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Assessment of the chemical and mineral stability of ash – slag mixtures and the leachability of heavy metals under simulated weathering conditions

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Abstract: Solid waste from coal combustion deposited in landfills many years ago may constitute a potential secondary raw material resource for industrial applications. However, this requires the examination of a wide range of parameters of these wastes. This study aimed to determine the changes in chemical and mineralogical composition of ash-slag mixtures derived from coal-based power generation, as well as the leachability of heavy metals under the influence of accelerated weathering conditions. The study was based on samples collected from different depths of an ash-slag landfill. The samples were subjected to innovative testing in a chamber simulating variable humidity and temperature conditions, followed by aging in a separate chamber designed primarily to evaluate the effects of ultraviolet radiation. Chemical composition analysis revealed the dominance of silica, aluminum, and iron, with only minor changes after simulated processes. X-ray diffraction methods confirmed the presence of amorphous phases, quartz, mullite, and hematite, as well as calcite as a secondary phase formed during long-term storage. Heavy metals exhibited low leachability (total ≤ 1.56 mg/kgd.m.), with concentrations below the permissible limits for non-hazardous waste landfills. The stability of pH and the absence of significant changes in mineral composition after testing indicate good resistance of the mixtures to weathering processes.

Introduction

Current efforts to replace coal-based power generation with renewable technologies are contributing to the gradual reduction in the mass of solid waste (ashes and slags) generated from the combustion process (Statistic Poland, 2024). However, in various industrial sectors that have traditionally utilized these materials, a problem is emerging regarding the availability of raw materials that meet the required quantitative and qualitative criteria. As a result, cement plants and other enterprises using combustion byproducts as raw materials have started exploring the potential of utilizing waste previously deemed unsuitable and landfilled many years ago. This approach aligns well with the principles of the circular economy. Nevertheless, apart from the content of hazardous substances, an important issue in assessing the suitability of such waste for reuse in other industrial applications, is the variability of the chemical composition within the deposited waste mass (Adamczyk et al. 2024, Faragó et al. 2023, Słomkiewicz 2025, Yu et al. 2023). Moreover, post-production waste directed to landfills may pose a potential threat to the soil and groundwater environment, as it is exposed to precipitation, natural infiltration, and other factors that may lead to the release of heavy metals and their migration in the environment (Zhou et al. 2025, Żygadło and Woźniak 2009). These factors, along with weathering and aging processes, lead to changes in the structure and chemical composition of the waste. Such changes may occur during the interaction of combustion residues with moisture and atmospheric gases. As a result of CO_2 absorption, secondary reactions may take place. leading to the formation of calcite, which in turn can affect the chemical stability of the waste by reducing its reactivity (Cheng et al. 2025, Żygadło and Woźniak 2009). On the other hand, combustion residues also tend to dissolve certain components upon contact with water. The solubility of these components in the environment is further intensified by mineral weathering processes (Zhou et al. 2025). Weathered waste generally exhibits lower contents of sulfides and carbonates and is enriched in secondary minerals such as jarosite, gypsum, and iron oxyhydroxides. It also shows decreased pH values and reduced heavy metal concentrations (Liu et al. 2021). Heavy metals are contaminants whose release strongly depends on changes in conditions and processes occurring within the

waste mass. Knowledge of the content and, above all, the leachability of heavy metals from waste is a prerequisite for further waste management and utilization (Mizerna and Król 2023).

The parameter controlling the course of geochemical processes, including sorption, dissolution, and precipitation, is the pH of the environment. The persistence of acidic conditions increases the leachability of heavy metals, especially zinc (Zn), lead (Pb), and cadmium (Cd), which poses a risk of these elements migrating into soils and groundwater (Wang et al. 2022). A moist environment contributes to the release of hydroxide ions (OH^-), which significantly increase the pH. Alkaline conditions play a critical role in the chemical reactions occurring within the mass of deposited waste, causing precipitation of, among others, calcium hydroxide. This can intensify the dissolution reactions of calcium sulfate. High concentrations of OH^- ions may also contribute to the dissolution of the glassy phase and accelerate the release of the silicate group. Subsequent reactions lead to the solidification of the waste and the formation of various crystalline phases (Żygadło and Woźniak 2009).

One type of waste generated during coal combustion consists of ash-slag mixtures. Their properties depend on the quality of the coal, combustion conditions, and the method of disposal to the waste landfill (Hycnar et al. 2014). Combustion residues, i.e., fly ash and bottom ash from pulverized coal boilers, were often mixed with water to form an ash-slag slurry, which was transported to on-site disposal areas via pipelines. This method of management was common from the 1950s until the late 1980s. At that time, no records were kept of the individual fractions of the deposited mixtures, and their properties could therefore vary. The main components of ash-slag mixtures are aluminosilicates, constituting approximately 60 to 70% by mass. Oxides of calcium, iron, magnesium, and potassium occur in amounts of several percent, while oxides of titanium, sodium, and phosphorus are present in quantities up to 2%. Mineralogically, ash-slag mixtures are characterized by a high content of siliceous-aluminous glassy phase and a lower proportion of crystalline substances such as mullite, quartz, hematite, magnetite, and calcite. The management of combustion residues is handled by multiple companies that hold certificates and declarations of performance confirming that, after appropriate processing, the material can be used for specific purposes. Due to their physicochemical properties, ash-slag mixtures are applied, among others, in the construction, reconstruction, or repair of railway structures and subgrades (Gruchot and Zydroń 2013), railway and road embankments (Kolias et al. 2005), as well as road and highway base layers (Veolia Ekozec). However, due to not meeting the standards for cement additives, these mixtures have not yet been used in the cement industry.

