

Article

Removal of Pollutants from Secondary Waste from an Incineration Plant: The Review of Methods

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Received: 15 October 2020; Accepted: 26 November 2020; Published: 30 November 2020

Abstract: In order to use secondary waste from an incineration plant, it is necessary to process or treat it. Valorization of municipal solid waste incineration bottom ash (MSWIBA) is a popular treatment method. Moreover, there are other possibilities, such as alkaline pre-treatment, which can be used for the rest of the secondary waste from incineration plants, especially hazardous fly ash. The purpose of this study is to show the problem of secondary waste in Poland in relation to the rest of Europe. Due to the physicochemical research of secondary waste, the possibilities of the procedure and its management are indicated. By analyzing the literature and the market, the latest possibilities for improving the physicochemical properties of secondary waste are proposed. Searching for new methods for waste management is essential to the environment. This manuscript presents the problem of the increasing amount of waste, as well as possibilities to close the loop, and minimize the negative impact on the environment. Additionally, the article shows that environmental benefits can be achieved by replacing raw material with secondary waste.

Keywords: secondary waste; concrete; valorization; bottom ash; LCA; waste management; municipal solid waste incineration plant; NaOH pre-treatment;

1. Introduction

In 2017, approximately 29.4 million Mg of municipal solid waste incineration bottom ash (MSWIBA) was produced in Europe, from 492 million tons of municipal solid waste. The biggest producer of MSWIBA in Europe was Germany, which created 8.04 million Mg. In Poland, 0.24 million tons of MSWIBA was produced in six incineration plants. Figure 1 depicts the number of incineration plants and the amount of MSWIBA across European countries.

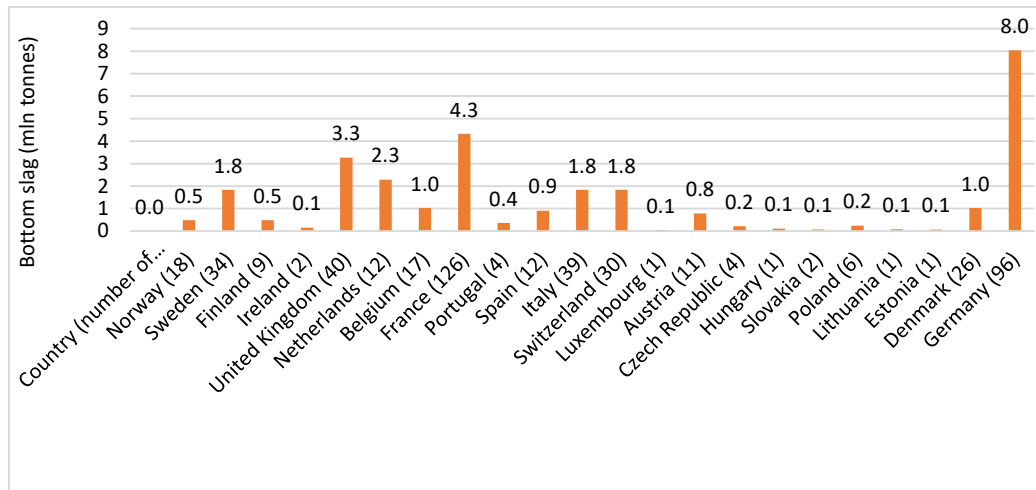


Figure 1. The number of incinerator plants and amount of bottom ash produced in Europe in 2017 [1].

If MSWIBA is subject to valorization, it can be used in the construction industry, e.g., during road building as an aggregate or concrete components. There are a few options for slag preparation: valorization, NaOH pre-treatment, Na_2CO_3 pre-treatment, CaOH_2 pre-treatment, as well as combinations of $\text{Na}_2\text{SiO}_3/\text{NaOH}$ pre-treatment [2–4].

MSWIBA in the construction industry is part of sustainable development and the circular economy. Concrete is exceptionally good for the environment, as it immobilizes contaminants and pollutants. Growing production and consumerism causes an increase in the amount of produced solid municipal waste, which then increases the amount of MSWIBA in Poland. In order to operate in line with the concept of a circular economy, it is a necessity to pre-recycle secondary waste. Figure 2 depicts the amount of municipal solid waste in Poland.

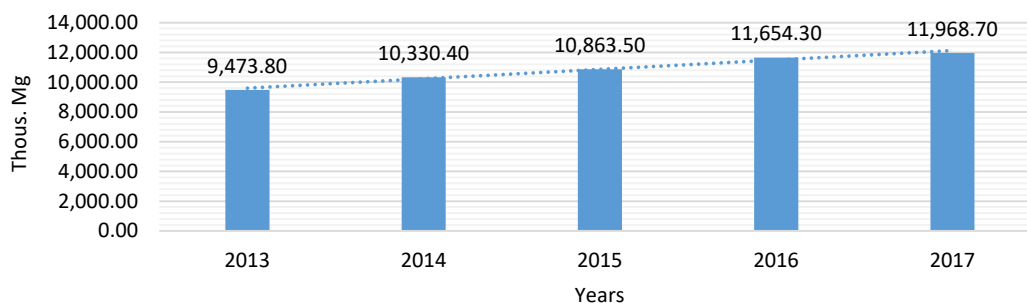


Figure 2. Amount of municipal solid waste in Poland [5–9].

1.1. Methods of Dealing with Secondary Waste

Immobilization of contaminants is necessary to obtain a product from secondary waste. First of all, secondary waste should be properly prepared, in order to change its parameters. The better the parameters, the greater the mechanical strength of the materials, lower absorbability, and better frost resistance. Different methods of valorization are used to achieve better parameters of ash [10,11]:

- Valorization, cementation;
- Bituminization;
- Vitrification;
- Alkali pre-treatment (NaOH, CaOH_2 , $\text{Na}_2\text{SiO}_3 + \text{NaOH}$, $\text{Na}_2\text{CO}_3 + \text{NaOH}$ pre-treatment);
- Solidification, stabilization;
- Other technologies (Synrock, Geodur).

