at the same age. The preparation of mortar test specimens and determination of the compressive strength were carried out in accordance with EN 196-1, 2018.

4.2 Chemical composition

The chemical compositions of OPC and selected biomass ashes are given in Table 6. Obtained chemical composition of pure WSA indicates the relatively high participation of major oxides \( \text{SiO}_2+\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3 (\approx70\%) \), as well as reactive silica (67%).

| Material | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | Na₂O | K₂O | SO₃ | P₂O₅ | LOI | SiO₂+ Al₂O₃+ Fe₂O₃ | Reactive SiO₂ |
|----------|------|-------|-------|-----|-----|------|-----|-----|------|-----|-----------------|---------------|
| Cement   | 21.25| 5.55  | 25.3  | 61.6| 2.37| 0.25 | 0.72| 3.75| -    | 1.77| 52.1            |               |
| WSA      | 69.13| 1.12  | 0.73  | 5.78| 2.50| 0.11 | 13.03| 0.20| 1.72 | 5.18| 70.98           | 67            |
| WSSA-1   | 56.36| 2.03  | 1.53  | 7.13| 3.54| 0.20 | 20.02| 0.18| 3.72 | 4.85| 59.92           | 41            |
| WSSA-2   | 54.01| 3.51  | 2.06  | 8.09| 3.22| 0.27 | 19.16| 0.38| 1.26 | 7.72| 59.58           | 44            |
| SSA      | 32.62| 4.58  | 1.46  | 15.78| 8.33| 0.85 | 20.96| 0.47| 3.72 | 10.73| 38.66           | 25            |
| SWA      | 43.66| 5.41  | 2.06  | 15.89| 5.05| 0.97 | 14.09| 0.76| 4.82 | 6.41| 51.13           | 25            |
| ORA      | 32.37| 6.32  | 2.45  | 14.00| 2.91| 0.89 | 17.85| 3.78| 1.44 | 17.61| 41.14           | 15            |
| WSSHA    | 44.12| 1.99  | 1.93  | 10.94| 4.91| 0.26 | 16.24| 0.45| 5.43 | 13.05| 48.04           | 35            |
| SHA      | 5.34 | 1.19  | 1.03  | 12.96| 9.94| 0.68 | 44.76| 9.71| -    | 12.64| 7.56            | 5             |
5 Catalogue of harvest residues ashes in APV Vojvodina

After biomass ashes preparation (sieving, grinding), along with determination of chemical composition test, the following testing were conducted for the purpose of catalogue creation:

- Specific gravity,
- Blaine fineness,
- Soundness,
- The pozzolanic activity,
- The activity index.

The obtained results of listed HRA properties are presented through the catalogue, given below.

Based on the results of an own experimental research [7-11,54-55], as well as the conclusions the other authors derived [43,49,52,56], a possible cement replacement level with tested types of HRA was estimated for their application in mortar and concrete. These values are also showed in the catalogue.

Considering the high amount of water-soluble potassium oxide in sunflower husk ash, this type of ash can be potentially utilized as the alkali solution for the activation of silica and alumina rich precursor and the production of alkali activated materials. However, more research regarding this assumption is inescapable.

5.1 Wheat straw ash: basic properties and possible application

| Ash origin          | Mitrosrem, Veliki Radinci               |
|---------------------|----------------------------------------|
| Basic data on the ash| Bottom ash, roughly sieved through a 4mm sieve |
| Available amount per year | 15 tons          |
| Reactive silica content | 67%            |
| Specific gravity    | 2380 kg/m³       |
| Blaine fineness     | 950 m²/kg        |
| Soundness           | satisfactory     |
| The pozzolanic activity | Class 10         |
| The activity index  | I₂₈=104%         |
|                     | I₉₀=108%         |
| Recommended cement replacement level in mortar | up to 50% (from the aspect of achieved mechanical properties of concrete) |
| Recommended cement replacement level in concrete | up to 50% (from the aspect of achieved mechanical properties of mortar) |
5.2 Mixed wheat and soya straw ash: basic properties and possible application

| Ash origin                      | Soja Protein, Bečej |
|---------------------------------|---------------------|
| **Basic data on the ash**       | Bottom ash, roughly sieved through a 4mm sieve |
| Available amount per year       | 300-1100 tons       |
| Reactive silica content         | 41%                 |
| Specific gravity                | 2370 kg/m³          |
| Blaine fineness                 | 1550 m²/kg          |
| Soundness                       | satisfactory        |
| **The pozzolanic activity**     | Class 5             |
| The activity index              | I₀₀=92%             |
| **Recommended cement replacement level in mortar** | up to 30% (from the aspect of achieved mechanical properties of concrete) |
| **Recommended cement replacement level in concrete** | up to 30% (from the aspect of achieved mechanical properties of mortar) |
5.3 Mixed wheat and soya straw ash: basic properties and possible application

| Ash origin               | IPOK, Zrenjanin |
|--------------------------|-----------------|
| Basic data on the ash    | Bottom ash, roughly sieved through a 4mm sieve |
| Available amount per year| 1100 tons       |
| Reactive silica content  | 44%             |
| Specific gravity         | 2380 kg/m³      |
| Blaine fineness          | 610 m²/kg       |
| Soundness                | satisfactory    |
| The pozzolanic activity  | Class 10        |
| The activity index       | $I_{28}=95\%$   |
|                         | $I_{90}=102\%$  |
| Recommended cement replacement level in mortar | up to 50% (from the aspect of achieved mechanical properties of concrete) |
| Recommended cement replacement level in concrete | up to 50% (from the aspect of achieved mechanical properties of mortar) |
5.4 Soya straw ash: basic properties and possible application