The aim of the study was to analyze changes in the chemical properties and leachability of heavy metals from coal combustion ash-slag mixtures subjected to humidity-temperature factors and UV irradiation simulating weathering processes. The research was conducted in the context of assessing the potential of stored ash-slag mixtures for industrial reuse as a secondary raw material. The study is innovative, as it not only provides unique data on the long-term stability of these wastes but also aligns with current trends in circular economy. Furthermore, industrial chambers were employed in a non-standard manner for accelerated aging tests of the materials. The ash-slag mixtures, both before and after testing in climatic and aging chambers, were subjected to the analyses of chemical and mineral composition, leachability of heavy metals (Zn, Cu, Pb, Ni, Cd, Cr, Ba, As, Mo, Sb, Se, and Hg), as well as assessment of the pH and electrical conductivity of water extracts from the waste.

Recovering waste previously deposited in landfills is also desirable from the perspective of rational waste management, in which stockpiling is considered the least preferred option for waste disposal.

Materials and methods

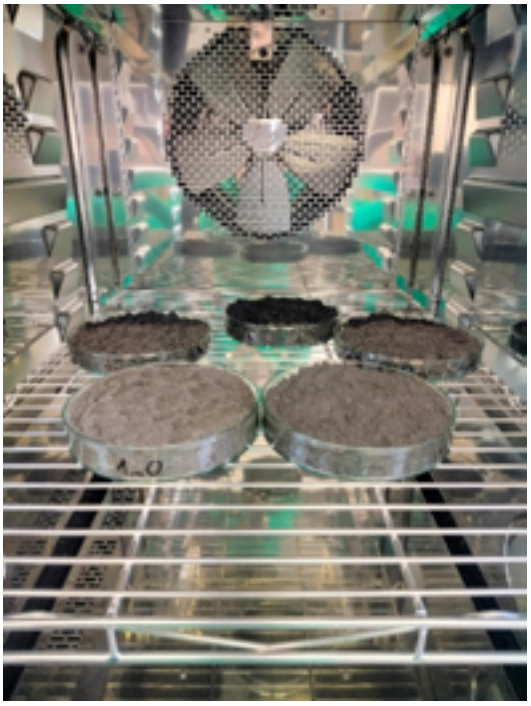
Preparation of test sample

The study materials consisted of ash-slag mixtures from coal-fired power generation, collected from one of the waste landfills in Poland. Ash-slag mixtures had been landfilled there from the 1970s onward. The landfill owner did not consent to disclose its location or any data enabling the identification of the waste origin. According to the Waste Catalogue (Ministry of Climate 2020), the materials under study were classified as "10 01 80 – ash-slag mixtures from wet disposal of combustion residues". Samples were collected from the entire depth profile of the landfill, from five layers at varying depths: the surface layer of the landfill (up to 1 m), depths of 0-6 m, 6-12 m, 12-18 m, and 18-24 m. Before sampling, the surface layer was removed to a depth of 50 cm, and only then was the actual material collected for chemical analyses. The layer up to 1 m was sampled using an excavator, while the remaining layers were sampled using a drilling method. According to the sampling program, the waste was treated as anthropogenic ground. Sampling was carried out in accordance with the procedures described in the Regulation of the Minister of the Environment of 1 September 2016 on the method of conducting the assessment of land surface contamination (Ministry of Environment 2016) and in accordance with the PN-ISO 10381 series of standards (Parts 1-5). In order to obtain a laboratory

Table 1: Sample designations

Sample description	Sample designation before chamber tests	Sample designation after chamber tests
From surface	1_0	1_0K
From depth 0 to 6 m	0-6	0-6K
From depth 6 to 12 m	6-12	6-12K
From depth 12 to 18 m	12-18	12-18K
From depth 18 to 24 m	18-24	18-24K

(a)



(b)

Fig. 1. Climate (a) and aging (b) chambers containing ash-slag mixture samples

sample representative of the analyzed depth interval, the collected material was thoroughly mixed, yielding an averaged sample representing the investigated layer. Samples from one measurement point (one depth profile) were used for the accelerated weathering tests of waste. Table 1 presents the sample designations used in the further part of the study.

Simulation of weathering conditions

The study on the influence of temperature-humidity conditions was conducted using a climate chamber (ClimeEvent, Weisstechnik GmbH) presented in Figure 1a. For the granular waste materials collected from the landfill, a climate cycle was applied comprising temperature variations from -20 °C to +60 °C and relative humidity ranging from 0% to 98%. Each cycle lasted 6 hours and was repeated over a period of 28 days (a total of 112 cycles). The temperature range was selected to simulate extreme environmental conditions. Although +60 °C does not occur in atmospheric air in Poland, it can be locally reached on the surface of waste due to intense solar irradiation. The inclusion of subzero temperatures allows for the evaluation of the effects of freeze-thaw cycling on the physical structure of the material. The extreme humidity values represent alternating periods of desiccation and wetting typical for open landfill conditions. The adopted methodology enables a comprehensive assessment of the durability and stability of the waste under near-real environmental conditions.

In the next stage of the study, the ash-slag mixtures were placed in an aging chamber (Q-SUN Xe-3, Q-Lab) to simulate the effect of UV radiation with periodic wetting (Figure 1b). The study applied a total ultraviolet radiation intensity (TUV, 300-400 nm) of 40 W/m², which reflects typical exposure conditions for landfill surfaces in a temperate climate (e.g., in Poland). Average daily UV values in this range are typically 35-50 W/m², therefore, the adopted intensity was considered representative for the summer season without introducing excessive energy loading of the sample. The test program involved cyclic operation of the chamber with a 5-hour irradiation phase and a 1-hour dark phase simulating nighttime conditions. Short water spray sequences were also included during exposure to simulate natural rainfall. All parameters used fell within the ranges recommended for standard accelerated aging tests in accordance with ISO 11341 and ASTM G155 (cycle 1), which define typical scenarios for xenon arc radiation exposure. The full test cycle was repeated over a 15-day period.