The primary method of secondary waste management in the incineration plant is bottom ash valorization (Figure 3). The valorized slag can be used in construction. Applying appropriate treatment is essential in order to achieve better product, which could be used in the industry [12].

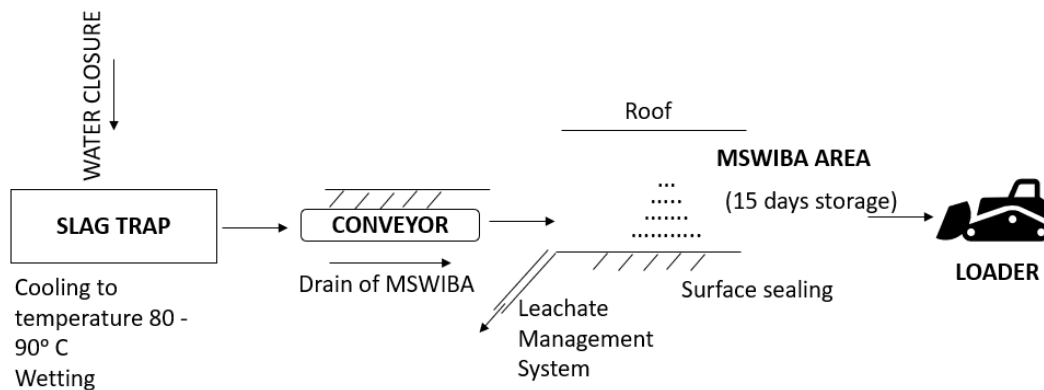


Figure 3. Municipal solid waste incineration bottom ash (MSWIBA) valorization plant [13].

1.2. Valorization Process

The slag trap is equipped with a water lock. The water is kept constant. This prevents false air from entering the chamber, as well as exhaust fumes and dust from the chamber leaking outside the system. MSWIBA is cooled to a temperature of 80°C–90 °C. Appropriate hydration prevents secondary dusting. MSWIBA is transported using a conveyor belt to the MSWIBA area, which has to be roofed, paved, sealed, and equipped with a leachate management system. MSWIBA should be stored for 15 days. Then, the loader transports it to the installation responsible for sorting and mechanical treatment of MSWIBA (Figure 4).

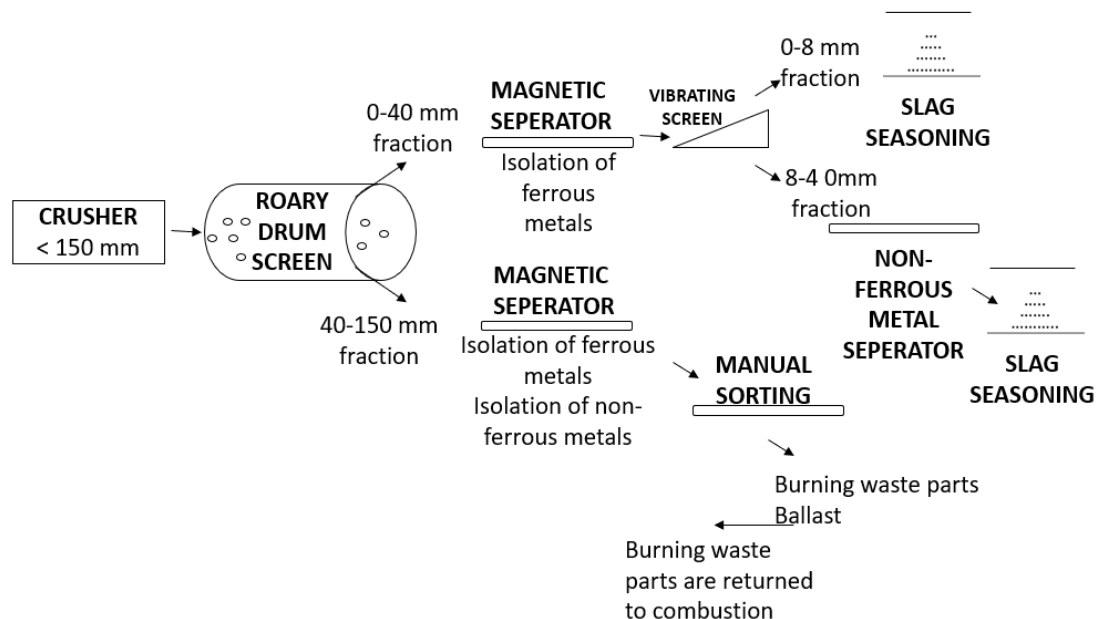


Figure 4. Installation responsible for sorting and mechanical treatment of MSWIBA [13].

MSWIBA is crushed on a <150 mm fraction; then, a rotary drum screen separates the 0–40 mm and 0–150 mm fraction. These fractions then reach the magnetic separators, where ferrous metals are isolated. The 0–40 mm fraction is directed to the vibrating screen, in which a separation into 0–8 mm and 8–40 mm fractions occur. Smaller fraction—without ferrous metals—is heaped into a pile. The 8–

40 mm fraction is directed towards a non-ferrous metal separator, and then it is also heaped into a pile. After isolating ferrous and non-ferrous metals from the 40–150 mm fraction, the MSWIBA is transported to manual sorting. Combustible waste is returned to the chamber.

The slag with 0–8 mm and 8–40 mm diameter is seasoned in order to achieve the right properties. This fraction mainly consists of non-combustible substances (silicates, as well as aluminum and iron oxides). The MSWIBA seasoning consists in penetration of moisture from the air into the slag, followed by the hydration processes. The seasoning process improves the MSWIBA properties and limits the leaching of heavy metals. After the valorization process, MSWIBA may be used in the construction industry [13].

