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Original Article

Heavy-Metal Immobilization in Municipal Solid Waste Incineration Fly Ash Using Akadama Soil–Mixed Geopolymer Solidification

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Abstract

Municipal solid waste incineration (MSWI) fly ash contains hazardous metals that may leach into the environment after landfill disposal. This study investigated Akadama soil–mixed geopolymer solidification as a cement-free stabilization and detoxification treatment for MSWI fly ash. Dried fly ash and Akadama soil were mixed at a 1:1 mass ratio, activated with 33 wt% sodium hydroxide solution, molded, and oven-dried to produce geopolymer solidification bodies. Leaching behavior was evaluated for As, Cd, Cr, Pb, Fe, Mn, Sr, and Zn using a standard procedure and a 28-day tank leaching test. Elemental concentrations were determined by ICP-AES. Unconfined compressive strength and resistance to accelerated ultraviolet irradiation were also examined. The treatment successfully produced a solid monolithic matrix and substantially suppressed heavy-metal release. Leached concentrations were below regulatory limits for all investigated elements except Pb. Tank-test concentrations were generally lower than those obtained from powdered samples, demonstrating the importance of monolithic integrity in limiting water contact. The initial compressive strength was 0.800 MPa, below the 0.98 MPa landfill criterion, and decreased to 0.350 MPa after UV exposure. Despite this mechanical deterioration, metal leaching showed no significant increase. Akadama soil–mixed geopolymerization is therefore promising, although strength enhancement and improved Pb immobilization remain necessary.

Keywords: : MSWI fly ash, Akadama soil, Geopolymer solidification, Heavy-metal leaching, Waste stabilization

1. Introduction

Municipal solid waste incineration (MSWI) fly ash is characterized by the concentration of heavy metals contained in municipal waste. After landfill disposal, there is a risk of these metals leaching into the environment through contact with environmental water, such as rainwater. To understand the leaching behavior and toxicity of these elements, various studies have been conducted, including crystalline phase analysis, elemental analysis, and chemical speciation (Davidovits, 1989; Lam et al., 2010; Toniolo and Boccaccini, 2017). MSWI fly ash is classified as “specially controlled general waste” and is disposed of in final landfill sites after undergoing intermediate treatment as prescribed by the Minister of Health, Labour and Welfare (Odion et al., 2019). Currently, solidification/stabilization using cement is widely employed as an intermediate treatment method for the detoxification of fly ash before landfilling (Rios et al., 2016; Fujii et al., 2018; Kaseda et al., 2024). However, cement solidification faces issues such as the deterioration of the solidified body due to organic acids and