Chemical and mineralogical composition analysis

Chemical composition analysis was performed using X-ray fluorescence (XRF) in accordance with the EN 15309:2007 standard. Mineralogical composition was determined using X-ray powder diffraction (XRD). The step size was set to 0.2 degrees 2θ, and the scan rate was 4 degrees per minute. Diffractograms were recorded in the angular range of 2-70 degrees 2θ. Quantitative phase analysis was carried out using the Rietveld refinement method with Profex software.

Heavy metal leaching

Water extracts were prepared from the tested materials in accordance with the standard leaching procedure for waste characterization, as specified in EN 12457-2:2002. Each sample was leached with deionized water at a liquid-to-solid ratio (L/S) of 10 dm³/kg. The suspensions were agitated on a laboratory shaker for 24 hours at room temperature and subsequently filtered through 0.45 μm membrane filters. For each material, three parallel replicates were prepared. The filtered eluates were analyzed for pH and electrical conductivity (EC), and the content of heavy metals was determined. The concentrations of heavy metals (Zn, Cu, Pb, Ni, Cd, Cr, Ba, As, Mo, Sb, and Se) were determined using inductively coupled plasma optical emission spectrometry

(ICP-OES) with an Agilent 5800 spectrometer, according to EN ISO 11885:2009. Mercury (Hg) was determined separately using a direct mercury analyzer AMA 254, based on atomic absorption spectrometry with thermal decomposition and gold amalgamation. The scope of analyzed metals was selected based on the legal requirements for assessing waste acceptance at landfills (Ministry of Economy 2015).

Quality control

All reagents used in the study were of high purity. To ensure analytical precision and quality control of heavy metals, the analysis was performed using triplicate sample measurements, analysis of blank controls, and testing of a certified reference material (CRM), specifically "Trace Metals - Fly Ash 3" (Sigma-Aldrich, Lot: LRAD2821). The CRM was prepared using microwave acid digestion according to EPA Method 3051A. The percentage recovery of the analyzed heavy metals in the CRM ranged from 91 to 118%. The accuracy of the ICP-OES analysis was below 5% relative standard deviation (RSD).

Results and discussion

The chemical composition of the main components of the ash-slag mixtures, both before and after chamber testing, is presented in Figure 2. The dominant component in all samples was silica (49.4-57.8%), with the highest content observed in the sample taken from a depth of 12-18 meters. This was followed by Al_2O_3 (19.7-27.1%) and Fe_2O_3 (8.3-13.5%). The surface layer sample (1_0) showed the highest iron oxide content. The oxides of the remaining components were found at levels below 4.4%. No significant changes in the chemical composition of the mixtures were observed as a result of exposure to weathering conditions compared to the reference samples.

Phase identification studies using X-ray diffraction (XRD) are presented in Table 2. To comprehensively verify whether any changes occurred in the mineral composition of the waste, a quantitative phase analysis was carried out. The ash-slag mixture collected from the surface layer of the landfill (sample 1_0) contained approximately 55% amorphous phase (glass) and 25% quartz. The presence of mullite, magnetite, and hematite was also identified. Additionally, secondary phases such as calcite were detected, which likely formed through crystallization during the long-term disposal of the waste. In contrast, the samples collected from deeper layers were characterized by a higher proportion of the amorphous phase (approximately 70%) and a lower quartz content (8-11%). The differences in the amorphous phase content may be attributed to devitrification processes of the glassy matrix and its transformation into clay minerals, typically associated with weathering processes (Adamczyk and Nowak 2013). It is presumed that this is the reason for the occurrence of additional phases such as kaolinite in the samples collected from depths of 12-18 m and 18-24 m, and muscovite in the deepest sample. The diffractograms of the studied waste materials (Figure 3) exhibit typical diffraction lines that are commonly observed in slags of energy origin.

Quartz is one of the most ubiquitous minerals found in ashes resulting from the combustion of fuels. It crystallizes at approximately 850 °C and may even form as a result of the transformation of dissolved silica during the aging process (Faragó et al. 2023, Zhu et al. 2021). The presence of SiO_2 affects the physicochemical properties of the waste, which is of significant importance for its potential economic utilization. Fly ashes rich in silica exhibit pozzolanic properties (binding ability), enhancing the strength of construction materials, such as concrete produced with their addition. Mullite, in turn, is

Table 2: Mineral composition of the ash-slag mixtures (mean ± SD, *n* = 3)

Mineral phase	Content (% of mass)									
	1_0	1_0K	0-6	0-6K	6-12	6-12K	12-18	12-18K	18-24	18-24K
Quartz	25.44 ±0.30	23.23 ±0.30	11.20 ±0.25	10.60 ±0.25	10.10 ±0.20	10.40 ±0.20	9.90 ±0.20	9.10 ±0.20	8.20 ±0.25	7.90 ±0.25
Mullite	11.04 ±0.20	11.93 ±0.20	15.00 ±0.30	14.90 ±0.20	16.60 ±0.30	15.70 ±0.20	15.10 ±0.20	14.60 ±0.20	15.00 ±0.20	15.10 ±0.20
Mg-ferrite	-	-	0.77 ±0.06	0.85 ±0.06	0.37 ±0.05	0.29 ±0.05	0.31 ±0.05	0.34 ±0.05	0.65 ±0.06	0.59 ±0.06
Magnetite	3.72 ±0.10	5.02 ±0.15	-	-	0.38 ±0.06	0.32 ±0.06	0.54 ±0.06	0.53 ±0.05	0.69 ±0.05	0.64 ±0.06
Hematite	2.53 ±0.10	2.31 ±0.10	0.64 ±0.05	0.70 ±0.04	0.53 ±0.05	0.71 ±0.05	0.57 ±0.06	0.46 ±0.05	0.76 ±0.05	0.70 ±0.04
Calcite	2.02 ±0.09	1.77 ±0.08	2.50 ±0.10	2.50 ±0.10	1.90 ±0.10	2.08 ±0.09	1.72 ±0.09	1.71 ±0.09	1.97 ±0.08	2.03 ±0.08
Kaolinite	-	-	-	-	-	-	1.10 ±0.10	1.40 ±0.10	1.30 ±1.30	1.27 ±0.09
Muscovite 2M1	-	-	-	-	-	-	-	-	0.78 ±0.09	0.98 ±0.09
α-Fe	-	-	0.25 ±0.01	0.35 ±0.01	0.27 ±0.01	0.19 ±0.01	-	-	0.32 ±0.01	0.26 ±0.01
Amorphous phase	55.47 ±0.25	55.96 ±0.25	69.70 ±0.30	70.00 ±0.30	69.80 ±0.30	70.30 ±0.30	70.70 ±0.30	71.80 ±0.30	70.30 ±0.30	70.50 ±0.30