1.3. NaOH pre-Treatment

NaOH pre-treatment can be used for different secondary waste, e.g., MSWIBA after slag valorization, hazardous fly ash, and granulated blast furnace slag. It improves physical and chemical properties, reduces leaching of pollutants and prepares the industrial byproduct.

To increase reactivity, one should grind a sample by using—for example—a grinder, crusher, roll crusher, hammer crusher, tumbling mill, cracker, ring mill machine, but it is not a necessity. On the other hand, it is much easier to remove pre-treatment liquid from the greater fraction, if there is a need.

Using NaOH pre-treatment reduces leaching of pollutants, such as, among others, heavy metals (As, Ba, Cr, Cu, Pb, Ni, Se, Zn) Al, and Al/Zn [4]. Due to the reduction of Al, the concrete does not swell. Reduction of heavy metals leaching allows to achieve the standard requirement, and has environmental benefits. Table 1 shows leaching of heavy metals from MSWIBA after NaOH pre-treatment. It also displays (by percentage) how much the leachability of the presented elements has decreased.

Table 1. Leaching of heavy metals from MSWIBA after NaOH pre-treatment.

	As	Ba	Cr	Cu	Pb	Ni	Se	Zn
2 weeks NaOH treatment	60.00%	92.23%	>99%	96.85%	>99%	70.98%	70.00%	98.52%
3 h NaOH treatment	50.00%	85.92%	>99%	94.49%	>99%	45.08%	72.50%	94.39%

The quality of pre-treatment affects the molar concentration, length of time (from hours to weeks), temperature, ratio, sample fraction, and chemical composition. The longer the treatment, the higher temperature, and higher ratio, the better the effects [4].

2. Materials and Methods

The research part covered municipal solid waste incineration bottom ash after valorization (MSWIBABV) and municipal solid waste incineration bottom ash after valorization (MSWIBAAV) analysis. Table 2 shows the standards and norms, according to which the tests were carried out. The study included physicochemical analysis of MSWIBABV and MSWIBAAV, leaching of MSWIBAAV and MSWIBAAV impurities, as well as qualitative examination of cement beams. Samples for unification were taken from various parts of the storage.

The leaching from waste was prepared for analysis and assessment of the degree of environmental nuisance. The water extract was made in a 1:10 proportion of waste to distilled water, shaken for 24 h, and then filtered.

Table 2. Standards, according to which tests were carried out [14–34].

Norms	Type of Norms	Designation
PN-Z-15008-02:1993	Determination of moisture content.	Determination of moisture content
PN-EN 1097-3:2000	Determination of bulk density and voids.	Determination of bulk density
PN-EN 15169:2011	Characterization of waste. Determination of the loss due to roasting of waste and sludge.	Determination of loss on ignition (LOI)
PN-EN 15935:2013-02	Glass in construction; glazing with structural sealant; Part 2: Installation rules.	Determination of loss on ignition (LOI)
PN-Z-15011-3:2001	Determination of total organic carbon.	Determination of total organic carbon (TOC)
PN-EN ISO 6878:2006	Water quality. Determination of phosphorus. Ammonium molybdate Spectrometric method.	Determination of phosphorus (P)
PN-ISO 334:1997	Determination of Sulfur with the Eschka method.	Determination of sulfur (S)
PN-ISO 587:2000	Solid fuels. Determination of chloride using the Eschka mixture.	Determination of chlorine (Cl)
PN-G-04523:1992	Solid fuels. Determination of nitrogen content by the Kjeldahl method.	Determination of nitrogen (N)
PN-EN 12457-4:2006	Characterization of waste-leaching-compliance test for leaching of granular waste material and sludge. Part 4: One Stage Batch Test at a Liquid to Solid Ratio of 10 l/kg for Materials with Particle Size below 10 mm (without or with Size Reduction).	Leachability
PN-EN ISO 10523:2012	Water quality; determination of pH.	Determination of pH
PN-ISO 994-3:1994	Determination of sodium (Na), calcium (Ca), potassium (K), lithium (Li), barium (Ba) by flame photometry.	Determination of sodium (Na), calcium (Ca), potassium (K), lithium (Li), barium (Ba)
PN-ISO 6059:1999	Water quality. Determination of total calcium and magnesium content (general hardness). Titration method with EDTA.	Determination of calcium (Ca)
PN-EN ISO 9963-1:2001	Water quality; determination of basicity part 1: determination of general basicity and alkalinity towards phenolphthalein.	Determination of general alkalinity
PN-ISO 9297:1994	Water quality. Determination of chloride ion concentration by titration (Mohr's Method).	Determination of chloride (Cl)

PN-ISO 9280:2002	Water quality. Determination of sulfate– Gravimetric method using barium chloride.	Determination of sulfates (VI)
PN-EN 450- 1:2012	Fly ash for concrete. Part 1: Definitions, specifications and compliance criteria.	Determination of secondary waste category in terms of LOI and force
PN EN 196-1	Cement testing methods. Part 1: Determination of strength.	Determination of strength
PN-EN 12620:2004	Aggregates for concrete.	Requirements for aggregates

The LCA (Life cycle assessment) method, which can be used in order to analyze the environmental results of the work, is based on analysis from cradle-to-grave. In order to compare the environmental impact of using the sub-products in concrete production, the LCA analysis was conducted in the fossil depletion and climate change impact categories, as a representative of the problem for resource depletion and the main environmental problem linked with this topic. The methodology has 18 different impact categories, but those two are the most important in the area of cement production. The analysis was conducted using SimaPro Analyst 9.0 software and ReCiPe midpoint (H) methodology, which is one of the most popular in this type of analysis presented by independent software: <https://www.ipoint-systems.com/blog/lcia-indicator/>. The Ecoinvent 3.0 database was used, while the data taken refers to an average impact of 1 kg of production of different types of cement. The analysis includes production of cement from raw materials and/or additional components, taking into account all processes of production, extraction, and transportation to the final consumer. The analysis does not include the final disposal, because concrete is a specific type of waste. It is too complicated to correctly assess the disposal of ingredients of concrete in our scenario. The analysis is focused on the positive impact of managing the waste from thermal treatment in the incineration plant.

