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MSWIBA Formation and Geopolymerisation to Meet the United Nations Sustainable Development Goals (SDGs) and Climate Mitigation

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Abstract: Sustainable Development Goals (SDGs) constitute an action plan for the environment and people. One of the main goals is to limit the increase in global average temperature to 2 °C and aim for a stop at 1.5 °C. The goals of the circular economy (CE) are in line with the SDGs. In the waste management chain, the last CE element is a recovery in the municipal solid waste incineration plant (MSWIP). However, during recovery, municipal solid waste bottom ash (MSWIBA) is created (in about 30% of the bunch). The development of MSWIBA in the construction industry is a possibility of closing the cycle. This article shows the MSWIBA formation process, alkali pre-treatment of MSWIBA, and its geopolymerisation. Studies have determined the mechanical properties of geopolymer with MSWIBA and leachability from crushed and from monolith geopolymer. Alkali pre-treatment improves MSWIBA mechanical properties and upgrades immobilisation. Moreover, geopolymerisation is a better solution than concreting, because of the lack or low consumption of high-emission and energy-intensive cement. A SWOT analysis was carried out for the proposed solution.

Keywords: municipal solid waste incineration bottom ash; sustainable development goals (SDGs); circular economy; NaOH alkali pre-treatment; geopolymer; environment; IBA; MSWIBA

1. Introduction

A growing population, consumption, and expanding cities have direct impacts on environmental pollution [1]. Stable economic development lasted until the contractual year 1850, when the industrial revolution occurred. Since then, the anthropogenic pollution of the environment has gradually been increasing. According to the United Nations (UN), this translates into climate change, which includes:

1. An increase in average global temperature: In 1995–2006, this amount was 0.75 °C, which is higher than in 1901–2000, during which it was 0.6 °C. According to the United Nations Framework Convention, the limit value is an increase in the global average temperature of 2 °C compared with pre-industrial levels (while the Paris Agreement aims to limit the temperature increase to 1.5 °C). This is a limit value that helps to avoid exceeding the critical point of the Earth's climate system [2].
2. Rising ocean levels: This condition correlates with an increase in the global average temperature. The global average sea level has risen by about 1.8 mm per year since 1961. The reason is melting glaciers, ice caps, and polar ice sheets.

3. Ocean acidification: The emitted CO_2 reacts with the water to form carbonic acid, leading to acidification. Water acidification affects marine biodiversity (e.g., mussels, corals, oysters) through the lower availability of calcium carbonate, which is a building material of shells and skeletal materials [3].
4. Rising ocean temperature is changing marine biodiversity and modifying water currents, which are washing away glaciers. Melting glaciers are causing sea levels to rise, and this is affecting coastlines and the possibility of complete flooding of some areas where people live. The flooding of areas and the escape of people from areas of excessive heat (which may occur in the future) could exacerbate the migration crisis.
5. The breakdown of the cryosphere is related to the methane gun hypothesis. This hypothesis assumes that an increase in water temperature may trigger the release of methane from methane clathrate deposits, which are found in the seabed and permafrost. Methane has a greenhouse effect 80 times greater than CO_2 and is 28 times more reactive than CO_2. Five scenarios are presented in the Intergovernmental Panel on Climate Change (IPCC) report. The most critical is the increase in the mean temperature by a minimum of 4.4 °C. In this scenario, the pace of economic growth is the highest, but the level of carbon dioxide emissions doubles by 2050 [2,4–6].

According to the UN, the cause of climate change is environmental pollution and greenhouse gas emissions. The year 2015 was a special one for the UN countries. In 2015, the Paris Agreement was adopted at the Paris climate conference (COP21), and in the same year, the Sustainable Development Goals (SDGs) were also adopted. SDGs do not have the same binding force under international law as the climate agreement, but their goals are similar. SDGs are the focal point for the 2030 Agenda. According to the UN member states, the way to improve the condition of the environment and human life is to implement the Agenda for Sustainable Development. Agenda concerns 5 × P (people, planet, prosperity, peace, and partnership). The agenda includes 17 Sustainable Development Goals and 169 targets to be achieved by 2030. Figure 1 shows the UN temperature model, which is the same as NASA's temperature model.

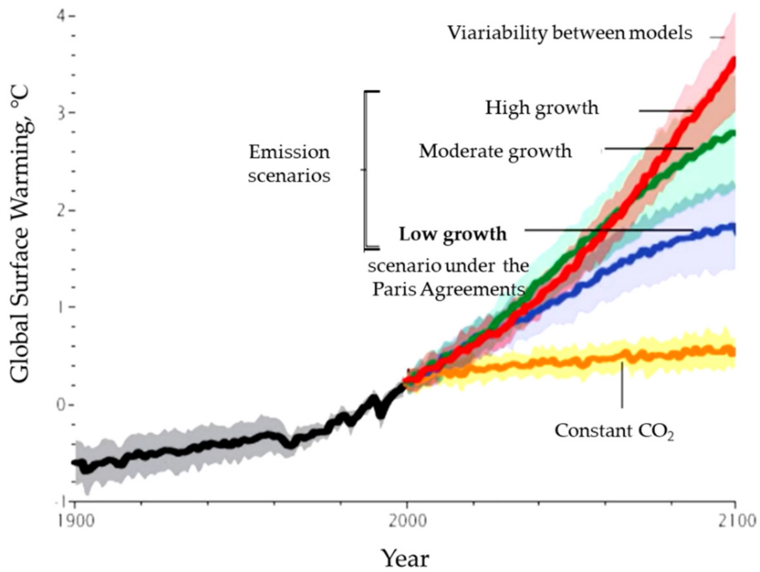


Figure 1. Temperature model with various scenarios related to human activity [7,8].