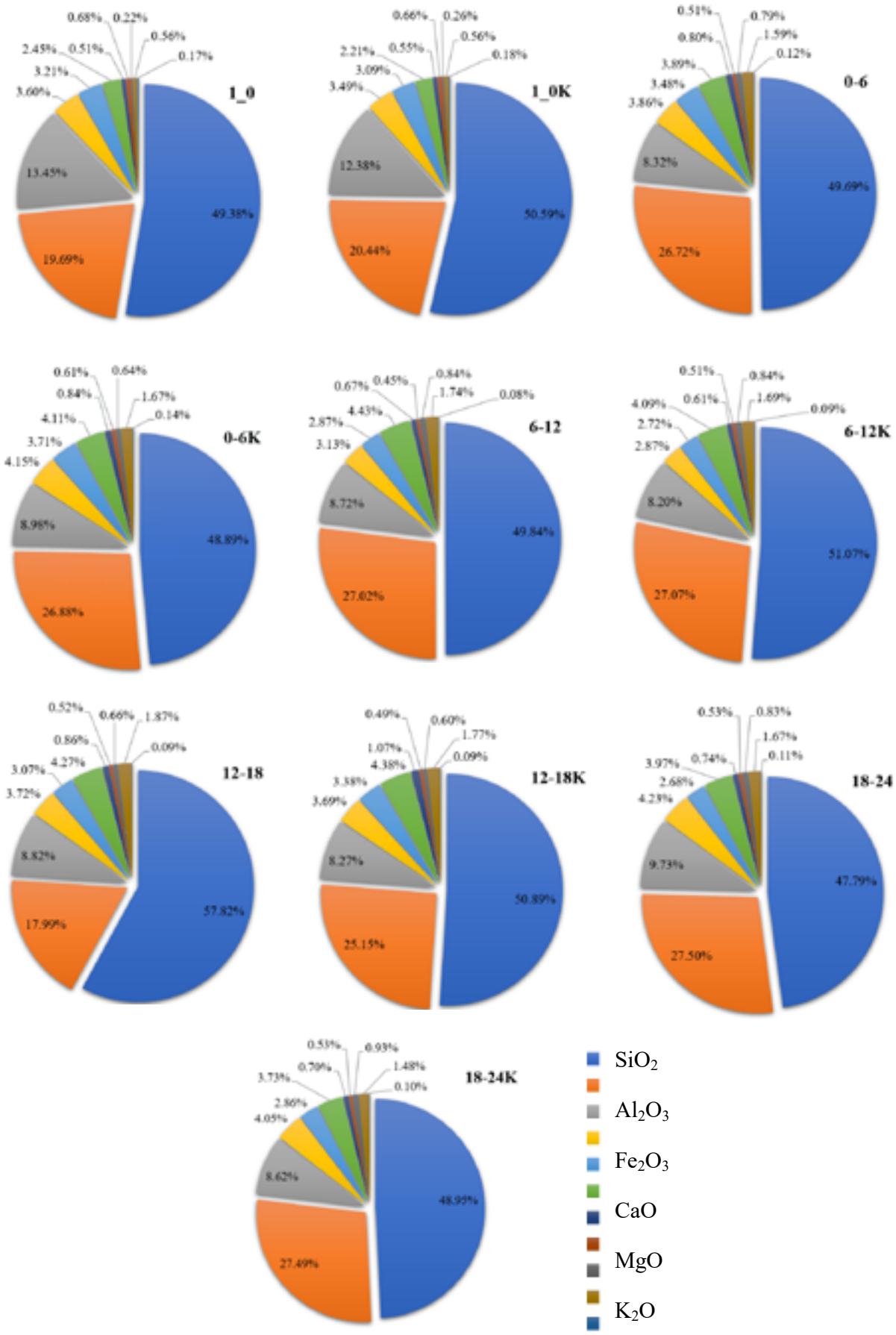


Fig. 2. Chemical composition of the ash-slag mixtures

a product of the thermal decomposition of clay minerals and other aluminosilicates (Font et al. 2010). This mineral is characterized by a high melting point (approximately 1850 °C) and low thermal expansion, which imparts materials containing mullite with significant resistance to temperature fluctuations. The presence of mullite also increases hardness and abrasion resistance, which is advantageous in applications requiring high mechanical strength (Sultana et al. 2011). Calcite is also an important mineral component, as it can influence the chemical stability of the waste by reducing its reactivity and contribute to the immobilization of heavy metals and other contaminants, which may limit their leaching (Maeda et al. 2011).

The transformation of the phase composition of deposited waste is a natural and inevitable process. Adamczyk and Nowak (2013) observed significant changes occurring in slag mass after several years of landfilling. They also reported differences in phase composition between samples collected from different landfill depths. However, and this is crucial for achieving the research objective of this study, the mineral compositions of the analyzed mixtures did not change after the waste was subjected to simulated weathering and aging conditions. The invariability of the phase composition provides essential information on the stability of the tested waste, which is of importance for its potential future utilization.