carbon dioxide generated during waste decomposition (Zhang et al., 2012; Kaseda et al., 2025). As a cement-free detoxification method, Geopolymer Solidification (GS) has gained attention (Altaher et al., 2025). The GS method is noted for being an environmentally friendly detoxification process with low CO_2emissions (Gürses et al., 2023). Investigations into its inhibition mechanisms and performance are ongoing (Borthakur et al., 2026). The GS bodies obtained through this process are expected to serve as alternatives to conventional Portland cement-based concrete, and research is actively progressing in this area (Bonde et al., 2024; Lu and Sun, 2025).The GS method is a process for producing amorphous polymers through the reaction between aluminosilicates (reactive fillers) and alkaline solutions (Lu and Sun, 2025). Solidification occurs via the alkaline dissolution of the reactive aluminosilicate precursors and the subsequent polycondensation reaction of leached silicate (SiO_4^{4-}) and aluminate (AlO_4^{5-}) monomeric species, forming a three-dimensional amorphous to semi-crystalline aluminosilicate network.. Although reactive fillers are mixed as raw materials for the GS body, there are few studies regarding the specific types of these fillers (Gürses et al., 2023). It has been reported that using MSWI fly ash as a raw material for aluminosilicates allows hazardous elements within the ash to be fixed within the geopolymer structure, thereby achieving detoxification through stabilization (Barbhuiya et al., 2025). Additionally, to prevent the release of hazardous substances into the environment via water, soil layers are often placed beneath disposal sites for specific general (industrial) wastes like MSWI fly ash (Ram et al., 2023; Somadas and Sarvade, 2025). Since both MSWI fly ash and soil contain high amounts of silicates and aluminates, we focused on a method to produce GS bodies simply by adding an aqueous sodium hydroxide solution to a mixture of fly ash and soil. In this study, assuming a landfill soil environment, we attempted to suppress the leaching of heavy metals by solidifying a mixture of MSWI fly ash and soil using the GS method. Because this treatment involves creating GS bodies from a fly ash-soil mixture acting as a reactive filler, it is referred to as the "MSWI fly ash-soil mixed GS method."Although alkali-activated materials and conventional geopolymers (e.g., based on fly ash and metakaolin) have been extensively investigated for toxic metal encapsulation (e.g., Barbhuiya et al., 2025), the application of naturally weathered volcanic ash soils—specifically Akadama soil (Kanto loam)—remains scarcely explored beyond radiocesium remediation. Akadama soil possesses distinctive mineralogical characteristics, notably an abundance of amorphous allophane and imogolite phases, high specific surface area, and exceptional variable-charge ion exchange capacity. Solidifying municipal solid waste incineration (MSWI) fly ash using an Akadama-soil-based geopolymer system (GS method) provides a dual stabilization mechanism: physical entrapment within the three-dimensional aluminosilicate gel matrix and specific chemisorption/ion exchange onto the volcanic soil mineral surfaces. Thus, this study systematically evaluates the encapsulation efficiency of toxic heavy metals (As, Cd, Cr, and Pb) from high-alkali MSWI fly ash using the GS method, establishing optimal binder-to-soil proportions and assessing long-term leaching stability.As a result of examining this mixed GS method, it was found that *Akadama* soil—a major soil type of the Kanto Loam layer—was effective in suppressing the leaching of radioactive cesium. Soil formed from weathered volcanic sediments possesses the ability to adsorb heavy metals and organic matter due to the influence of clay minerals, as well as oxides and hydroxides of Fe and Al, and humus content. Previous studies verified the "Akadama soil-mixed GS method" and suggested that the adsorption capacity of the soil worked effectively for radioactive cesium; however, an evaluation of its effectiveness in suppressing heavy metal leaching has not yet been conducted. In this study, considering that the leaching suppression mechanism for radioactive cesium might also be applicable to heavy metals, we produced MSWI fly ash-Akadama soil mixed GS bodies using readily available volcanic Akadama soil.

2. Experimental

2.1. MSWI Fly Ash and Soil Samples

Municipal solid waste incineration (MSWI) fly ash collected from a typical MSWI facility (furnace type: stoker-type incineration plant; capacity: 40 tons/day × 2 furnaces) was used as the sample. In this incineration facility, slaked lime spraying was employed for flue gas treatment, and the MSWI fly ash was collected using a bag filter. The MSWI fly ash had a particle size ranging from 0.1 to 1000 μm²⁴⁾. Quantitative analysis of the sample had been previously performed for crystalline phases by powder X-ray diffraction (XRD), major elements by X-ray fluorescence (XRF), and heavy metal elements by inductively coupled plasma atomic emission spectrometry (ICP-AES) ^{3),5)}. As for the soil sample used in the GS method, Akadama soil (Akagi Engei Co., Ltd.)—prepared by drying, crushing, and sieving red soil from the Kanto Loam layer—was utilized.

2.2. Preparation of MSWI Fly Ash–Soil Mixed GS Bodies

The MSWI fly ash and Akadama soil were first dried and homogenized before use. The required quantities of fly ash and Akadama soil were weighed according to the prescribed mixing ratio and thoroughly blended. A 33 wt.% NaOH solution was then added at a constant solid-to-liquid ratio of 1:0.5. The mixture was mechanically stirred until a visually homogeneous paste was obtained. The paste was subsequently transferred into molds and compacted under the same conditions for all formulations. After molding, the specimens were cured under the conditions described below before being subjected to the leaching and mechanical tests.

The experiments were conducted as preliminary single measurements; therefore, the reported values should be interpreted as indicative rather than statistically validated results. No formal significance testing was performed, and the absence of error bars reflects the lack of independent replicate measurements.

2.3. Experimental design and selection of mixing ratios.

The present study was designed as a proof-of-concept investigation to evaluate whether Akadama soil could improve the immobilization of heavy metals in MSWI fly ash through the GS method. The initial formulation was selected on the basis of the workability of the mixture, the formation of a sufficiently coherent solid body, and the preliminary leaching performance. Accordingly, the NaOH concentration and the solid-to-liquid ratio were kept constant, while the fly ash-to-Akadama soil mass ratio was varied. This single-factor design enabled the specific effect of the soil fraction on heavy-metal leaching to be evaluated without introducing simultaneous changes in other processing variables. The effects of alkali concentration, curing conditions, and activator composition were not systematically optimized in the present study and should therefore be investigated in future work.