The low-growth-emission scenario is a scenario resulting from the Paris Agreement, i.e., limiting the average global temperature below 2 °C. A high-growth scenario can disintegrate the cryosphere. According to this scenario, by 2200, climate change may no longer be controllable [9,10].

Failure to take climate action will result in biodiversity depletion and natural disasters. Numerous natural disasters such as floods, hurricanes, droughts, landslides, tornadoes, hurricanes, etc. have been recorded since 1992 (Hurricane Andrew, USA, losses of USD 26.5 trillion). The greatest losses were recorded in 2017 in the USA, which was affected by Hurricanes Harvey, Irma, and Maria. The losses amounted to USD 221 trillion.

This paper presents research on the management of municipal solid waste incineration bottom ash (MSWIBA) in geopolymerisation, which fits into the circular economy and the SDGs, particularly SDG 9 Industry, Innovation, and Infrastructure; SDG 12 Responsible Consumption and Production; and SDG 13 Climate Action. In particular, the MSWIBA management is in line with Target 12.5 "By 2030, significantly reduce waste generation through prevention, reduction, recycling, and reuse"; Target 9.4 "By 2030, upgrade infrastructure and modernise industry to make it sustainable, with increased resource efficiency and wider adoption of clean and environmentally friendly technologies and industrial processes, with all countries taking action within their means".

Figure 2 shows the ideal circular economy for MSWIBA. The SDG targets shown are in line with the CE targets. The figure shows the recycling of secondary waste generated in the process of energy production from municipal waste.

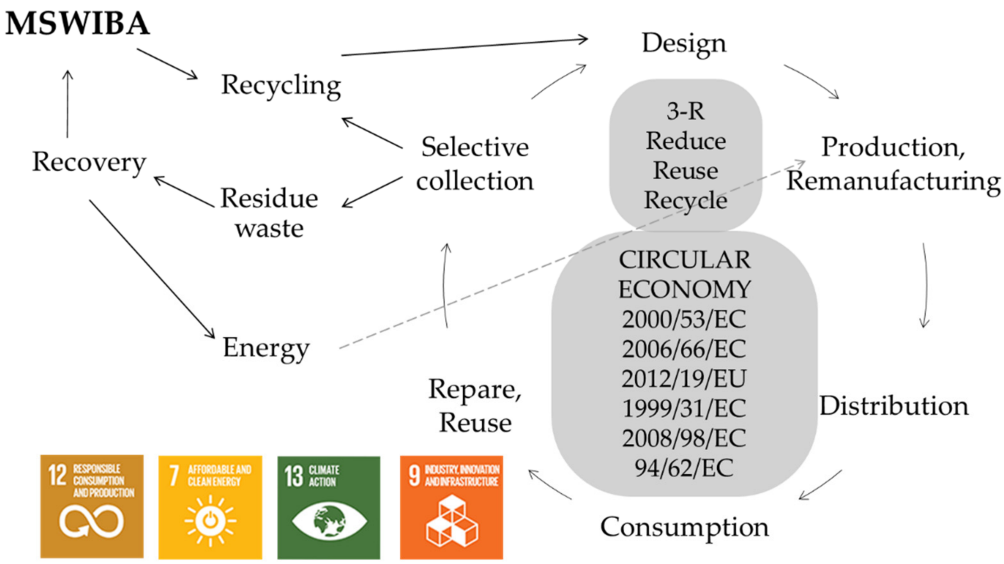


Figure 2. MSWIBA ideal circular economy and attributed SDGs [11,12].

MSWIBA is created during municipal waste burning in an incineration plant. MSWIBA is produced in the amount of about 30% of the bunch. The quantity and quality of MSWIBA depend on the incineration and the valorisation process. MSWIBA is light grey and does not have a dusty appearance. It is characterised by variability in composition due to the heterogeneous nature of municipal waste. Table 1 provides a literature analysis of various MSWIBAs. Table 2 shows the heavy metal content of MSWIBAs.

Table 1. Oxide analysis of selected MSWIBAs [13].