A parameter indicating the environmental safety of the ash-slag mixtures is their low tendency for heavy metal leaching (Table 3). In all five tested samples, the release of As, Ba, Cr, Mo, Sb, and Se was observed. The total leachability of these elements ranged from 1.04 to 1.56 mg/$kg_{d.m.}$, depending on the sampling depth. However, based on a comparison with the leaching limit values for landfill acceptance specified in the applicable legal regulations (Ministry of Economy 2015), the tested waste may be classified as non-hazardous waste, since the limit values for acceptance at inert waste landfills were exceeded for Cr, Sb, and Se. The concentrations of the remaining analyzed heavy metals were below the limit of quantification. The low contamination of the water extracts with dissolved ions was also confirmed by the specific electrical conductivity (EC) measurements. As a result of the influence of humidity, temperature, and UV irradiation, slightly lower concentrations of released metals were generally observed. In most cases, these differences were within the range of measurement uncertainty.

The obtained results indicate only minor differences in heavy metal leaching between the analyzed depth intervals, with no consistent depth-dependent trend. In particular, the data do not show systematic enrichment of the 6-12 m layer that could be attributed to downward migration of metals leached from the overlying 0-6 m layer. Although arsenic showed a higher leaching value at 6-12 m than at 0-6 m, this pattern was not observed for the other analyzed elements, and no monotonic increase with depth was found. Thus, under the conditions of this study, the leaching behavior appears to be controlled mainly by the mineral composition of the ash-slag mixtures. Szwalec et al. (2017) also reported low concentrations of heavy metals in water extracts from ash mixtures originating from the Skawina Power Plant waste landfill (Poland). Literature reports suggest that the low release of these elements results from their predominant association with stable aluminosilicate phase structures (Horckmans et al. 2006. Rao et al. 2008). Metals bound to silicates and the amorphous phase are considered immobile and of no significant toxicological relevance.

A key parameter influencing the leachability of heavy metals is pH. Alkaline conditions enhance the adsorption efficiency of heavy metals, thereby limiting their release into the aqueous environment (Nocoń et al. 2025, Wang et al. 2024). Water extracts from ash-slag mixtures collected from the surface layer of the landfill exhibited a pH of 9.8 (Table 3). For the remaining samples, this parameter ranged from 8.9 to 8.5. The decrease in pH in deeper layers of the deposited waste resulted from binding reactions occurring within the mixtures. Additionally, during landfilling, the material's acid neutralization capacity could be reduced due to the leaching of contaminants by infiltrating water, which in turn led to a pH drop (Astrup et al. 2006). Literature reports (Adamczyk and Nowak 2013, Szwalec et al. 2017) indicate that the pH of eluates from ash-slag mixtures may decrease to nearly neutral values ($6.5 \leq pH \leq 7.8$). Importantly, the ash-slag mixtures investigated in this study retained a slightly alkaline pH. Furthermore, the pH values did not change significantly after the samples were subjected to exposure in chambers. The alkaline nature of these waste materials is a desirable feature. In the case of their application, for example, as cement additives, it promotes chemical reactions that are essential for cement hydration and hardening.

In summary, as demonstrated in studies (Brännvall et al. 2014, Catalano et al. 2012, Faragó et al. 2023, Nocoń et al. 2023, Zhu et al. 2021, Żygadło and Woźniak 2009), aging processes of wastes, as well as other atmospheric factors such as temperature fluctuations, influence changes in waste composition and heavy metal leaching levels. However, as shown in this study, the investigated ash-slag mixtures, despite being exposed to weathering processes, exhibited chemical stability. This is significant for their potential industrial application. It is assumed that natural leaching processes of mobile forms of heavy metals occurred during the long-term storage of these wastes. From an environmental protection perspective, landfill disposal remains the least desirable management method due to the risk of leaching harmful substances by infiltrating rainwater percolating through the deposited waste mass. This phenomenon can lead to contamination of groundwater or surface waters over a considerable area. On the other hand, weathering and aging processes occurring over many years in the landfill have enabled the formation of a potential industrial raw material. Obviously, whether the investigated ash-slag mixtures meet all the requirements for industrial use requires further in-depth research.

Conclusions

This work investigated ash-slag mixtures originating from coal-fired power generation that were subjected to simulated weathering conditions. Based on the results of the study, it was concluded that the samples collected from the landfill at depths below 1 meter exhibited a higher content of the amorphous phase and a lower quartz content compared to samples from the surface layer of the landfill. Natural phase transformations in the tested materials occurred during several decades of storage, and no further significant changes in phase composition were observed under additional simulated exposure to weathering processes. Leaching tests showed the

Table 3: Values of pH and electrical conductivity (EC) of water extracts and leached concentrations of heavy metals in the leaching test (mean ± SD, *n* = 3)