Figure 5 depicts secondary waste from an incineration plant. From 1000 kg of burning waste, approximately 300 kg of slag is produced in the incinerator plant. Figure 5a depicts MSWIBABV and Figure 5b depicts MSWIBAAV. Slag valorization is carried out on the incinerator premises.

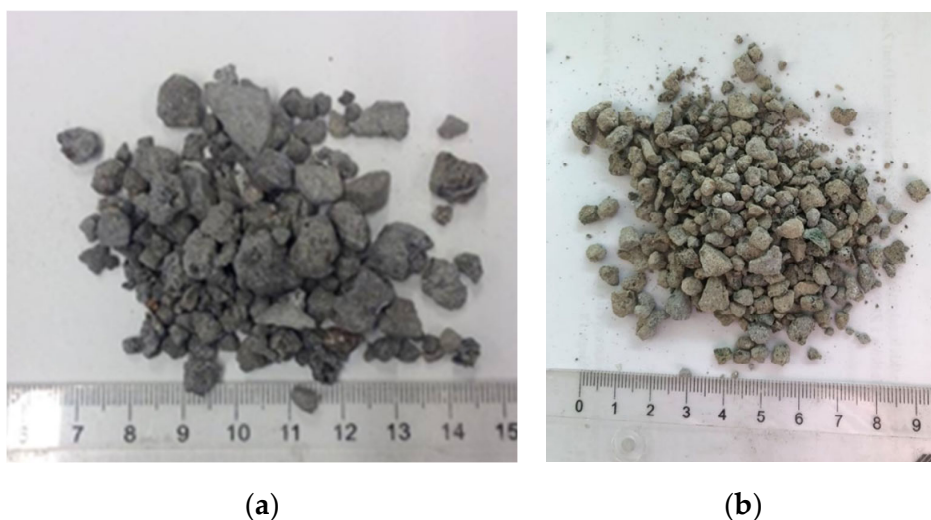


Figure 5. Secondary waste from an incineration plant: (a) municipal solid waste incineration bottom ash after valorization (MSWIBABV); (b) municipal solid waste incineration bottom ash after valorization (MSWIBAAV).

MSWIBABV and MSWIBAAV were collected from the same Polish incinerator plant. MSWIBABV has 0–10 mm fraction. MSWIBAAV has 0–8 fraction. MSWIBABV contains inclusions and impurities: glass, porcelain, ferrous, and non-ferrous metals. MSWIBAAV contains less water, ferrous, and non-ferrous metals, but still contains glass and porcelain. MSWIBABV is divided into different fractions after the valorization process, which depends on the recipient. The 0–8 mm MSWIBAAV fraction is one of the few produced at the Polish incineration plant. Both wastes are odorless, do not dust, and are not hazardous waste.

3. Results

In both slags, physicochemical properties were studied. Table 3 shows moisture (M), Decomposable Organic Substance (DOS), Undecomposable Organic Substance (UOS), and Mineral Substance (MS), crucial for concrete mixture and bulk density (ρ), which, in turn, is important for transport and storage.

Table 3. Physicochemical properties of bottom slags [14–16].

Parameter	Symbol	Unit	MSWIBABV	MSWIBAAV
Moisture	M	%	4.18	8.65
Bulk density	ρ	kg/m ³	1109.28	1077.33
Decomposable Organic Substance	DOS	%	1.37	1.39
Undecomposable Organic Substance	UOS	%	3.68	1.05
Mineral Substance	MS	%	94.96	97.55

Both slags are characterized by high humidity, which negatively affects pozzolana activity. Usually, the humidity should be in the range of 1–3%; therefore, the slag should be dried before it is used in the concrete or cement mix [16]. Table 4 depicts the contents of macroelements in slags. It is important to study the secondary waste before using it in concrete, as chemical changes may occur in the concrete at the molecular level.

Table 4. Macroelements in slags [18–23].

Parameter	Symbol	Unit	MSWIBABV	MSWIBAAV
Total Organic Carbon	TOC	%	0.64	0.65
Nitrogen	N	%	0.31	0.26
Orthophosphate (V)	P ₂ O ₅	%	1.06	1.05
Phosphorus	P	%	0.46	0.45
Sodium	Na	%	0.59	0.57
Potassium	K	%	0.24	0.27
Lithium	Li	%	0.007	0.008
Calcium	Ca	%	1.39	1.45
Barium	Ba	%	0.18	0.23
Sulphur	S	%	0.48	0.20
Chlorine	Cl	%	0.41	0.12

Both slags are characterized by a low TOC content (MSWIBABV 0.64% and MSWIBAAV 0.65%), which leads to less water demand, better frost resistance of mortar and concrete, as well as a lighter color of the mixture.

The low sulfur content in MSWIBAAV (0.20%) does not affect the formation of sulfate corrosion, the formation of ettringite in the free spaces of concrete and swelling. The chlorine content is also low (MSWIBABV 0.41% and MSWIBAAV 0.12%), which means that the reinforcements are not exposed to corrosion and the concrete is not cracked [24]. In terms of pH, both slags are alkaline, which means they can be used in concrete, as low pH would cause reinforcement corrosion.

Table 5 shows the leachability of pH, which should be alkaline for use in concrete and other selected contaminants.

Table 5. Leachability of selected contaminants.—Properties of the water extract of municipal solid waste incineration bottom ash before valorization (MSWIBABV) and after valorization (MSWIBAABV) [25–27].