Parameter	CaO	SiO_2	MgO	Al_2O_3	FeO_3	P_2O_5	Na_2O	K_2O	Cl	Ref.
MSWIBA	50.4	13.4	2.3	1.3	8.8	3.2	12.7	1.8	3.2	[14]
	27.9	35.5	2.6	6.7	3.7	4.7	2.7	1.7	N.P	[15]
	25.9	42.1	3.7	8.6	5.7	3.8	3.9	1.9	N.P	[16]
	49.8	10.8	2.4	5.7	9.6	3.2	1.7	10.7	N.P	[17]
	32.3	32.9	2.3	12.2	6.0	3.1	2.2	N.P.	2.1	[18]

Table 2. The heavy metal content of MSWIBA.

Symbol	Zn	Ba	Cu	Pb	Mn	Ni	Cr	Cd	Co	Ref.
Unit					mg/kg					
Parameter	Zinc	Bar	Copper	Lead	Manganese	Nickel	Chrome	Cadmium	Cobalt	
	3193	1126	2321	687	620	105	393	n.d. **	n.d. **	[19]
	3016	3970	391	988	1360	139	634	n.d. **	n.d. **	[20]
	3800	1300	2700	1400	100	240	450	n.d. **	n.d. **	[21]
	n.d. **	n.d. **	2954	176	463	116	49	blq. *	6.17	***

* blq.—below the limit of quantitation; ** n.d.—no data; *** own research, inserted into the descriptive part for comparative purposes. Description of research in Materials and Methods section.

Table 1 showed that MSWIBA is rich in CaO. The basic requirement of geopolymer is the material should be rich in silica and alumina. Hence, in the literature, zeolite is used.

Waste incineration plants are the last element of the waste management chain included in the circular economy. Currently, some waste cannot be managed due to the treatment cost and the lack of highly efficient technology. Treatment in a waste incineration plant enables energy to be recovered from the waste to meet the needs of both the incineration plant itself and the population (e.g., the whole city). The waste incineration plant receives a mixed or contaminated fraction that cannot be recycled or transformed into RDF (e.g., due to an excessively high content of chlorine, sulphur, or heavy metals) [22].

No radioactive waste is sent to the waste incineration plant. Potential radioactive waste is captured through a radioactivity measurement gate before entering the incineration plant; hence, MSWIBA is also not radioactive.

During thermal transformation, bottom ash is the most formed, according to EWC 19 01 12 "bottom ash and slag other than those mentioned in 19 01 11" [23].

Figure 3 shows the process of incineration of municipal waste and the establishment of MSWIBA.

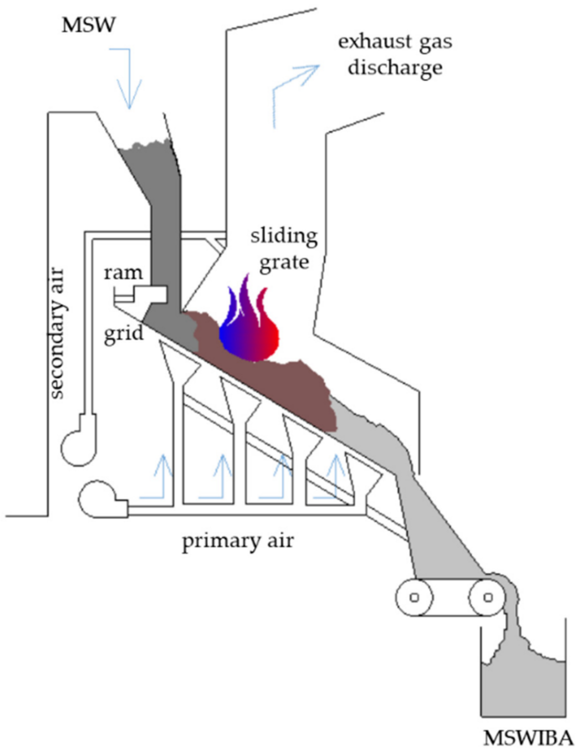


Figure 3. The process of thermal treatment of municipal solid waste and establishing the MSWIBA.

After thermal treatment, a valorisation process is carried out. The MSWIBA valorisation consists of its stabilisation by storing it for a specified period (optimally up to 2 weeks, but you can even one year). The valorisation process is described in more detail in the article [24]. Currently, the part of the MSWIBA that does not swell is used as an aggregate additive in road bases or in concrete.

Despite the MSWIBA valorisation process, its use in building mixtures must be carefully considered due to the possible aluminium content. Metallic aluminium starts at a pH of 9–9.5. The aluminium content causes the mixture to swell through the evolution of hydrogen and Al $(OH)_3$, which is described by Equation (1) and shown in Figure 4. The Al $(OH)_3$ gel is the cause of the swelling [25–27].

$$2Al + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2\uparrow \quad (1)$$

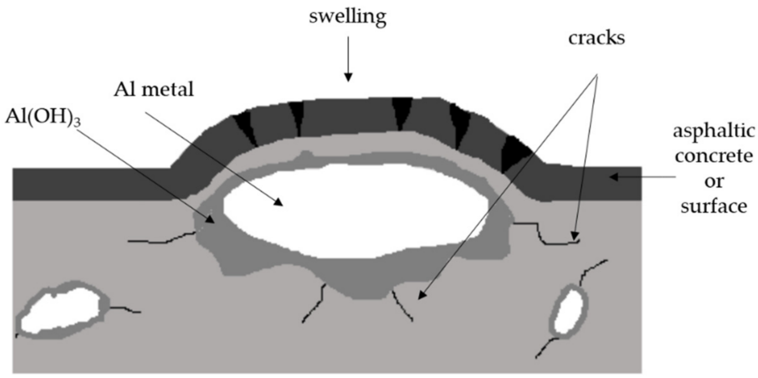


Figure 4. MSWIBA or mixtures with MSWIBA swelling, due to the aluminium content and high pH.