| Ash origin        | Hipol, Odžaci |
|-------------------|---------------|
| Basic data on the ash | Bottom ash, roughly sieved through a 4mm sieve |
| Available amount per year | 700 tons |
| Reactive silica content | 25% |
| Specific gravity | 2400 kg/m³ |
| Blaine fineness | 520 m²/kg |
| Soundness | satisfactory |
| The pozzolanic activity | Insufficient |
| The activity index | I₂₈=70%  
| | I₉₀=69% |
| Recommended cement replacement level in mortar | up to 10% (from the aspect of achieved mechanical properties of concrete) |
| Recommended cement replacement level in concrete | up to 10% (from the aspect of achieved mechanical properties of mortar) |
5.5 Silo waste ash: basic properties and possible application

| Ash origin            | Soja Protein, Bečej |
|-----------------------|---------------------|
| **Basic data on the ash** | Bottom ash, roughly sieved through a 4mm sieve |
| Available amount per year | 300-1100 tons |
| Reactive silica content | 25% |
| Specific gravity      | 2390 kg/m³ |
| Blaine fineness       | 1180 m²/kg |
| Soundness             | satisfactory |
| **The pozzolanic activity** | Class 5 |
| The activity index    | I₂₈=90%  
|                       | I₆₀=100% |
| **Recommended cement replacement level in mortar** | up to 30% (from the aspect of achieved mechanical properties of concrete) |
| **Recommended cement replacement level in concrete** | up to 30% (from the aspect of achieved mechanical properties of mortar) |
# Harvest residues ash as a pozzolanic additive for engineering applications: a review and the catalogue

## 5.6 Oil rapeseed ash: basic properties and possible application

**Oil rapeseed ash, before sieving and grinding**

**Oil rapeseed ash, after sieving and grinding**

| Ash origin            | Knot Autoflex, Bečaj                  |
|-----------------------|---------------------------------------|
| **Basic data on the ash** | Bottom ash, roughly sieved through a 4mm sieve |
| Available amount per year | 60 tons                               |
| Reactive silica content | 15%                                   |
| Specific gravity       | 2320 kg/m³                           |
| Blaine fineness        | 610 m²/kg                             |
| Soundness              | satisfactory                          |
| The pozzolanic activity | Insufficient                         |
| The activity index     | I₂₈=86%                               |
|                       | I₉₀=85%                               |
| Recommended cement replacement level in mortar | up to 30% (from the aspect of achieved mechanical properties of concrete) |
| Recommended cement replacement level in concrete | up to 30% (from the aspect of achieved mechanical properties of mortar) |
5.7 Mixed wheat straw and sunflower husk ash: basic properties and possible application

| Ash origin                  | Soja Protein, Bečej |
|-----------------------------|---------------------|
| Basic data on the ash       | Bottom ash, roughly sieved through a 4mm sieve |
| Available amount per year   | 300-1100 tons       |
| Reactive silica content     | 35%                 |
| Specific gravity            | 2185 kg/m³          |
| Blaine fineness             | 1065 m²/kg          |
| Soundness                   | satisfactory        |
| The pozzolanic activity     | Insufficient        |
| The activity index          | I₂₈=76%             |
|                             | I₉₀=83%             |
| Recommended cement replacement level in mortar | up to 30% (from the aspect of achieved mechanical properties of concrete) |
| Recommended cement replacement level in concrete | up to 30% (from the aspect of achieved mechanical properties of mortar) |
5.8 Sunflower husk ash: basic properties and possible application

![Sunflower husk ash](image)

**Sunflower husk ash** *(grinding processing was not necessary)*

| Ash origin     | Victoria Oil, Šid |
|----------------|-------------------|
| Basic data on the ash | Fly ash |
| Available amount per year | 720 tons |
| Reactive silica content | 5% |
| Specific gravity | 2200 kg/m³ |
| Blaine fineness | 610 m²/kg |
| Soundness | satisfactory |
| The pozzolanic activity | Insufficient |
| The activity index | $I_{28}=0$  
$I_{90}=0$ |
| Recommended cement replacement level in mortar | Not recommended as SCM |
| Recommended cement replacement level in concrete | Not recommended as SCM |

6 Conclusions and further research

The aim of this study was to collect and analyze the ashes originating from harvest residues combustion, locally available in Vojvodina. Novel and useful information on the characteristics of wheat straw, soya straw, sunflower husk, oil rapeseed and silo waste based ashes is presented through the catalogue, which is the first step in defining an environmentally friendly route for this type of waste, offering an opportunity for the creation of new sustainable cement-based composites, thereby. Experimental research of HRA as potentially building materials should result in guidelines relevant for their further use of as mineral/inert additives in cementitious systems. To achieve this goal, further investigations will include determination of HRA influence on basic properties of mortars, concretes and other composites. The results of such experimental research should verify the possibility to obtain biomass ash-based ECO composites with comparable or better physical and mechanical properties than those of the reference composites. As the catalogue demonstrated a high variability of HRA properties, other directions of the ashes application (construction of roads and embankments, alkali-activated materials, etc.) are also possible and up for research, depending on the type of the ash. These composites will be characterized by a lower consumption of cement, thus reducing the CO₂ emissions and meeting the principles of sustainable development.
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