The NaOH concentration was fixed at 33 wt.% and the solid-to-liquid ratio was maintained at 1:0.5 throughout the experiments. These values were selected to provide adequate alkaline activation and sufficient workability during mixing and molding.

2.4. Heavy Metal Leaching Test

Leaching tests were conducted on the municipal solid waste incineration (MSWI) fly ash, Akadama soil, the prepared GS bodies, and the samples after the accelerated ultraviolet irradiation test, in accordance with Notification No. 13 of the Environment Agency of Japan (Environment Agency, Japan, 1973).

Because the present study was designed as a single-factor evaluation, the optimization focused on the fly ash-to-Akadama soil mass ratio while the NaOH concentration and solid-to-liquid ratio were maintained constant. The results therefore indicate the influence of the soil proportion under the selected processing conditions rather than defining a global optimum for all possible GS formulations.

The formulation containing the selected fly ash-to-Akadama soil ratio showed the lowest leaching concentrations under the tested conditions. Since the experiments were not conducted with independent replicates, this result should be regarded as an observed trend rather than a statistically confirmed optimum.

For the test, powdered MSWI fly ash was prepared by crushing it in a mortar, and then mixed with deionized water at a solid-to-liquid ratio of 1:10. The mixture was

shaken at 200 rpm for 6 h at room temperature using a shaker (Advantec, TBK602DA). After completion of the leaching operation, the suspension was filtered through a glass fiber filter (Whatman GF/F, diameter 47 mm) to separate the solid and liquid phases. The filtrate was then brought to a fixed volume and subjected to ICP-AES measurement.

In the Notification No. 13 test, powdered samples are used. However, when considering actual landfill disposal conditions, it is necessary to evaluate leaching from the solidified bodies themselves. Therefore, in this study, a tank leaching test method, which is commonly used for evaluating trace-component release from hardened concrete, was applied to the solidified samples in order to reproduce conditions closer to real landfill environments.

The main differences from the Notification No. 13 test were that the samples were not crushed and not shaken; instead, they were immersed in deionized water at a solid-to-liquid ratio of 1:10 for 28 days. The leachates obtained from the tank leaching test were also analyzed by ICP-AES.

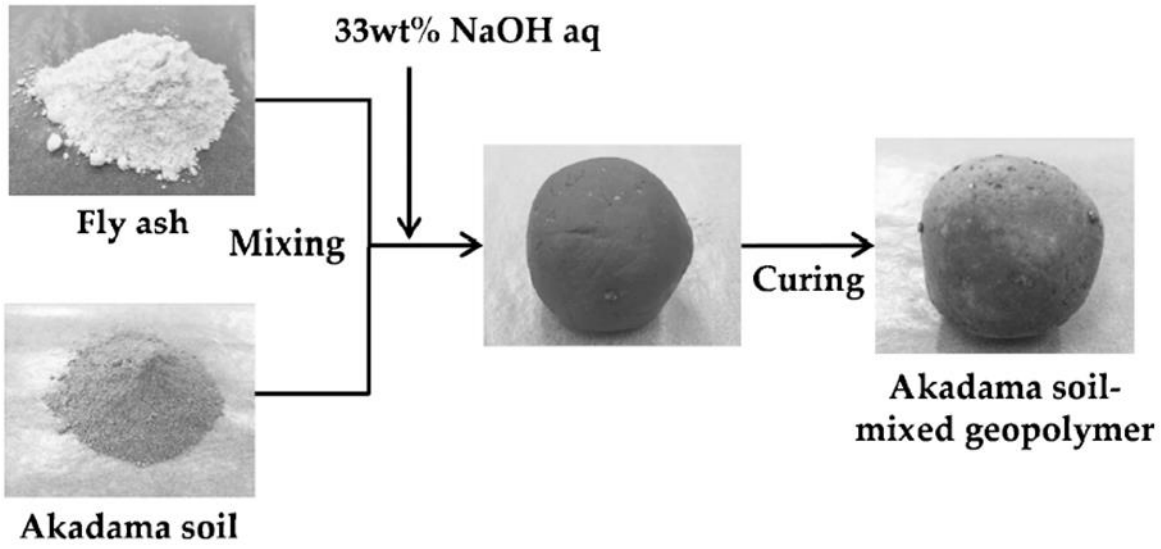


Figure 1. Schematic illustration of the fabrication process for Akadama soil–fly ash geopolymer specimens.