The production of 1 Mg of cement consumes about 1 Mg of mineral resources (depending on the technology) and emits 0.5–1 Mg of CO_2. This translates into 5% of global carbon dioxide emissions and 2% of European CO_2 emissions, as shown in Figure 5. Cement production emission in the EU decreased by 28 million tonnes of CO_2 equivalents in the period 1990–2020, and it decreased by 4 million Mg in the period 2019–2020 [28].

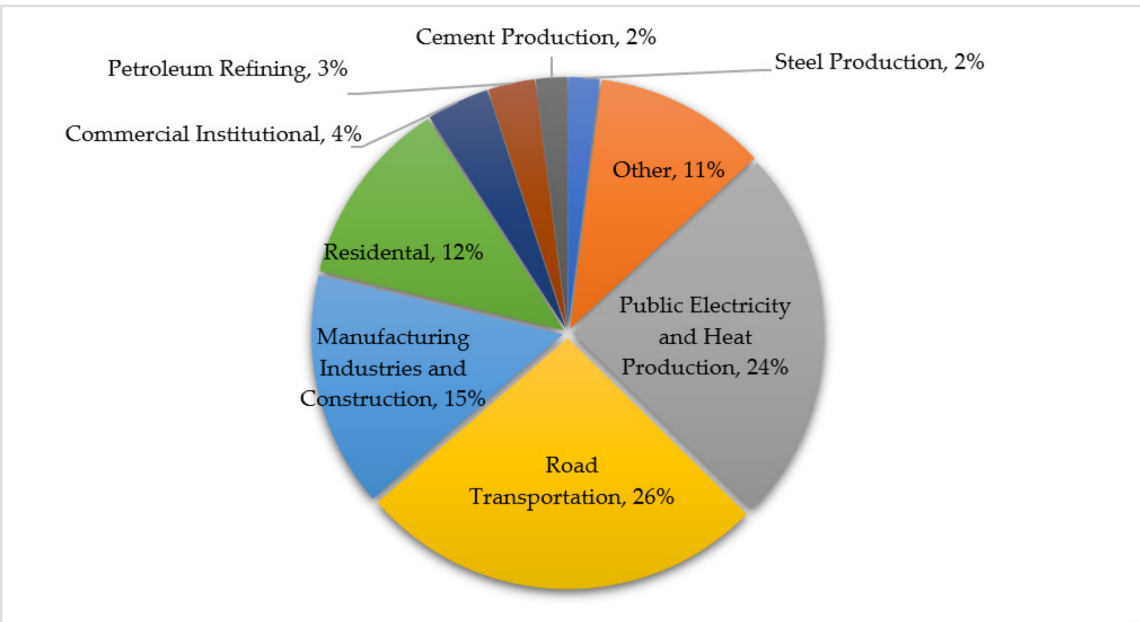


Figure 5. European CO_2 emissions from individual sectors of the economy in 2020 [28].

Despite the use of alternative fuels in cement production, most emissions are related to process emissions. During cement production, calcium carbonate is decomposed. As cement production is an energy-intensive and carbon-intensive process, this translates into ever-increasing cement prices. This is linked to the introduction of CO_2 emission charges by the European Union. The goal is to reduce carbon dioxide emissions by at least 40% by 2030.

Traditional concrete uses natural aggregates, which also exacerbates environmental degradation. According to *Science* magazine, about 40 billion Mg of sand is extracted annually in the world. The substitution of natural aggregates is one of the elements of sustainable development.

A geopolymer is a material in which no or very little cement is used, thus reducing the most emissive component of the building mix. Geopolymers are also known as polysilanes and alkali-activated aluminosilicate binders (AAAS), which are based on mineral basic aluminosilicates and alkaline activators of aluminosilicates. The combination of ingredients creates inorganic polymers.

Geopolymer is different from concrete due to zero or little amount of hydraulic binding material (e.g., CEM I or CSA cement [10,29]), in which the hardening results from the hydration of calcium silicates and aluminates. Geopolymers are created by the mineral polycondensation reaction, i.e., geosynthesis. There are three basic structural units, namely polysialate (PS), poly(siloxosialate) (PSS), and poly(disiloxosialate) (PSDS).

The hardening of geopolymer structures occurs after a few hours at room temperature, shorter in the temperature range of 60–80 °C. The duration of the process varies from a few seconds to several hours.

The advantages of geopolymer material are low shrinkage, fast setting time, and resistance to high temperatures [30].