Parameter	Symbol	Unit	MSWIBABV	MSWIBAABV
pH	pH	-	9.59	8.29
Total hardness	Th	mg/dm ³	230.21	205.18
General alkalinity	Ga	mg/dm ³	4.50	4.50
Mineral alkalinity	Ma	mg/dm ³	none	none
General acidity	Ga	mg/dm ³	0.50	0.50
Mineral acidity	Ma	mg/dm ³	none	none

Table 6 depicts the leachability of selected macroelements of MSWIBABV and MSWIBAABV. Studies of leachability from waste are particularly important for the environment. Norms and standards are defined by law.

Table 6. Leachability of selected macroelements of bottom slags [28,29].

Parameter	Symbol	Unit	MSWIBABV	MSWIBAABV	Limit Value ¹	Limit Value ²
Chlorides	Cl-	g/dm ³	0.35	0.35	-	-
	Cl-	mg/dm ³	350.00	345.60	1000.00	800.00
Sulfates	SO4-	mg/dm ³	130.00	110.00	500.00	1000.00
Phosphate trianion	PO4	mg/dm ³	7.1	6.9	-	-
Phosphorus	P	mg/dm ³	2.26	2.25	3.00	-
Sodium	Na	mg/dm ³	199.51	198.80	800.00	-
Potassium	K	mg/dm ³	58.29	60.60	80.00	-
Lithium	Li	mg/dm ³	0.18	0.20	-	-
Calcium	Ca	mg/dm ³	101.04	103.60	-	-
Barium	Ba	mg/dm ³	33.8	19.29	2.00	20.00
The sum of chlorides and sulfates	TDS	mg/dm ³	490.00	455.60	-	-

¹ Regulation of the Minister of Environment of 18 July, 2014, on the conditions to be met when discharging sewage into water or soil, and on substances particularly harmful to the aquatic environment (*Journal of Law*, item 1800) [30]; ² Regulation of the Minister of Economy of 16 July, 2015, on allowing waste to be stored in landfills (*Journal of Law*, item 1277) [31].

The parameters of leachability specified by the regulations relate to chlorides, sulfates, phosphorus, sodium, potassium, and barium. Only barium is surpassed in both slags. After using the slag in the concrete mix, it is necessary to check the leachability of this element from the concrete. The barium will likely be immobilized; however, this is a necessity to make sure leachability is within normal limits.

Figure 6 depicts loss on ignition (LOI) in 600 °C, 815 °C, and 950 °C in MSWIBABV and MSWIBAABV.

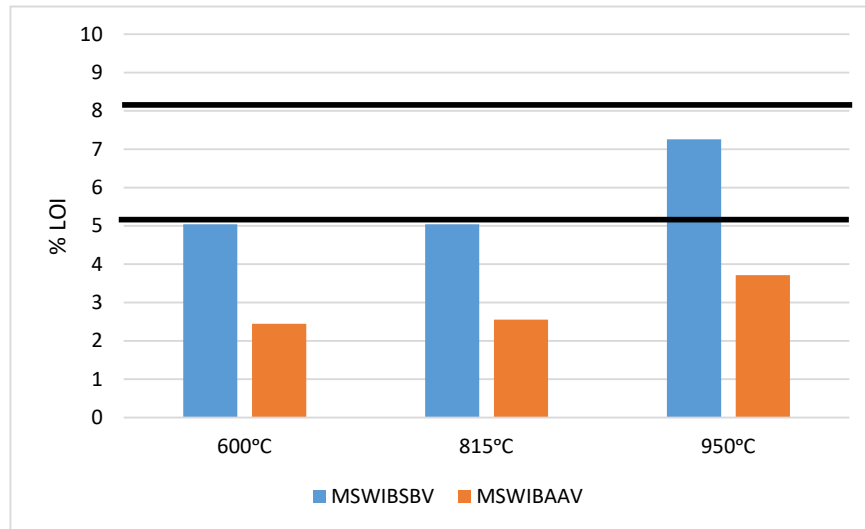


Figure 6. Loss on ignition (LOI) in 600 °C, 815 °C, and 950 °C [15].

In Figure 6, the 5% limit value for waste in Category A was marked. In terms of LOI, MSWIBABV cannot be used in Category A concrete, because the LOI at 950 °C is 7.26%, but MSWIBAABV can be used in Category A (Table 7). Both slags can be landfilled, because the value does not exceed 8% at 600 °C.

Table 7 presents the use of waste in three categories of concrete. MSWIBAABV can be used in Category A, while MSWIBABV can be used in Category C.

Table 7. Requirements for the chemical composition of the waste [32].

Parameter	The Content of the Ingredient (%)
Category A	≤5.0
LOI Category B	≤7.0
Category C	≤9.0

Heavy metals are some of the most dangerous pollutants for the environment. They occur in large quantities in secondary waste, but mainly in fly ash. MSWIBAABV is waste that can be used as a raw material in construction, because environmental standards are met. Table 8 shows the amount of heavy metals in MSWIBABV and MSWIBAABV.

Table 8. Heavy metals in MSWIBABV and MSWIBAABV.

Parameter	Symbol	Unit	MSWIBABV	MSWIBAABV
Manganese	Mn	ppm	1178.35	403.04
Cadmium	Cd	ppm	LOQ *	LOQ *
Nickel	Ni	ppm	45.99	10.41
Lead	Pb	ppm	379.50	176.47
Cobalt	Co	ppm	13.58	6.18
Chrome	Cr	ppm	1618.31	49.32
Copper	Cu	ppm	1192.1	2484.10

* LOQ—The limit of quantification.