2.5. Experimental Apparatus

Elemental analysis of the solutions was performed using an inductively coupled plasma atomic emission spectrometer (ICP-AES) (iCAP 6500 Duo, Thermo Fisher Scientific). The analytical wavelengths used for each element were as follows: As (189.042 nm), Cd (214.438 nm), Cr (283.563 nm), Fe (238.204 nm), Mn (259.373 nm), Pb (182.205 nm), Sr (215.284 nm), and Zn (202.548 nm). Argon (Ar) was utilized as the purge and plasma gas, and measurements were conducted in the axial direction.

The concentrations of As, Cd, Cr, Fe, Mn, Pb, Sr, and Zn in the leachates were determined by inductively coupled plasma atomic emission spectrometry (ICP-AES). Calibration solutions were prepared over the concentration range of 0.001–2.5 mg L^{-1}, as appropriate for each element. Calibration linearity, blank correction, and quality-control measurements were checked before and during the analytical sequence. Values below the relevant LOD were reported as below the detection limit.

The concentration of each element in the liquefied samples was determined using the external standard method (calibration curve method). Standard solutions for calibration were prepared by appropriately mixing and diluting 1000 $mg \cdot L^{-1}$ ICP-grade multi-element standard stock solutions (Wako Pure Chemical Industries, Ltd.) with 2 $mol \cdot L^{-1}$ nitric acid. A series of multi-element working standards with concentrations of 0.001, 0.01, 0.1, 0.25, 0.5, 1.0, and 2.5 $mg \cdot L^{-1}$ were used to construct the calibration curves.

To evaluate the physical properties of the soil-mixed GS bodies, unconfined compressive strength (UCS) tests were conducted using a tabletop universal testing machine (MCT-1150, A&D Co., Ltd.). Additionally,

ultraviolet (UV) degradation tests were performed using a UV irradiation system (QRU-2161-D, ORC Manufacturing Co., Ltd.) equipped with a high-pressure UV lamp (output: 800 W, arc length: 100 mm) for a duration of 24 hours.

Analytical quality was monitored using reagent blanks, calibration verification standards, and, where applicable, duplicate samples. The calibration curves were accepted only when the required linearity criteria were satisfied were used with concentrations outside the calibration range were appropriately diluted and reanalyzed. These quality-control procedures were used to minimize potential contamination, matrix effects, and instrumental drift.

3. Results and Discussion

3.1. Heavy Metal Content and Leaching behavior from MSWI Fly Ash and Soil

To determine the heavy metal content in the municipal solid waste incineration (MSWI) fly ash, approximately 1 g of the fly ash sample was digested with reference to JIS K 0102. Nitric acid alone was selected as the digestion reagent, omitting sulfuric acid to avoid the formation of insoluble white sulfate precipitates $PbSO_4$and $CaSO_4$.

The total heavy metal concentrations in the MSWI fly ash sample measured by ICP-AES were as follows:

- As: Below detection limit (detection limit: $2.72\ \text{mg} \cdot \text{kg}^{-1}$)
- Cd: $97.8 \pm 2.3\ \text{mg} \cdot \text{kg}^{-1}$
- Cr: $176 \pm 17\ \text{mg} \cdot \text{kg}^{-1}$
- Fe: $10.3 \pm 0.2\ \text{g} \cdot \text{kg}^{-1}$
- Mn: $10.2 \pm 0.1\ \text{g} \cdot \text{kg}^{-1}$
- Pb: $9432 \pm 84\ \text{mg} \cdot \text{kg}^{-1}$
- Sr: $1331 \pm 27\ \text{mg} \cdot \text{kg}^{-1}$

Zn: $35.6 \pm 0.1\ \text{g} \cdot \text{kg}^{-1}$

(Note: The detection limit for As represents the value converted from the detection limit of the digested liquid sample to the As concentration in the solid fly ash matrix).

Among the four regulated elements with established landfill disposal thresholds in Japan (As, Cd, Cr, and Pb; Ministry of the Environment Notification No. 13, 1973), the leached concentrations of Cd, Cr, and Pb (excluding As, which was below the analytical detection limit) exceeded their respective regulatory limits by factors of approximately 3.3, 2.0, and 933, respectively, underscoring the necessity of stabilization before disposal.