Parameter	1_0	1_0K	0-6	0-6K	6-12	6-12K	12-18	12-18K	18-24	18-24K
pH (-)	9.76 ±0.02	9.26 ±0.02	8.88 ±0.01	8.85 ±0.01	8.76 ±0.04	8.44 ±0.06	8.64 ±0.00	8.63 ±0.01	8.47 ±0.03	8.41±0.09
EC (µS/cm)	1148 ±25	1166 ±35	743 ±1	788 ±5	802 ±3	811 ±28	1056 ±23	1032 ±13	1109 ±23	1126 ±5
As (mg/kg$_{d.m.}$)	0.10 ±0.03	0.12 ±0.01	0.23 ±0.02	0.16 ±0.00	0.34 ±0.00	0.24 ±0.03	0.19 ±0.08	0.18 ±0.01	0.21 ±0.00	0.12 ±0.02
Ba (mg/kg$_{d.m.}$)	0.61 ±0.02	0.64 ±0.05	0.66 ±0.00	0.85 ±0.17	0.55 ±0.00	0.68 ±0.05	0.59 ±0.02	0.57 ±0.01	0.93 ±0.30	0.49 ±0.00
Cd (mg/kg$_{d.m.}$)	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cr (mg/kg$_{d.m.}$)	0.03 ±0.01	0.02 ±0.00	0.11 ±0.01	0.06 ±0.03	0.02 ±0.00	<0.02	0.06 ±0.02	0.03 ±0.01	0.07 ±0.01	0.02 ±0.00
Cu (mg/kg$_{d.m.}$)	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Mo (mg/kg$_{d.m.}$)	0.04 ±0.01	0.01 ±0.01	0.14 ±0.01	0.09 ±0.01	0.11 ±0.00	0.06 ±0.01	0.16 ±0.00	0.10 ±0.00	0.13 ±0.01	0.12 ±0.00
Ni (mg/kg$_{d.m.}$)	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Pb (mg/kg$_{d.m.}$)	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06
Sb (mg/kg$_{d.m.}$)	0.12 ±0.03	0.05 ±0.01	0.07 ±0.01	0.05 ±0.01	0.04 ±0.01	0.04 ±0.01	0.10 ±0.03	0.08 ±0.01	0.07 ±0.01	0.06 ±0.01
Se (mg/kg$_{d.m.}$)	0.15 ±0.03	0.13 ±0.01	0.11 ±0.05	0.10 ±0.01	0.12 ±0.05	<0.08	<0.08	<0.08	0.15 ±0.04	0.10 ±0.00
Zn (mg/kg$_{d.m.}$)	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
Hg (mg/kg$_{d.m.}$)	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005

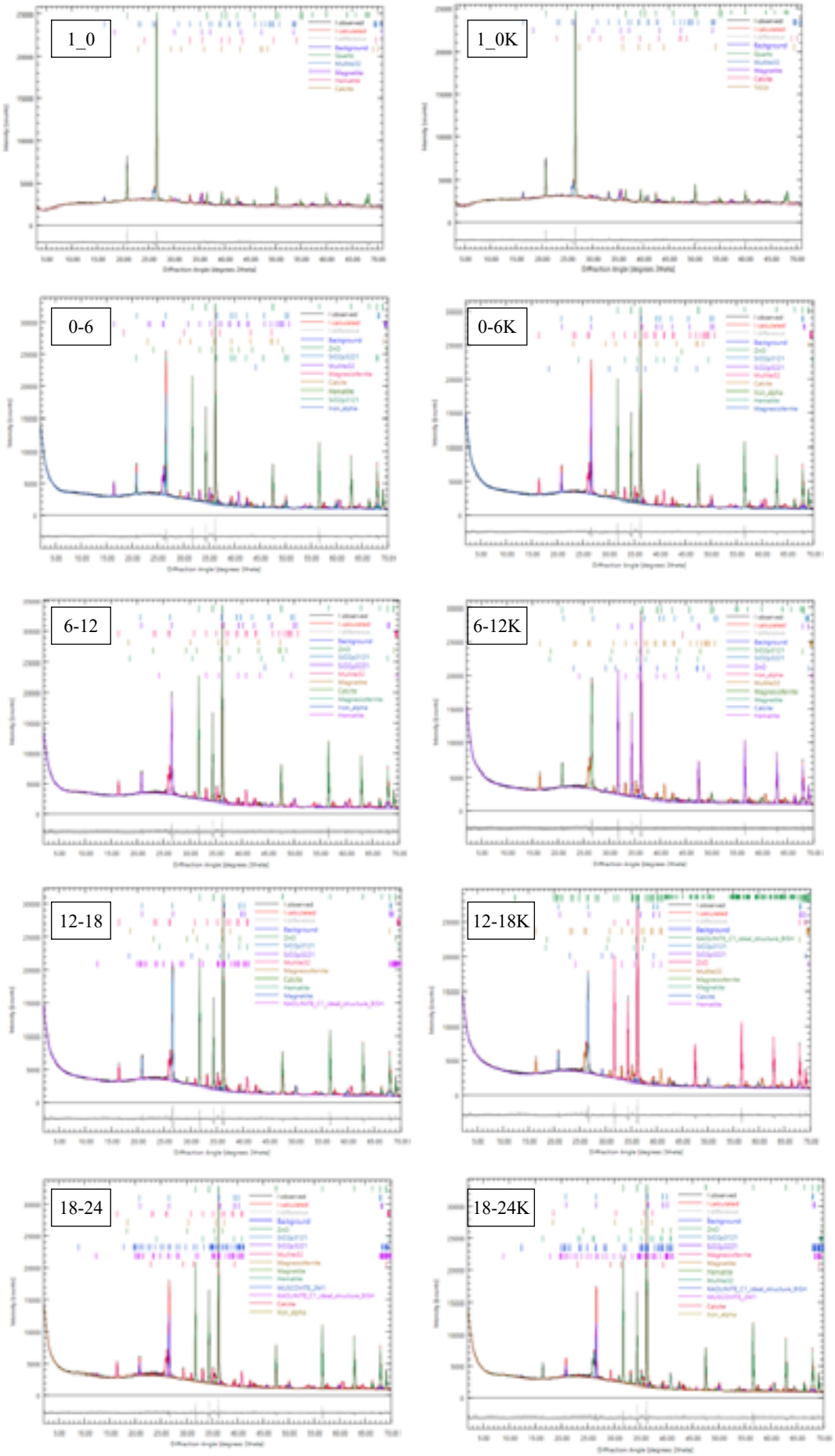


Fig 3. Diffractograms of ash-slag mixture samples

release of As, Ba, Cr, Mo, Sb, and Se among the 12 analyzed elements, and the recorded values remained low. Moreover, no consistent increase in heavy metal release was observed after exposure to water, variable temperature, and UV radiation. These findings indicate a limited susceptibility of the studied material to changes in chemical release under the applied experimental conditions.