Table 9 shows strength tests of 30% slag and CEM I 42.5 R and 30% slag and CEM I 42.5 SR. There was no swelling, cracking, or rupture occurring in the tested slags. However, this is not the rule, as the content of swelling compounds (e.g., Al, sulfides) is related to the properties of the waste being processed. Flexural and compressive strengths of mortar are comparable and similar. The 42 mm mortar beam has a strength of 2.75 MPa. The 44 mm mortar beam has a strength of 2.63 MPa.

Slightly more compressive strength has a 42 mm mortar beam (70.86 MPa), in comparison to a 44 mm mortar beam (69.94 MPa), which is adequate to the strength of mortar.

Table 9. Strength tests—slag accounts for 30% by weight of cement [33].

Type of Cement in Mortar	Height of Mortar Beam (mm)	28 Days Flexural Strength of Mortar (MPa)	28 Days Compressive Strength of Mortar (MPa)
30% slag and CEM I 42.5 R	44	2.629	69.94
30% slag and CEM I 42.5 SR	42	2.750	70.86

The physical and chemical properties of this aggregate (slag) should fulfil the following requirements:

- Grain content below 0.125 mm to 10% by weight;
- Content of foreign impurities up to 1% by weight;
- Content of SO₃ sulfur compounds up to 2%;
- LOI must not exceed 6%, if the slag is used only as aggregate for concrete, and 12% if it is used as a component of a fine mixture with other aggregate.

Concrete made of slag with unknown properties (or those that do not meet standard conditions) may undergo unfavorable processes. The content of sulfur, aluminum, burnt coal, slag age, or LOI compounds greater than the permissible values may cause swelling of concrete, but that is not a rule. Older slag causes less swelling in the concrete.

A negative characteristic of slag concrete is its high bulk density with low compressive strength, slow drying, and high humidity, which adversely affects the thermal conductivity. The low quality of slag concrete leads to its limited range of use. It should not be used for reinforced concrete or concretes exposed to permanent moisture above 75%.

According to PN-60/B-23011, the acceptable coal content in the slag found by roasting is up to 30%; however, for reinforced concrete, it is recommended to use aggregate with a carbon content below 5%.

Soluble sulfur salts are a very harmful admixture of slag. They react with cement components and form compounds that increase in volume and, thereby, break down concrete [34]. The most harmful of these compounds are highly hydrated calcium sulfate-aluminate-3CaO • A1₂O₃ • 3CaSO₄ (30–31) H₂O. Moreover, sulfur compounds, in particular hydrogen sulfide formed from them, promote the development of fungi in wooden elements, if they are in direct contact with slag concrete. The sulfur content of the slag also affects the rusting of steel parts placed in slag concrete. Therefore, these parts should be previously protected against corrosion.

Calcium oxide in slag up to 8% is harmless, if it occurs in the form of fine grains smaller than 2 mm, evenly distributed in the slag mass, and easily quenched with water. Slag cannot be used when containing more than 8% calcium oxide, when it is in a form of coarse grains, has uneven fraction or over-burnt lime, which is hard to stuff out.

Ash and dust in lightweight concrete are undesirable, because they increase the volumetric weight of concrete, and also contain the most sulfur admixtures. There is the possibility to get rid of them by sifting slag through a 0.5 mm sieve, or by shoveling the slag in a strong wind that blows away the ash (which is less accurate) [35–38].

4. Environmental Analysis

The important aspect of the implementation of Circular Economy (CE) assumptions is a plan for reduction of MSWIBA weight deposited at landfills and increase of the share of waste, which can be returned or reused in the system [39–41]. This is a huge challenge—doing it without any cost for the environment. Some methods, which can be used for those purposes, are identified in the manuscript.

However, before each implementation, the method should be tested and analyzed, in terms of the environment. In order to assess the impact, the comparison between the current stage and new model should be made. The best approach to assess the real impact is the LCA analysis, but it requires a lot of data and specific information. The most important facts can help in order to realize the general direction.

Basically, the environmental analysis can help to identify, in full life cycle, the real impact on the environment. Those tools are also important in comparing different scenarios of the production, use, or disposal phase [41,42]. Thanks to the environmental approach, one can assess the real impact and choose the best possible scenario. The circular economy strives to develop waste management in the most efficient way, from reuse and recycle, and finally to landfill. However, each case needs to be analyzed separately, because, during the recycling and treatment, the environmental cost is also present [43–45].

Regarding the treatment of MSWIBA, an assessment of three scenarios can be conducted. The first scenario states that the MSWIBA, after necessary treatment, is directed to the landfill. The second scenario consists of using valorized MSWIBAAV as a replacement of raw material in concrete production. The third scenario shows the potential of using the more advance methods of treatment, in order to achieve better product at the end of the life. Figure 7 shows the scenarios, which have positive and negative impact on the environment.