Next, the leaching behavior of heavy metals from both the MSWI fly ash and the soil was evaluated using ICP-AES. Figure 2 shows the leached amounts of heavy metals determined by the Environment Agency Notification No. 13 leaching test using 5 g of each sample. Among the four regulated elements with established landfill disposal limits (As: 0.3 ppm, Cd: 0.09 ppm, Cr: 0.3 ppm, Pb: 0.3 ppm), Cd, Cr, and Pb (excluding As) were detected at levels approximately 3.3, 2.0, and 933 times higher than their respective regulatory thresholds, highlighting the critical need for stabilization/detoxification treatment. Furthermore, because heavy metal leaching from the soil itself was also observed, subsequent leaching evaluations were conducted taking into account all four leached elements from the soil matrix.

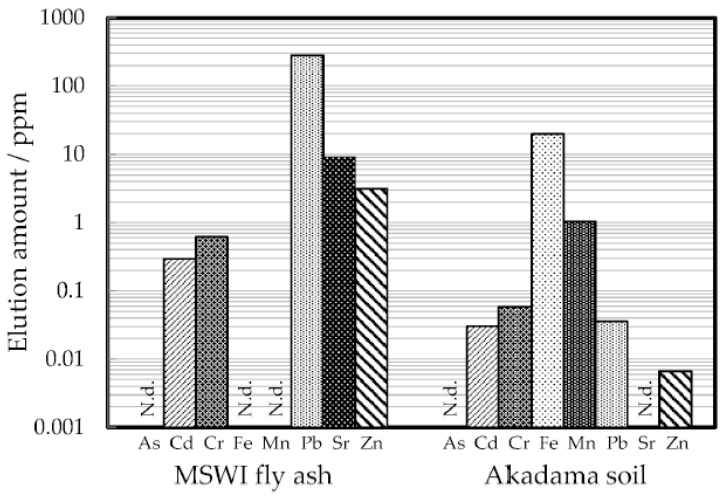


Figure 2. Comparison of heavy metal leachability between untreated MSWI fly ash and Akadama soil based on the Japanese Notification No. 13 test (Environment Agency, Japan, 1973).
N.d. denotes not detected. The analytical detection limits were 0.633 ppb for As, 0.333 ppb for Cd, 1.429 ppb for Cr, 2.54 ppb for Fe, 15.9 ppb for Pb, 2.10 ppb for Sr, and 0.485 ppb for Zn.

3.2. Optimization of the MSWI Fly Ash–to–Soil Mixing Ratio

To optimize the formulation, five types of soil-mixed GS specimens were synthesized with MSWI fly ash–to–Akadama soil mass ratios of 1:1, 1:1.5, 1:2, 1:2.5, and 1:3, followed by the Notification No. 13 leaching test. Table 1 summarizes the heavy metal leaching rates from the MSWI fly ash under varying mixing ratios. The mixing ratio was evaluated based on the heavy metal leaching rate, defined as the percentage of leached heavy metals relative to the total heavy metal content in the fly ash sample.

The leaching rate exhibited an increasing trend as the proportion of soil increased, which can be attributed to the leaching of heavy metals inherently present within the Akadama soil itself. Consequently, a mass ratio of 1:1 (MSWI fly ash : Akadama soil) was identified as the optimal mixing ratio.

As shown in Figure 2, although Cd leached from both the raw MSWI fly ash and Akadama soil, formulating them into the soil-mixed GS matrix reduced the Cd leaching rate to below the detection limit. This indicates that the soil-mixed geopolymerization (GS) process possesses a high encapsulation efficiency for Cd.

To isolate and verify the intrinsic leaching suppression capacity of the soil itself, an unsolidified physical mixture containing 2.5 g of soil and 2.5 g of fly ash (without alkaline activation/GS treatment) was tested under Notification No. 13 conditions (Fig. 3). Overall, the leached amounts from the simple mixture were lower than those from the raw fly ash alone. Because Kanto loam possesses a high adsorption capacity for cationic species such as $Pb^{2+}$and Cd^{2+}compared to other volcanic ash soils, it is inferred that simple physical mixing with soil exerts a partial leaching suppression effect. Therefore, the overall heavy metal immobilization mechanism in the GS process is strongly governed by the inherent physicochemical properties of the incorporated soil. These results indicate that heavy metal immobilization is governed by a combined mechanism: (i) specific chemisorption of cationic species onto the variable-charge surfaces of allophane and imogolite in the volcanic soil fraction, and (ii) physical entrapment and chemical encapsulation within the newly formed three-dimensional aluminosilicate geopolymer gel matrix. The substantial further reduction in leaching observed upon geopolymerization compared to unsolidified physical mixtures confirms that network encapsulation plays an indispensable role alongside soil adsorption.