The obtained results provide a basis for further evaluation of ash-slag mixtures as a secondary raw material, for example in the cement industry, and may serve as a foundation for developing quality criteria for the industrial application of such waste. Currently, ash-slag mixtures do not meet the criteria for classification as fly ash or slag suitable for use in cement. However, considering their potential future application, comprehensive studies are required, focusing on key parameters such as moisture content, unburned carbon content, water demand, activity index, reactive SiO_2 content, and natural radioactivity. At the same time, any future industrial application should also take into account technological feasibility and logistical constraints related to waste excavation, handling, and transport.

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Data Availability

The data on heavy metal leaching produced by this study are available at https://data.mendeley.com/datasets/2btzb2z2yb/1.

References

Adamczyk, Z., Komorek, J., Białecka, B. & Nowak, J. (2024). Assessing the Potential of Rare Earth Elements in Bottom Ash from Coal Combustion in Poland. *Materials,* 17, 17, 4323. DOI:10.3390/MA17174323

Adamczyk, Z. & Nowak, J. (2013). Transformations of the phase composition of bottom ash slags in a landfill isolated from the environment, *Górnictwo i Geologia*, 8, 1, pp. 5–16. (in Polish)

Astrup, T., Mosbæk, H. & Christensen, T. H. (2006). Assessment of long-term leaching from waste incineration air-pollution-control residues. *Waste Management*, 26, 8, pp. 803–814. DOI:10.1016/J.WASMAN.2005.12.008

Brännvall, E., Andreas, L., Sjöblom, R. & Lagerkvist, A. (2014). Changes of Fly Ash Properties during Aging. *Journal of Environmental Engineering*, 141, 5, 04014083. DOI:10.1061/(ASCE)EE.1943-7870.0000910

Catalano, J. G., Huhmann, B. L., Luo, Y., Mitnick, E. H., Slavney, A. & Giammar, D. E. (2012). Metal release and speciation changes during wet aging of coal fly ashes. *Environmental Science and Technology*, 46, 21, pp. 11804–11812. DOI:10.1021/ES302807B

Cheng, Y., Li, Z., Zhang, P., Chen, J. & Qin, C. (2025). CO2 mineralization and heavy metal leaching of multi-source ashes from municipal solid waste incineration. *Separation and Purification Technology*, 354, 128825. DOI:10.1016/j.seppur.2024.128825

Faragó, T., Špirová, V., Blažeková, P., Lalinská-Voleková, B., Macek, J., Jurkovič, Ľ., Vítková, M. & Hiller, E. (2023). Environmental and health impacts assessment of long-term naturally-weathered municipal solid waste incineration ashes deposited in soil-old burden in Bratislava city, Slovakia. *Heliyon*, 9, 3, e13605. DOI:10.1016/J.HELIYON.2023.E13605

Font, O., Moreno, N., Querol, X., Izquierdo, M., Alvarez, E., Diez, S., Elvira, J., Antenucci, D., Nugteren, H., Plana, F., López, A., Coca, P. & Peña, F. G. (2010). X-ray powder diffraction-based method for the determination of the glass content and mineralogy of coal (co)-combustion fly ashes. *Fuel*, 89, 10, pp. 2971–2976. DOI:10.1016/J.FUEL.2009.11.024

Gruchot, A. & Zydroń, T. (2013). Geotechnical Parameters of the Ash-slag Mixture from Hard Coal Burning Concerning Its Usability for Earthworks. *Annual Set The Environment Protection*, 15, pp. 1719–1737. (in Polish)

Horckmans, L., Swennen, R. & Deckers, J. (2006). Geochemical and mineralogical study of a site severely polluted with heavy metals (Maatheide, Lommel, Belgium). *Environmental Geology*, 50, 5, pp. 725–742. DOI:10.1007/S00254-006-0245-X/FIGURES/8

Hycnar, J. J., Szczygielski, T., Lysek, N. & Rajczyk, K. (2014). Means of optimizing coal combustion product utilization. *Piece Przemysłowe & Kotły*, 5–6, pp. 36–47

Journal of Laws of the Republic of Poland. (2015). *Regulation of the Minister of Economy of the Republic of Poland of 16 July 2015 on the acceptance of waste for landfill disposal (Journal of Laws, 2015, item 1277)*.

Journal of Laws of the Republic of Poland. (2016). *Regulation of the Minister of the Environment of 1 September 2016 on the manner of assessing contamination of the land surface (Journal of Laws, 2016, item 1395).*

Journal of Laws of the Republic of Poland. (2020). *Regulation of the Minister of Climate of 2 January 2020 on the Waste Catalogue (Journal of Laws, 2020, item 10)*.

Kolias, S., Kasselouri-Rigopoulou, V. & Karahalios, A. (2005). Stabilisation of clayey soils with high calcium fly ash and cement. *Cement and Concrete Composites*, 27, 2, pp. 301–313. DOI:10.1016/J.CEMCONCOMP.2004.02.019

Liu, Y., Wu, S., Southam, G., Chan, T. S., Lu, Y. R., Paterson, D. J. & Huang, L. (2021). Bioaugmentation with Acidithiobacillus species accelerates mineral weathering and formation of secondary mineral cements for hardpan development in sulfidic Pb-Zn tailings. *Journal of Hazardous Materials*, 411, 124988. DOI:10.1016/J.JHAZMAT.2020.124988

Maeda, H., Imaizumi, H. & Ishida, E. H. (2011). Utilization of calcite and waste glass for preparing construction materials with a low environmental load. *Journal of Environmental Management*, 92, 11, pp. 2881–2885. DOI:10.1016/J.JENVMAN.2011.06.021