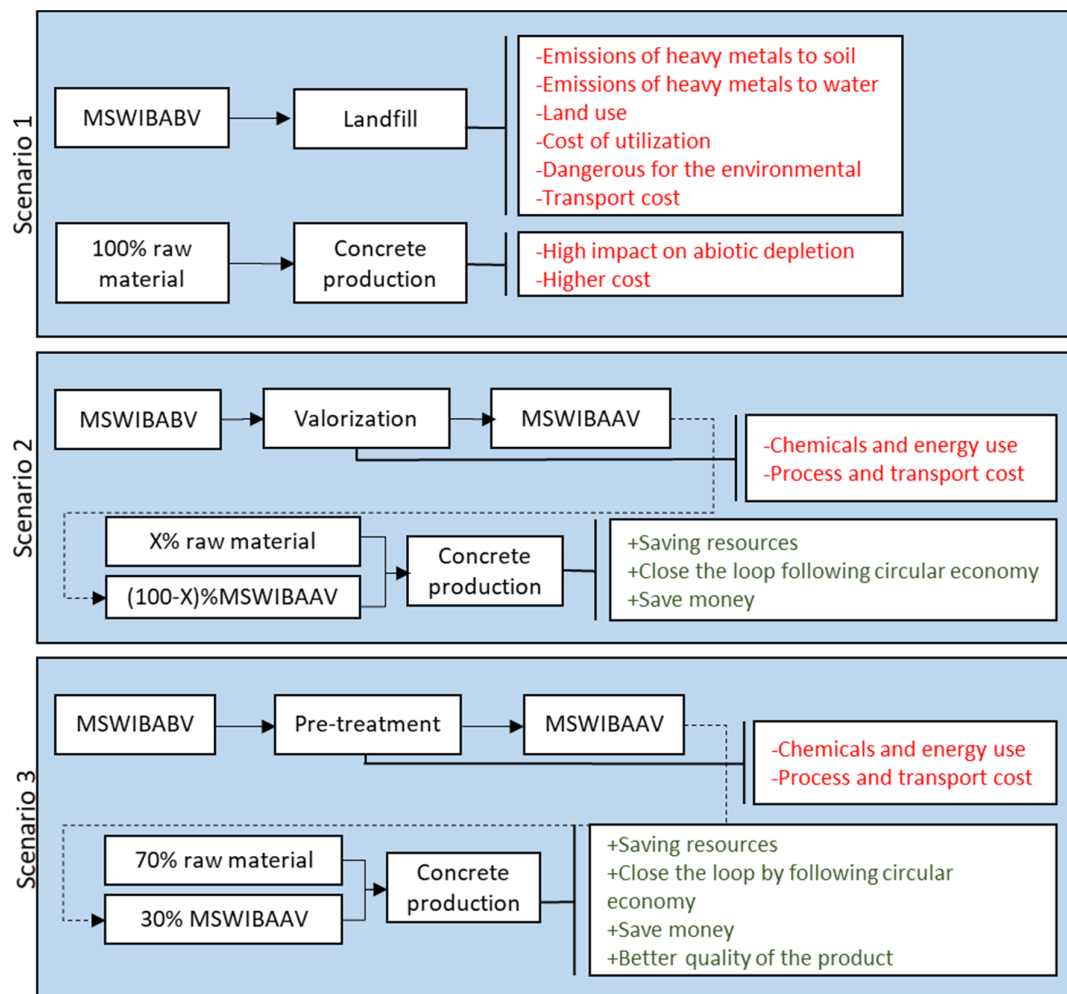


Figure 7. Positive and negative effects of different types of utilization MSWIBA.

The sub-product, which can be replaced in concrete production, is cement, which can be created from the raw material, fly ash, or slag as a supplement. The results are presented in the unit of oil equivalent per 1 kg of product and CO₂ equivalent per 1 kg of product, in Figure 8.

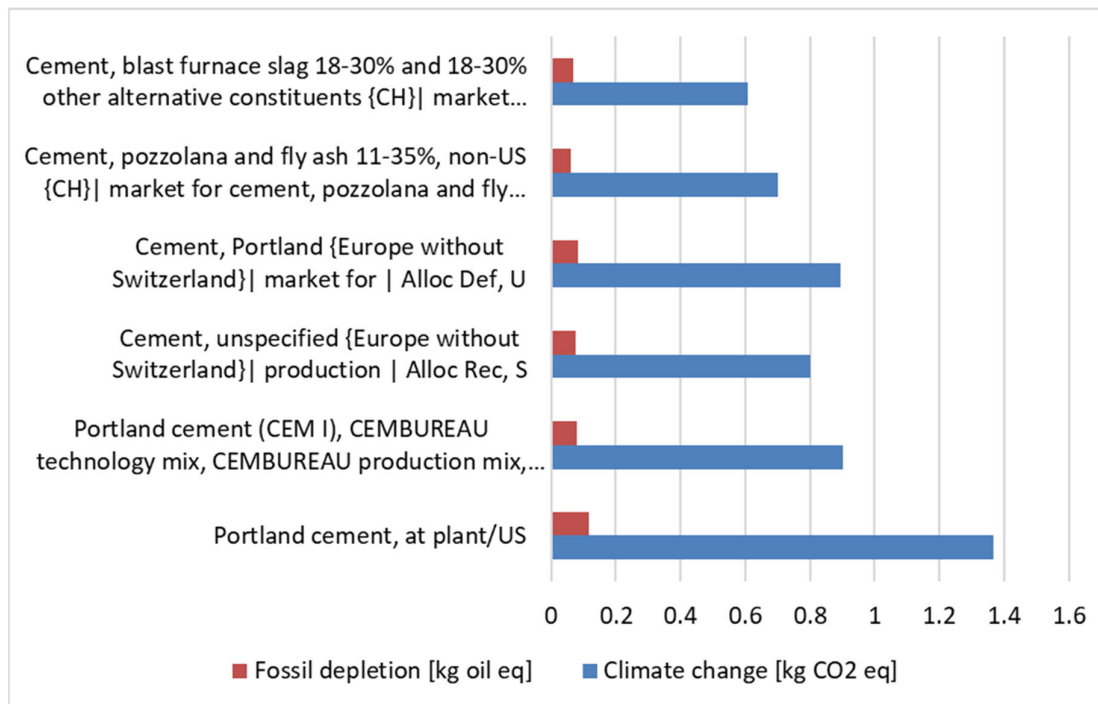


Figure 8. LCA results of different types of cement production.