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Table 1. Influence of fly ash–Akadama soil mass ratios on the elution efficiency of trace elements.

Ratio (fly ash: soil)	**Elution rate, %**				
	1:1	1:1.5	1:2	1:2.5	1:3
As	N.d.	N.d.	N.d.	N.d.	N.d.
Cd	N.d.	N.d.	N.d.	N.d.	N.d.
Cr	0.478	1.42	2.81	1.94	2.44
Fe	0.0143	0.350	0.0614	0.175	0.725
Mn	0.0157	0.0435	0.344	0.0381	0.0416
Pb	0.0253	0.111	0.0359	0.0762	0.613
Sr	0.727	1.57	1.82	0.973	0.889
Zn	0.0151	0.102	0.0351	0.0591	0.0537

N.d. : not detected (Lower limit of detection: As: 0.633 ppb; Cd: 0.333 ppb

3.3. Leaching Behavior of MSWI Fly Ash–Soil Mixed GS Matrix

Figure 3 illustrates the leached amounts of heavy metals from the soil-mixed GS matrix, evaluated in accordance with Environment Agency Notification No. 13. As a result of the leaching tests, all target elements except Pb were reduced to levels well below their respective landfill regulatory thresholds, demonstrating a clear leaching suppression effect. In particular, the leached concentration of Cd from the Akadama soil-mixed GS matrix dropped below the analytical limit of detection.

Comparing the leached concentrations of the four detected elements between the raw MSWI fly ash and the Akadama soil-mixed GS specimens revealed significant reductions:

- Cr: reduced to approximately 1/3

- Pb: reduced to approximately 1/500
- Sr: reduced to approximately 1/19
- Zn: reduced to approximately 1/23

These findings indicate that the Akadama soil-mixed geopolymerization (GS) method serves as an effective stabilization/detoxification route for MSWI fly ash. It is documented that hazardous elemental compounds are adsorbed in proportion to the amount of positively charged amorphous minerals present in soils (Fontes and Alleoni, 2006; Yu et al., 2023). Further investigations incorporating other types of soil are envisioned for future work.

Assuming a municipal waste landfill scenario where the disposed fly ash is compacted to a density of 1 g/cm^3, reaching a liquid-to-solid ratio (L/S, mL/g) of 10 would require approximately 17 to 40 years (Zhang, 2016). Consequently, the batch leaching test conducted in this study (using 50 mL of deionized water and 5 g of sample, corresponding to an L/Sratio of 10) simulates the cumulative metal leaching expected over a period of 17–40 years post-disposal.

However, under actual landfill conditions, the stabilized material would not exist in a pulverized form. Thus, assessing immobilization efficacy purely through the Notification No. 13 test—which requires sample pulverization—risks underestimating the actual leaching suppression capacity of the monolithic GS matrix. To address this limitation, a tank leaching test was conducted, with the results shown in Figure 4.

Although variations depended on the specific metal species, the leached amounts obtained from the Notification No. 13 test were generally higher than those from the tank leaching test. In the Notification No. 13 protocol, the sample is crushed prior to immersion in water, thereby compromising the physical integrity of the monolithic body and significantly increasing the effective contact surface area with water. This surface area expansion is believed to be the primary cause of the elevated heavy metal release observed in the Notification No. 13 batch test.

While the empirical leaching reductions strongly support this synergistic mechanism, further direct spectroscopic and microstructural investigations (e.g., SEM-EDS, XRD, FTIR, and XPS) will be conducted in future studies to elucidate the exact coordination environment and speciation of the encapsulated metals.