Veolia EKOZEC. (2025). Ash-slag mixtures, (https://ekozec.pl/produkty/uboczne-produkty-spalania/mieszanka-popiolowo-zuzlowa (2026-02-20)) (in Polish)

Mizerna, K. & Król, A. (2023). The importance of time and other determinants in the assessment of heavy metals release during solid waste management. *Scientific Reports*, 13, 1, 1651. DOI:10.1038/s41598-023-28926-0

Nocoń, M., Korus, I. & Kamińska, G. (2025). Leaching of heavy metals from post-neutralization sludge from zinc and lead metallurgy using complexing, alkaline and acidic agents. *Desalination and Water Treatment*, 322, 101148. DOI:10.1016/J.DWT.2025.101148

Nocoń, M., Korus, I. & Loska, K. (2023). Quantitative and qualitative analysis of slags from zinc and lead metallurgy. *Archives of Environmental Protection*, 49, 3, pp. 26–37. DOI:10.24425/aep.2023.147326

Rao, C. R. M., Sahuquillo, A. & Lopez Sanchez, J. F. (2008). A review of the different methods applied in environmental geochemistry for single and sequential extraction of trace elements in soils and related materials. *Water, Air, and Soil Pollution*, 189, 1-4, pp. 291–333. DOI:10.1007/S11270-007-9564-0/TABLES/11

Słomkiewicz, P., Dołęgowska, S., Piekacz, K., Wideł, D. & Włodarczyk-Makuła, M. (2025). A new ecological mineral-carbonaceous material for adsorption of organic pollutants - A step towards a circular economy. *Archives of Environmental Protection*, 51, 2, pp. 62–72. DOI:10.24425/aep.2025.154757

Statistic Poland. (2024). *Environmental Protection 2024*, (http://stat.gov.pl (2026-02-20))(in Polish)

Sultana, P., Das, S., Bagchi, B., Bhattacharya, A., Basu, R. & Nandy, P. (2011). Effect of size of fly ash particle on enhancement of mullite content and glass formation. *Bulletin of Materials Science*, 34, 7, pp. 1663–1670. DOI:10.1007/S12034-011-0374-Z/METRICS

Szwalec, A., Gruchot, A., Mundała, P., Zawisza, E. & Kędzior, R. (2017). Physicochemical and geotechnical properties of an ash-slag mixture deposited on a landfill in terms of its use in engineering. *Geology, Geophysics and Environment*, 43, 2, pp. 127–127. DOI:10.7494/GEOL.2017.43.2.127

Wang, F., Li, W., Wang, H., Hu, Y. & Cheng, H. (2024). The leaching behavior of heavy metal from contaminated mining soil: The effect of rainfall conditions and the impact on surrounding agricultural lands. *Science of The Total Environment*, 914, 169877. DOI:10.1016/J.SCITOTENV.2024.169877

Wang, H., Ju, C., Zhou, M., Chen, J., Kan, X., Dong, Y. & Hou, H. (2022). Acid rain-dependent detailed leaching characteristics and simultaneous immobilization of Pb, Zn, Cr, and Cd from hazardous lead-zinc tailing. *Environmental Pollution*, 307, 119529. DOI:10.1016/J.ENVPOL.2022.119529

Zhou, J., Liu, Z., Li, Z., Xie, R., Jiang, X., Cheng, J., Chen, T. & Yang, X. (2025). Heavy metals release in lead-zinc tailings: Effects of weathering and acid rain. *Journal of Hazardous Materials*, 483, 136645. DOI:10.1016/J.JHAZMAT.2024.136645

Zhu, J., Wei, Z., Luo, Z., Yu, L. & Yin, K. (2021). Phase changes during various treatment processes for incineration bottom ash from municipal solid wastes: A review in the application-environment nexus. *Environmental Pollution*, 287, 117618. DOI:10.1016/J.ENVPOL.2021.117618

Żygadło, M. & Woźniak, M. (2009). Observations of changes in the properties of coal ash during weathering processes. *Energetyka*, 11, pp. 771–775. (in Polish)

Ocena stabilności chemicznej i mineralnej mieszanin popiołowo-żużlowych oraz wymywalności metali ciężkich w warunkach symulowanego wietrzenia

Streszczenie. Odpady stałe pochodzące ze spalania węgla, zdeponowane na składowiskach wiele lat temu, mogą stanowić potencjalne źródło surowców wtórnych do przemysłowych zastosowań. Wymaga to jednak zbadania szerokiego zakresu parametrów tych odpadów. Celem badań było określenie zmian składu chemicznego i mineralogicznego mieszanin popiołowo-żużlowych pochodzących z energetyki opartej na spalaniu węgla, a także wymywalności metali ciężkich pod wpływem przyspieszonych procesów wietrzenia. Badania przeprowadzono z wykorzystaniem próbek pobranych z różnych głębokości składowiska mieszanin popiołowo-żużlowych. Próbki poddano innowacyjnym testom w komorze symulującej zmienne warunki wilgotności i temperatury, a następnie starzeniu w oddzielnej komorze zaprojektowanej przede wszystkim do oceny wpływu promieniowania ultrafioletowego. Analiza składu chemicznego wykazała dominację krzemionki, glinu i żelaza oraz jedynie niewielkie zmiany po przeprowadzonych procesach symulacyjnych. Metody dyfrakcji rentgenowskiej potwierdziły obecność faz amorficznych, kwarcu, mulitu i hematytu, a także kalcytu jako fazy wtórnej powstałej podczas długotrwałego składowania. Metale ciężkie wykazywały niską wymywalność (łącznie ≤ 1,56 mg/kg s.m.), a ich stężenia pozostawały poniżej dopuszczalnych limitów dla składowisk odpadów innych niż niebezpieczne. Stabilność pH oraz brak istotnych zmian w składzie mineralnym po przeprowadzonych badaniach wskazują na dobrą odporność mieszanin na procesy wietrzenia.