When analyzing a particular result, it can be observed that, in the fossil depletion category, the cement from raw material production has the biggest impact on the environment in each case—CEM I, Portland cement, and unspecified—average in EU (Europe). This is related to the depletion of the raw material in relation to the total reserves that are available and using fossil fuels in order to extract the product. By using secondary waste, which has the smallest impact on the environment, this valuable raw material can be saved, while additionally utilizing waste that is difficult to manage (cement with slag and ash). The only downside is that this waste must be prepared and processed before use (like in any process, chemicals and energy are used). However, when considering the overall environmental impact, especially the emissions to water and soil avoided during possible landfill, the process has a lower environmental impact in the fossil depletion category than the use of raw material in cement production. The same result can be observed in the case of the climate change category. The biggest impact can be seen in case of cement production from raw sources. The results for cement production using fly ash or slag are lower than basic ones. It is also linked to the process of production and utilization of fly ash as a secondary waste.

The result shows the basic advantages of the analyzing method of MSWIBA utilization and points the potential link with environmental benefits. Additionally, the concept is strongly associated with the principles of a circular economy, and can help in achieving the final assumptions for difficult secondary type waste, such as MSWIBA. In order to see a full picture, the LCA should be conducted based on real data on real examples [46].

5. Discussion

The variability of physicochemical composition of slag is the critical factor of slag as a potential component of mortar and concrete. Seasons also have a direct impact, which means that the slag has a different composition in different seasons. Waste collection also affects the quality of secondary

waste. A changeable stream of municipal waste can cause different quality of slag, which means that the recipient is forced to conduct ongoing analyses and recognize changes in concrete mixes.

Slag from an incineration plant does not have radioactive isotopes, because municipal waste is checked at the entrance gate, equipped with a radioactivity sensor, so there is no need to check it. Slag meeting the PN-EN 12620: 2004 standard may become valuable raw material and an alternative to aggregates [47,48]. Slag placed in the concrete mix delays the setting of the structure. Initial compressive strength is low, but after 28 days, ternary concrete containing 20–25% slag and 3–5% silica dust exceeds the strength of the control test. The compressive strength of the concrete mix is optimal when combining dust and slag. The combination of this secondary waste also affects the increased immobilization of pollution. Concrete with slag composition (instead of a smaller fraction component, e.g., cement) has a higher porosity and, hence, less thermal conductivity; however, the concrete matrix structure can be compacted by adding fly dust from the incineration plant. Due to the consolidation of various wastes, a synergy effect occurs [49–53].

When neutralizing secondary waste from combustion, the phenomenon of solidification and stabilization is also used in the case of stabilization, while the chemical nature of the element changes. As a result of sorption, substitution, and precipitation, the pollution changes to an insoluble form, preventing leaching into the environment. Solidification makes it possible to change physical characteristics by obtaining waste materials with a relatively low liquid phase content. Efficiency of the solidification/stabilization process is described by matrix permanency and leaching of heavy metals. The precise indication of solidifying composite is complicated, because s/s is described by many different parameters, among others, strength, water absorption, water penetration depth, and porosity [54,55].

Comparing the interdisciplinary literature, it is stated that the technology of recycling secondary waste should be developed. Valorization mainly concerns slag, which can be used in some branches of the construction industry. The next (e.g., in the case of slag) or the only one (e.g., in the case of fly ash) step is NaOH pre-treatment. Literature sources indicate that, depending on the temperature, time, and concentration of the NaOH [53], the properties of the waste can be improved, e.g., immobilization of heavy metals [4], strength of the produced building material, with the addition of activated waste [3].

6. Conclusions

Research on the alkaline activation of copper slag shows that, as a result of chemical reactions between ground copper slag and the alkaline activator (NaOH or sodium water glass), the following are formed:

- Low-basic hydrosilicates of the C-S-H type;
- Hydrated low-basic aluminates and aluminosilicates of the hydrogranate type;
- Calcite;
- Magnesium hydrosilicates;
- Mixed sodium-potassium compounds;
- Alkaline hydrated aluminosilicates of the hydronefeline, analcime, and natrolite type.

The resulting products are different from products in traditional cement. Choosing the right type and amount of activator is a complex task and depends mainly on the chemical composition and specific surface of the slag. Along with the decreasing CaO content, the content of C-S-H and C-A-H phases, formed as a result of hydration, decreases, and the content of zeolite-like phases increases [56–58].

The basis of waste management is the minimization of their generation (according to Directive 2008/98/EC on waste). Despite adhering to the waste management hierarchy and the recommendations of a circular economy, there will always be a waste stream that cannot be recycled. That is why it is important to look for new and more effective solutions. Waste management processes should follow best available technology (BAT).

Alkaline pre-treatment gives a chance in the management of secondary waste. Alkaline pre-treated waste should always be tested, because of the heterogeneity of the composition. Improving

secondary waste quality is in line with the principles of sustainable development and a circular economy [59–61].

The use of municipal solid waste incineration bottom ash saves raw material in the production of concrete and, thus, has a positive effect on the environment, especially in the abiotic depletion category. In addition, it has a positive impact, because we do not store it in a landfill, which does not fit into a circular economy. According to the idea of a circular economy, secondary waste is the biggest problem, because, almost always, it cannot be directly reused or recycled. The proposed form of municipal solid waste incineration bottom ash management gives this waste a second life, and minimizes its negative impact on the environment.

Author Contributions: Conceptualization, N.P., B.Ł.-P., M.B. and K.P.; methodology, N.P., B.Ł.-P., and M.B.; software, M.B.; validation, K.P., B.Ł.-P., and M.B.; formal analysis, N.P., B.Ł.-P., and M.B.; investigation, B.Ł.-P., M.B., and N.P.; resources, K.P.; data curation, M.B., B.Ł.-P., and N.P.; writing—original draft preparation, N.P., M.B.; writing—review and editing, B.Ł.-P. and K.P.; visualization, N.P. and M.B.; supervision, K.P. and B.Ł.-P.; project administration, K.P., B.Ł.-P., M.B., and N.P.; funding acquisition, K.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by subsidies granted for the year 2020 to the Department of Technology and Installations for Waste Management, Silesian University of Technology.

Conflicts of Interest: The authors declare no conflict of interest.

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