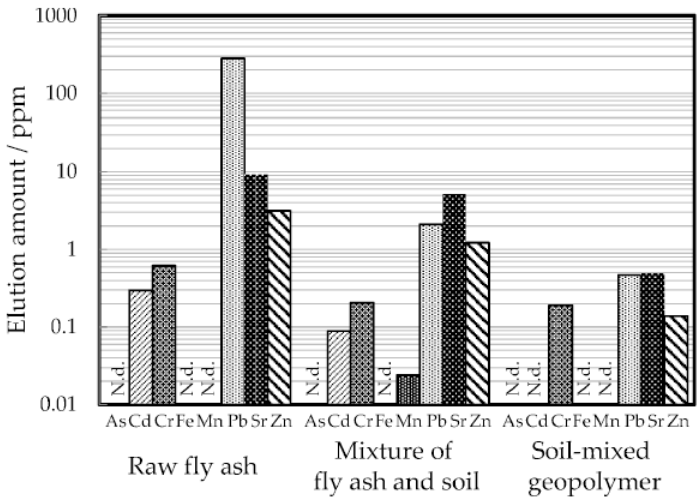


Figure 3. Comparison of heavy metal leaching concentrations obtained via the Japanese Notification No. 13 protocol (Environment Agency, Japan, 1973) for raw MSWI fly ash, a physical mixture of fly ash and Akadama soil, and the synthesized geopolymer matrix.

Note: N.d. denotes results below the analytical detection limits, which remain consistent with Fig. 2.

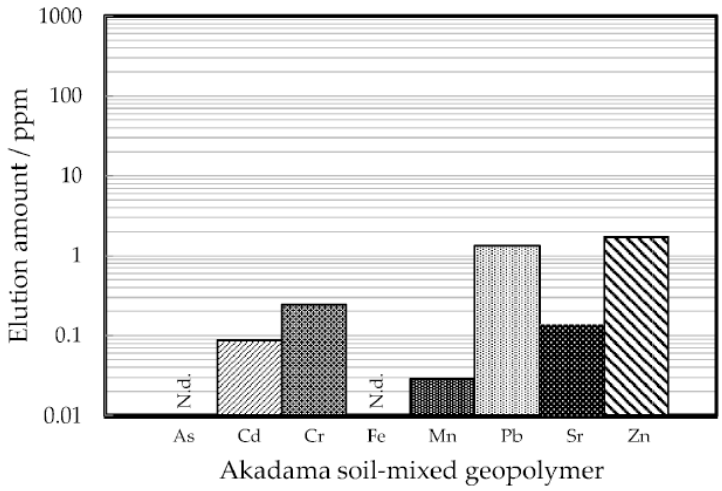


Figure 4. Heavy metal release from the Akadama soil-incorporated geopolymer matrix determined using the tank leaching test methodology.
Detection limits for N.d. (not detected) values are consistent with those reported in Fig. 2.

3.4. Physical Property Evaluation of Soil-Mixed GS Matrix

The compressive strength of the prepared Akadama soil-mixed geopolymer (GS) matrix was 0.800 MPa. Although evaluated with reference to Ministry of the Environment Notification No. 5 (Kaseda et al., 2024, 2025), the resulting strength fell below the landfill disposal criterion of 0.98 MPa. In geopolymerization (GS) processes, the SiO_2/Al_2O_3 molar ratio plays a pivotal role; hence, municipal solid waste incineration (MSWI) fly ash and metakaolin are commonly utilized as aluminosilicate precursors (Tan et al., 2022). The correlation between the Si and Al content within the soil matrix is likewise critical and warrants further investigation. Previous studies have evaluated geopolymer mixtures incorporating soil and recycled concrete aggregate (Rahman and Khattak, 2021; Huang and Wang, 2024; Wang et al., 2024), suggesting that optimizing soil types and additives could lead to more effective monolith formation.To evaluate environmental durability, an ultraviolet (UV) degradation test was conducted on the Akadama soil-mixed GS matrix, assessing both compressive strength and heavy metal leaching behavior before and after UV exposure. Following irradiation, the compressive strength decreased from an initial value of 0.800 MPa to 0.350 MPa (a reduction of more than 50%). The heavy metal leached concentrations before and after UV exposure are summarized in Table 2. Exposure to 24 hours of UV irradiation corresponds approximately to three years of natural solar radiation under actual landfill conditions. Although UV-induced degradation degraded the mechanical strength, no significant differences were observed in heavy metal elution levels before and after exposure.

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Table 2. Heavy metal leaching concentrations from the Akadama soil–incorporated MSWI fly ash geopolymer matrix prior to and following UV exposure, determined via Environment Agency Notification No. 13.
N.d., not detected (analytical limits of detection: 0.633 ppb for As and 2.54 ppb for Fe).