These properties cause geopolymers to have a lower carbon footprint than concrete. Moreover, the mechanical properties cause geopolymers to be better equipped to immobilise pollutants [31].

The use of MSWIBA geopolymers includes the following applications:

1. Basics and covering landfill surfaces. The rigid structure of geopolymers will prevent contact with rainwater, which increases the amount of leachate from landfills;
2. Utility areas, floors, and flat surfaces;
3. Barriers separating waste layers at various installations, e.g., RDF bunkers, waste bunkers, etc.;
4. The casting of simple elements due to the good formability of geopolymer paste, e.g., pipes, fences, etc.;
5. Places where hazardous waste is managed, i.e., radioactive or asbestos waste [32–34].

Previous research showed that the utilisation of MSWIBA to synthesise aerated geopolymer is feasible [35]. MSWIBA has also been successfully combined with metakaolin, biochar, and two kinds of activators—water glass and NaOH [36]. Geopolymers have also been made of a combination of MSWIBA, ordinary Portland cement, fly ash, superplasticiser, water, sodium hydroxide, and sodium silicate [37]. Another solution for MSWIBA geopolymerisation was 3 months of aging and mixing it with NaOH, water glass, and aluminosilicate powder [38]. In this paper, 2 weeks of aging alkali pre-treatment MSWIBA was studied, which was used in geopolymerisation with 30% NaOH and zeolite.

2. Materials and Methods

The research material is MSWIBA. The solid precursor used for geopolymerisation derives from a municipal solid waste incineration plant. The collected 0–8 mm fraction was sifted to the 0.125–0.2 mm fraction in order to replace the 100% natural fine sand aggregate. The MSWIBA screening process was carried out in accordance with the PN-EN 12620 + A1: 2010 Standard.

The physicochemical and leachability standards according to which the MSWIBA and geopolymer were tested are presented in Table 3.

Table 3. Parameters and methodology of MSWIBA and geopolymer research.

Parameters	Methodology
Moisture (M)	PN-Z-15008-02: 1993
Arsenic (As) Bar (Ba) Cadmium (Cd) Total chromium (Cr) Copper (Cu)	PN EN 12457-4:2006; PN EN 11885:2009
Mercury (Hg)	PN EN 12457-4:2006; PN EN 1483:2007
Molybdenum (Mo) Nickel (Ni) Lead (Pb) Antimony (Sb) Selenium (Se) Zinc (Zn) Chlorides (Cl^-) Fluorides (F^-)	PN EN 12457-4:2006; PN EN 11885:2009
Sulphur ($SO_4{}^{2-}$)	PN EN 12457-4:2006; PN ISO 9280:2022
Dissolved organic carbon (DOC)	PN EN 12457-4:2006; PN EN 1484:1999
Solid dissolved compounds (TDS)	PN EN 12457-4:2006; PN EN 15216:2010
Water extract (leachability)	PN-EN 12457-2: 2006
Sodium, potassium, lithium, calcium, bar (Na, K, Li, Ca, Ba)	PN-ISO 9964-2/Ak: 1997
Test of consistency—flow	PN-EN 12350-5
Strength tests	PN-EN 450-1:2012; PN-EN 196-1:2006
Loss of ignition (LOI)	PN EN 196-2:2006

In terms of MSWIBA and the need for the separation of ferrous and non-ferrous metals, MSWIBA contains enough metal in it to allow it to react and damage the matrix. Damage to the matrix is manifested by cracks, bubbles, and swelling of the mixture. The reaction is more rapid at higher pH. In the case of geopolymerisation and the use of 30% NaOH, the pH of which is 14, the reaction had serious effects on the matrix of the mixture. Figure 6 shows the cracks and swelling of the geopolymer mixture.

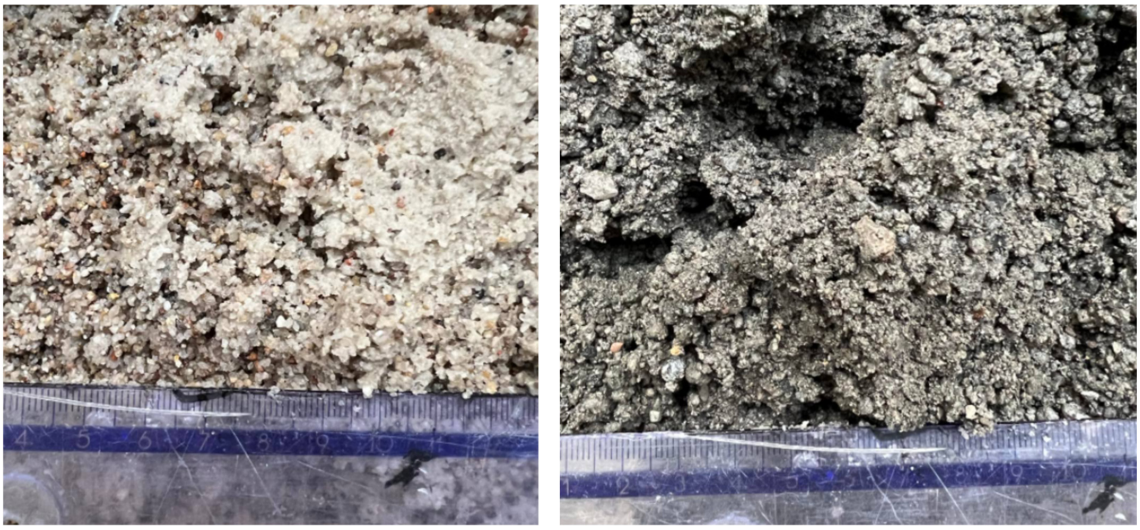
(**a**) (**b**)

Figure 6. Damaged structure of geopolymer mix with the addition of MSWIBA: (**a**) swelling and crack surface; (**b**) bubbled surface.

MSWIBA NaOH pre-treatment provides the possibility of avoiding the swelling reaction. The preparation involved the alkaline activation of MSWIBA. Alkali pre-treatment consisted of placing 0.125–0.2 mm MSWIBA fraction in 30% NaOH. Then, the sample was soaked for 6 h at room temperature. The next step was to wash MSWIBA with water until the pH was around 8. The MSWIBA thus prepared was mixed with zeolite and alkali.

Alkali was prepared by mixing 150 g water glass, 50 g 8M NaOH, and 50 g water. Alkali reacts with water by producing heat (about 60 °C). After the alkali had cooled, it was added to pre-treated MSWIBA (1350 g) and zeolite (225 g).

To select the amount of alkali, the absorbability of MSWIBA and sand was compared. Figure 7 shows the water absorption test, which consisted of flooding the sand, and the MSWIBA test with water, comparing their results.



(**a**) (**b**)

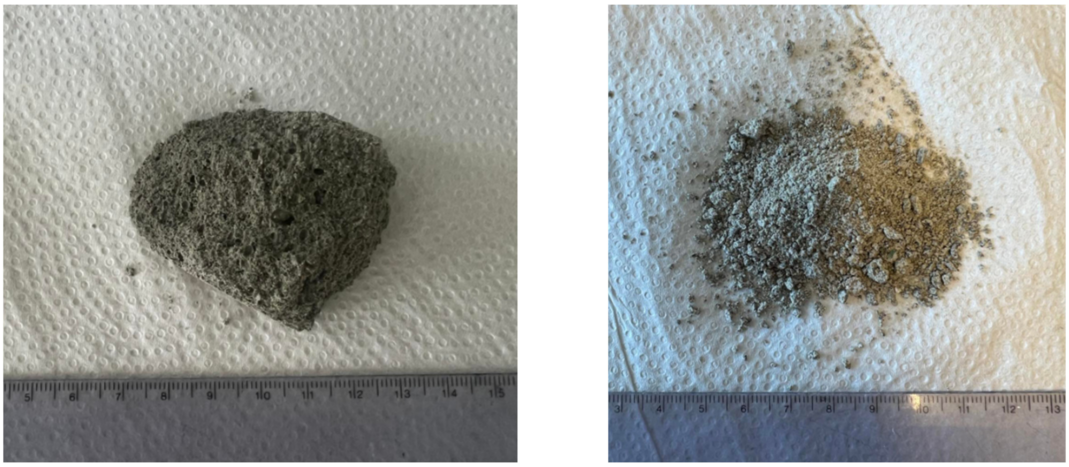
Figure 7. Comparison of water absorption to sand and sand substitute (MSWIBA) used in geopolymer mix: (**a**) sand; (**b**) MSWIBA.

In this study, sand was replaced by activated MSWIBA. Alkaline activation also increases the immobilisation of heavy metals and improves the mechanical properties of MSWIBA. Alkaline treatment increases the specific surface area by etching the MSWIBA grains, which increases the strength of the mix.

Zeolite is an additive with properties that immobilise pollutants. The dusty fraction was selected due to its larger specific surface area, which improves the effect of heavy metal immobilisation.

The prepared geopolymer was tested for compressive and flexural strength. The mixture was prepared with a mortar mixer, and then the bending and compressive strength were tested according to PN-EN 196-1.

To check the leachability of the geopolymer mixture, an aqueous extract was prepared. The water extract was made in a proportion of 1:10 (1 portion of geopolymer and 10 portions of water). Then, it was shaken for 24 h in a dark container and then filtered through a filter. To compare leachability, the extract was made of a piece of geopolymer and a crushed geopolymer. Figure 8 shows the geopolymer samples that were tested for leachability.



(**a**) (**b**)

Figure 8. Geopolymer with alkali pre-treated MSWIBA subjected to leachability tests: (**a**) geopolymer monolith form; (**b**) geopolymer crushed form.

3. Results

The research involved a trial in which MSWIBA was not activated. The test sample was cracked and swollen. Figure 9 shows the swollen sample.

Figure 9. Swollen sample with MSWIBA without NaOH pre-treatment.