Heavy metals	Elution amount (ppm)	
	Before UV irradiation	After UV irridiation
As	N.d.	N.d.
Cd	0.0875	0.0880
Cr	0.371	0.341
Fe	N.d.	N.d.
Mn	0.0285	0.0275
Pb	2.81	2.07
Sr	0.332	0.243
Zn	1.92	2.22
N.d. : not detected (Lower limit of detection: As: 0.633 ppb; Fe: 2.54 ppb		

4. Conclusions

As a stabilization/detoxification treatment for municipal solid waste incineration (MSWI) fly ash, Akadama soil-mixed geopolymer (GS) monoliths were fabricated, and their leaching suppression efficacy alongside physical properties were systematically investigated. The immobilization performance was evaluated via leaching tests targeting eight heavy metal elements present in the raw fly ash (As, Cd, Cr, Pb, Fe, Mn, Sr, and Zn). Physical integrity and durability were assessed using unconfined compressive strength testing and UV degradation tests.
Key findings of this study are summarized as follows:

1. Under the Ministry of the Environment Notification No. 13 test protocol, heavy metal leaching from the soil-mixed GS matrix remained well below the regulatory thresholds for all target elements except Pb. Significant elution suppression was successfully demonstrated for the four major constituent elements.
2. The MSWI fly ash–Akadama soil geopolymer mixture successfully formed a solid monolith. However, its unconfined compressive strength was 0.800 MPa, which falls short of the regulatory threshold of 0.98 MPa required for landfill disposal. Enhancing the mechanical strength of the GS body remains an objective for future research.
3. Following UV degradation testing, heavy metal leaching levels exhibited no noticeable change, whereas the compressive strength declined by more than half.
4. Given that the SiO_2/Al_2O_3ratio is vital for geopolymerization, employing different aluminosilicate precursors (such as metakaolin Kaseda et al., 2024) may alter both leaching suppression capability and mechanical performance.

In conclusion, optimizing soil formulation and additive selection offers substantial potential for improving the physical and chemical properties of the GS matrix. This geopolymerization approach represents a highly promising detoxification technology for MSWI fly ash, offering key environmental advantages including

volume expansion reduction and suppression of CO_2 emissions.

In the Nb $2p_{3/2}$ spectrum (Fig. 1b), Nb remains stably in the pentavalent dopant state regardless of Pt loading, indicating that the Nb dopant state is not measurably altered by Pt deposition under the present conditions. In contrast, the Sn $3d_{5/2}$ and Sn $3d_{3/2}$ spectra show that the SnO_2 peak near 487 eV shifts toward lower binding energy with increasing Pt loading (Fig. 1c), suggesting an increase in electron density in the support region near the Pt/support interface.A shoulder near 485.5 eV, assigned to PtSn alloy formation, is observed in the Sn 3d region, and its intensity increases with increasing Pt loading (Fig. 1c). This indicates that Pt–Sn interaction becomes more pronounced at higher Pt loading and supports the formation of an alloyed interfacial phase in addition to simple metal–support contact. Taken together, the HAXPES data directly demonstrate that Pt loading modifies the interfacial electronic structure and promotes PtSn-related features in Pt/Nb-SnO_2. Previously reported conductivity measurements showed that the electronic conductivity increased by approximately two orders of magnitude when the Pt loading was increased from [insert value] to [insert value], consistent with relaxation of the electron-depletion layer formed by the Schottky barrier at the Pt/Nb-SnO_2 interface [Shi et al., 2021]. In that earlier study, electron donation from Pt and PtSn formation were proposed to facilitate charge transport across the interface. In the present work, the HAXPES results provide spectroscopic evidence that is consistent with that interpretation, although the conductivity itself was not remeasured here. Therefore, the present contribution is to clarify the interfacial electronic evolution by direct spectroscopic observation, while the conductivity enhancement and its quantitative magnitude should be attributed to the earlier report.

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Declarations

Data and code availability

All data generated or analyzed during this study are available from the corresponding author upon reasonable request. No computational code was used in this study.

Declaration on Artificial Intelligence (AI) Use

The authors declare that Artificial Intelligence (AI) tools were employed in the writing, editing, and language refinement processes of this manuscript. However, all data presented are original and collected by the authors. The research team independently performed the interpretation, analysis, and conclusions drawn from the data. The authors take full responsibility for the content and integrity of this publication.

Conflicts of interest

The authors announced that they have no known conflicts of interest or personal relationships that could have appeared to influence the work reported in this manuscript.

Ethical approval

The authors declare no ethical issues; the research was conducted in full accordance with ethical standards. Also, this paper is neither under Review nor published elsewhere.

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