It was decided to activate MSWIBA alkaline and replace the fine aggregate with 100%. In terms of life cycle assessment (LCA), it is the most advantageous option due to the complete substitution of natural aggregate [24].

The physicochemical tests of MSWIBA are shown in Table 4. Research results were compared with the criteria of non-hazardous waste and non-municipal waste for storage in a landfill for non-hazardous and inert waste (Ordinance of the Minister of Economy of 16 July 2015 on allowing waste to be stored in landfills).

Tested MSWIBA did not exceed the standards that must be met for storage in landfills. Each batch of MSWIBA, before placing it in the construction mixture, is recommended to be tested due to the heterogeneity of the MSWIBA and compared with the standards. If the MSWIBA does not meet the standards, additional tests need to be performed on the mixture to ensure that contaminants do not leach into the environment.

A comparative study of the absorption of standard sand and MSWIBA showed that it was 2.35 times more water-consuming than the standard sand. For the standard 1350 g, 253 g of water entered the sand, while 595 g of water entered MSWIBA.

Table 4. Physicochemical properties of MSWIBA.

Parameter	Symbol	Unit	MSWIBA	Maximum Allowable Value *
Arsenic	As		0.02	2
Bar	Ba		0.42	100
Cadmium	Cd		0.1	1
Total Chromium	Cr		0.4	10
Copper	Cu		0.5	50
Mercury	Hg		0.01	0.2
Molybdenum	Mo		1	10
Nickel	Ni		0.4	10
Lead	Pb	mg/kg	3	10
Antimony	Sb		0.5	0.7
Selenium	Se		0.5	0.5
Zinc	Zn		0.1	50
Chlorides	Cl^-		868	15,000
Fluorides	F^-		2.63	150
Sulphur	$SO_4{}^{2-}$		877	20,000
Dissolved organic carbon	DOC		59	800
Solid dissolved compounds	TDS		4870	10,000
Loss on ignition	LOI	%	2,2	5
Total phosphorus content	TP	%	0,14	5

* Ordinance of the Minister of Economy of 16 July 2015 on allowing waste to be stored in landfills.

The consistency test indicated that the geopolymer was self-compacting. The spread was over 30 cm. Figure 10 shows the consistency test.

Figure 10. Consistency test.

The size of each of the created mortar samples was 16 × 4 × 4 cm. An example of the geopolymer sample with MSWIBA is shown in Figure 11.

The results of the geopolymer strength from MSWIBA are presented in Table 5.

Table 5. Strength of geopolymer from alkali pre-treated MSWIBA.

Average Compressive Strength (CS), MPa	FS Standard Deviation	Average Flexural Strength (FS), MPa	FS Standard Deviation
10	1.24	2.5	0.12

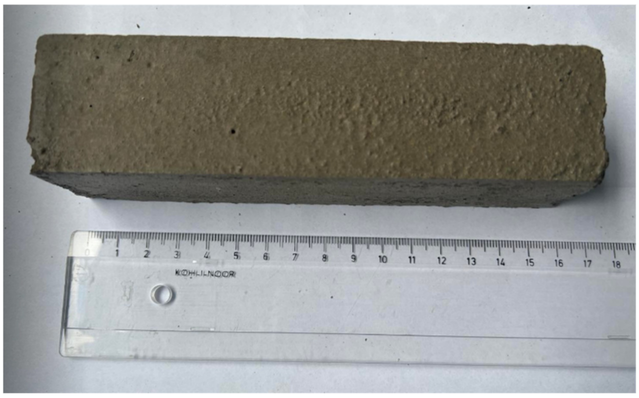


Figure 11. Geopolymer with MSWIBA.

Compressive strength was 10 MPa. Flexural strength was 2.5 MPa. To increase the strength, fly ash of the same or different origins could be added (e.g., fly ash from coal combustion, which is homogeneous and non-hazardous waste). Another solution was to add cement; this solution improves the strength but is a less favourable solution for the environment.

For the immobilisation study, MSWIBA, a monolith of geopolymer, and crushed geopolymer were investigated. Geopolymerisation has a significant impact on the immobilisation of pollutants. Table 6 shows the leachability of MSWIBA, a monolith of geopolymer, and crushed geopolymer.

Table 6. Leachability of MSWIBA, a monolith of geopolymer, and crushed geopolymer.

			MSWIBA (0.125–0.2 mm)		**Monolith of Geopolymer**		**Crushed Geopolymer**	
Parameter	Symbol	Unit	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Potassium	K		60.40	0.12	14.63	0.045	15.88	0.047
Lithium	Li		0.20	0.012	0.18	0.011	0.19	0.008
Calcium	Ca	mg/dm^3	153.54	0.26	142.3	0.15	143.3	0.17
Bar	Ba		20.89	0.23	12.07	0.16	12.9	0.17
Sodium	Na		197.96	3.61	3140	9.45	3055	8.83

In the leachability studies, the immobilisation of pollutants after geopolymerisation was analysed. The crushing of the research material resulted in a slight increase in leachability, which proved the tightness of the geopolymer structure. The amount of sodium increased significantly, which is related to the use of NaOH in the production of geopolymer. The results of heavy metal tests contained in MSWIBA are presented in the Introduction section. The authors' own research and the conducted analysis indicated a high heterogeneity in the data of the Ministry of Internal Affairs and Administration. This is due to the heterogeneity in the data of the Ministry of the Interior. The variability in the composition of MSWIBA is also influenced by the process, temperature, time of incineration of municipal waste, and the valorisation process. Thermal transformation influences, for example, the organic carbon content in MSWIBA. The valorisation process influences the humidity, the content of ferrous and non-ferrous metals, the leaching of sulphates, heavy metals, etc.

4. Conclusions

The 2030 Agenda for Sustainable Development, including SDGs, was adopted by all 193 UN member states through a General Assembly Resolution. They concern 5 × P. This research focused mainly on one of the P factors—the planet—which applies to SDG7, SDG9, SDG12, and SDG 13. The SDGs are aligned with CE, which aims to close the cycle and extend the life cycle of products and materials (LCA).

An incineration plant is the last step in CE. In the incineration plant, MSWIBA is produced in the greatest amount (approx. 30% of the bunch). Apart from MSWIBA, APCr is created in 4.2–6% of the bunch. The management of secondary waste allows incineration plants to be fully recirculated, as a result of which the secondary waste can be used in the construction industry.

Construction, with the highest carbon footprint of cement production, is likely the last element of CE in municipal solid waste management. Virtually every waste fraction can be recycled, only mixed or too contaminated (to be valuable and not cause emissions to a landfill) can be thermally transformed. Regarding the recovery aspect, electricity and heat are recovered. The resulting secondary waste, during recovery, has the properties of building materials and, therefore, can be a substitute for natural aggregates.

In terms of carbon footprint, cement is the weak link in a concrete mix. The concrete mix can, however, be replaced with a geopolymer mix that has little or no cement. Geopolymer plastics are characterised by better properties such as acid resistance, thermal insulation, non-toxicity, low shrinkage, low abrasion, and fire resistance. These parameters have particular effects on the durability of the mixture, which is enhanced by MSWIBA, in line with the current global trends, i.e., CE and SDGs.

Alkaline activation studies solve the problem of the swelling of the geopolymeric blend caused by the aluminium content in MSWIBA. Alkaline activation also increases the immobilisation of heavy metals and pollutants. In addition, alkali pre-treatment etches the surface of MSWIBA, thus improving the mechanical properties of MSWIBA. Geopolymerisation further reduces the leaching of pollutants into the environment, and geopolymeric material can be used in many aspects of construction management.

The tested MSWIBA had to be pre-treated because of swelling.

The alkali pre-treated MSWIBA geopolymer was self-compacting. It can be used as a spout in halls. Unfortunately, the geopolymer had low strength, so further attempts can be made to add cement, fly ash, or metakaolin in more efficient tests.

Too high a concentration of alkali causes foaming at the mixing stage. Therefore, 8M NaOH and water glass were selected, although a lower alkaline solution concentration reduces the degree of polymerisation.

Geopolymerisation increased the immobilisation of contaminants in the final material. Currently, to use MSWIBA, the waste incineration plant incurs its costs. MSWIBA geopolymerisation is also economically viable.

5. Discussion

Table 7 shows a summary SWOT analysis of the proposed solution for the use of secondary waste in geopolymerisation and the assigned SDGs.

Table 7. SWOT analysis of MSWIBA in geopolymerisation with SDGs.

Strengths	SDGs	Weaknesses
Lowering carbon footprint	12 13; 15	Poor strength of the mixture
The use of waste as a substitute for natural aggregate	8; 9; 11 12 13; 15	Working with dangerous, concentrated alkalis (production difficulties)
Many possible uses	8; 9	More research is needed before market launch Need for pre-treatment
Opportunities	**SDGs**	**Threats**
New materials and solutions	8; 9	New materials and solutions
Acquiring funds and development grants	17	No recipient (yet)
Lowering production costs	8	Public uncertainty about the waste product
Properties other than concrete mix	9	Public uncertainty about the waste product
Rising CO_2 fees, hence rising cement prices	8	

The SWOT analysis presents the strengths, weaknesses, opportunities, and threats and their assigned SDGs and a score for each.

Strengths and opportunities outweigh the threats and weaknesses. The analysis confirmed the development phase of research and geopolymers as new building materials, which translated into the highest rating for opportunities. In the analysis, it can be seen that "new materials and solutions" was found in both opportunities and threats but had a different value due to the positive prognosis of the preliminary research. Threats had low assessments due to the low probability of the event or the possibility of using geopolymer in various industries, in which the uncertainty of the society regarding the product will not be of great importance. The weaknesses include, among others, production problems, although geopolymers are already being produced; hence, it is known that this is not an insurmountable barrier but only a hindrance.

In summary, geopolymers using waste have environmental and economic potential. Using waste to create new products will contribute to reducing greenhouse gas emissions and improving the state of the environment.

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